CS/ECE 439: Wireless Networking

Physical Layer

Fall 2020

Wireless Physical Layer

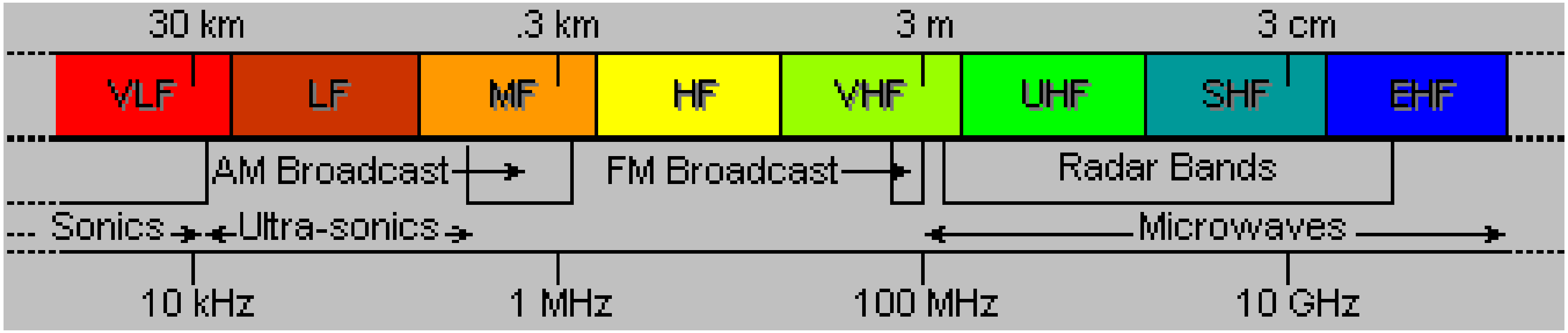
- RF introduction
  - Time versus frequency view
  - A cartoon view
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Modulation and coding
- Spectrum access

Wireless Networks Builds on …

- General networking
  - Internet architecture: who is responsible for what?
  - How is it affected by wireless links or congestion in wireless multi-hop networks?
  - How is it affected by mobility?
  - How about variable link properties and intermittent connectivity?
- Wireless communications
  - How does signal environment affect performance of a wireless link?
  - What wireless communication challenges can be hidden from higher layer protocols?

RF Introduction

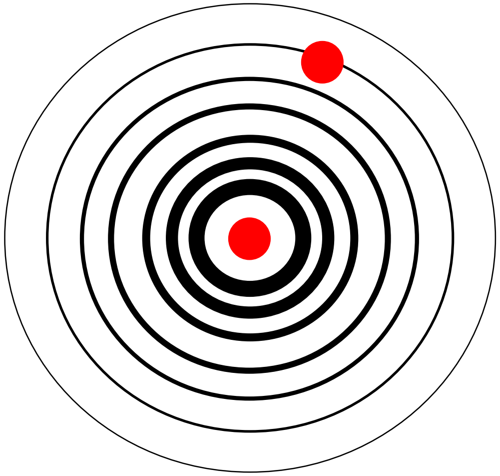
- RF = Radio Frequency
  - Electromagnetic signal that propagates through "ether"
  - Ranges 3 KHz .. 300 GHz
  - Or 100 km .. 0.1 cm (wavelength)



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

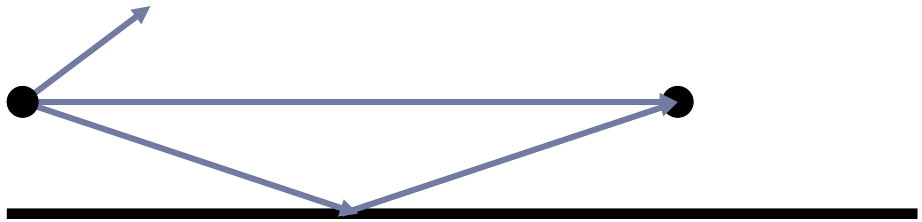
Cartoon View 1 – Energy Wave

- Think of it as energy that radiates from one 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

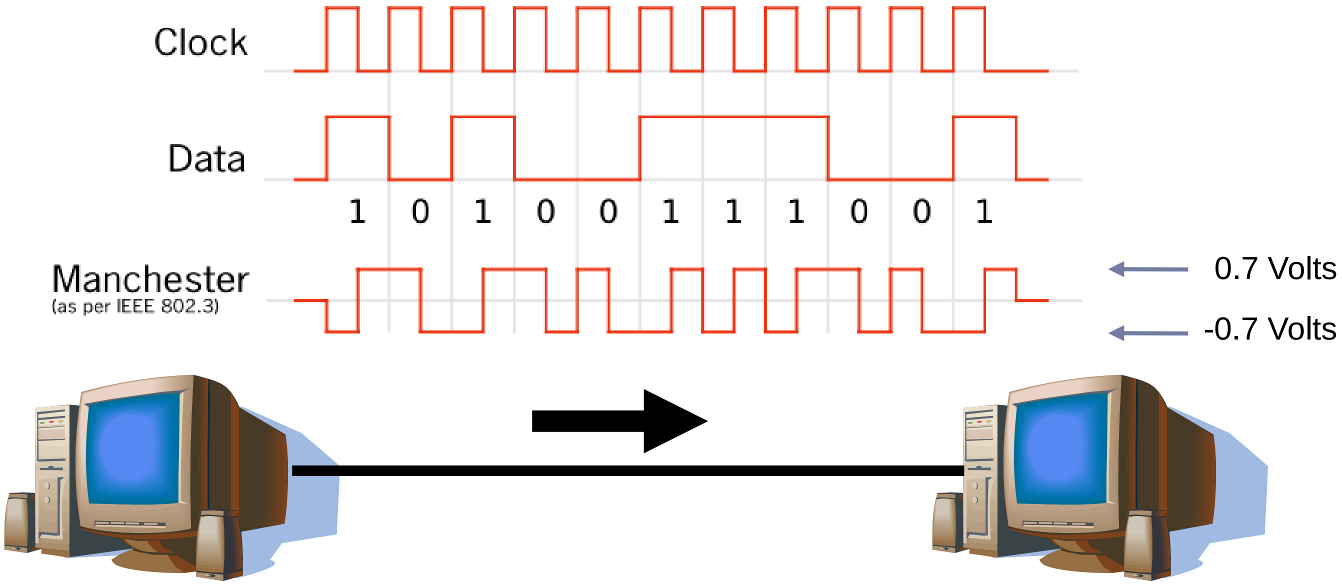


Cartoon View 2 – Rays of Energy

- Can also view it as a "ray" that propagates between two points
  - Rays can be reflected etc.
  - Can provide connectivity without line of sight
- A channel can also include multiple "rays" that take different paths
  - Known as multipath



But how can two hosts communicate?



- Encode information on modulated "Carrier signal"
  - Phase, frequency, and/or amplitude modulation

Analog vs. Digital Transmission

- Analog and digital correspond roughly to continuous and discrete
- Data: entities that convey meaning
  - Analog: continuously varying patterns of intensity (e.g., voice and video)
  - Digital: discrete values (e.g., integers, ASCII text)
- Signals: electric or electromagnetic encoding of data
  - Analog: continuously varying electromagnetic wave
  - Digital: sequence of voltage pulses

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

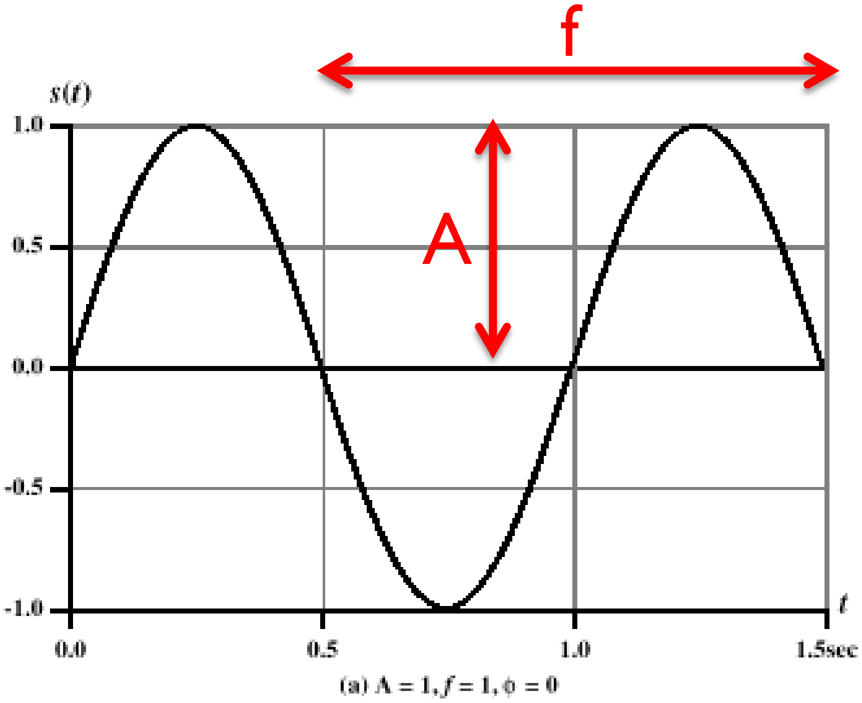
  - Allows us to take a frequency view
- Aperiodic signal
  - Analog or digital signal pattern that doesn't repeat over time
  - Can "make" an aperiodic signal periodic by taking a slice T and repeating it
  - Often what we do implicitly

Key Parameters of a (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

Sine Wave Parameters

- General sine wave
  - $s(t) = A \sin(2\pi f t + \phi)$
- Effect of parameters
  - $A = 1, f = 1$ Hz, $\phi = 0$; thus $T = 1$ s



(a) $A = 1, f = 1, \phi = 0$

- note: 2π radians = 360° = 1 period

Sine Wave Parameters

- General sine wave
  - If x-axis = time
    - *y-axis* = value of a signal at a given point in *space*
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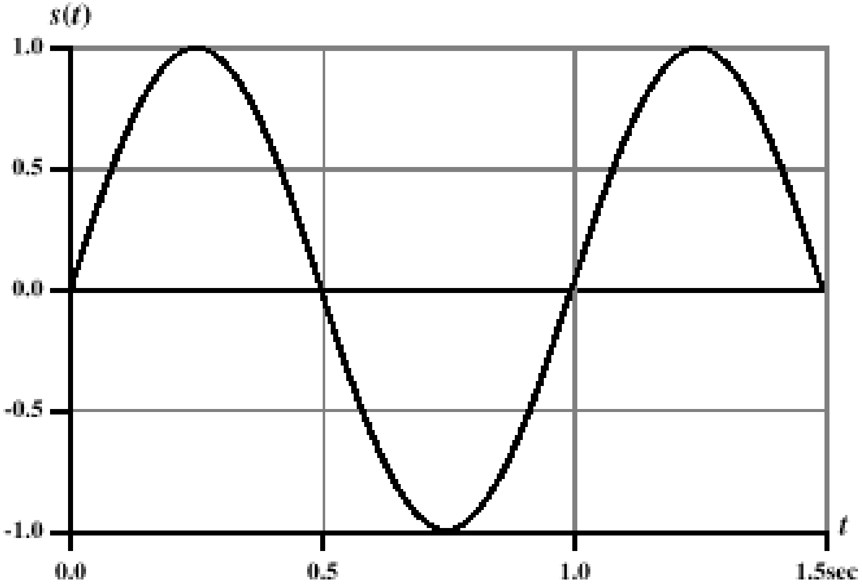
    - *y-axis* = value of a signal at a given point in *time*

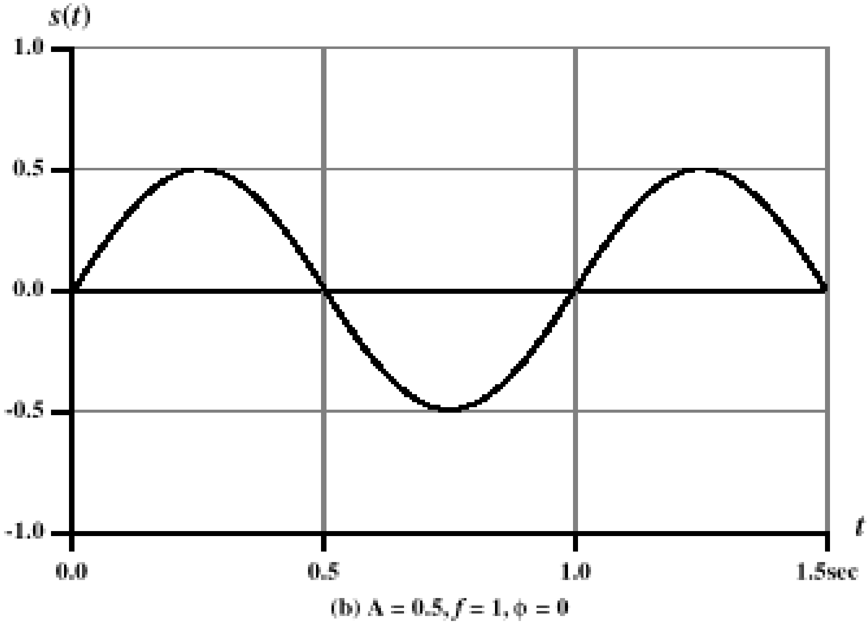


(a) $A = 1, f = 1, \phi = 0$

- note: *2π radians = 360° = 1 period*

Sine Wave Parameters

- General sine wave
  - $s(t) = A \sin(2\pi f t + \phi)$
- Effect of parameters
  - Reduced peak amplitude; $A=0.5$

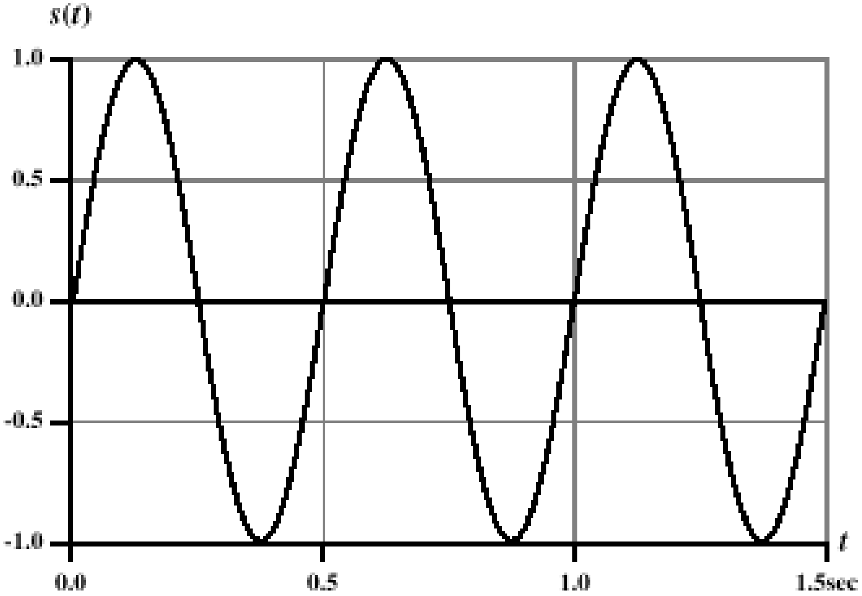


(b) A = 0.5, f = 1, ϕ = 0

- note: 2π radians = 360° = 1 period

Sine Wave Parameters

- General sine wave
  - $s(t) = A \sin(2\pi f t + \phi)$
- Effect of parameters
  - Increased frequency; $f = 2$, thus $T = ½$

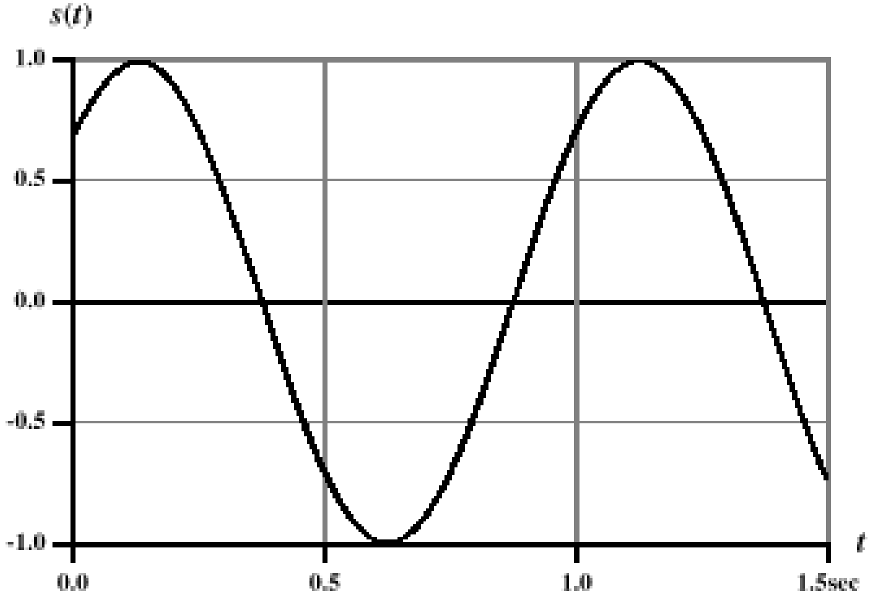


(c) $A = 1, f = 2, \phi = 0$

- note: 2π *radians* = *360°* = *1 period*

Sine Wave Parameters

- General sine wave
  - $s(t) = A \sin(2\pi f t + \phi)$
- Effect of parameters
  - Phase shift
    $\phi = \pi/4$ radians
    (45 degrees)

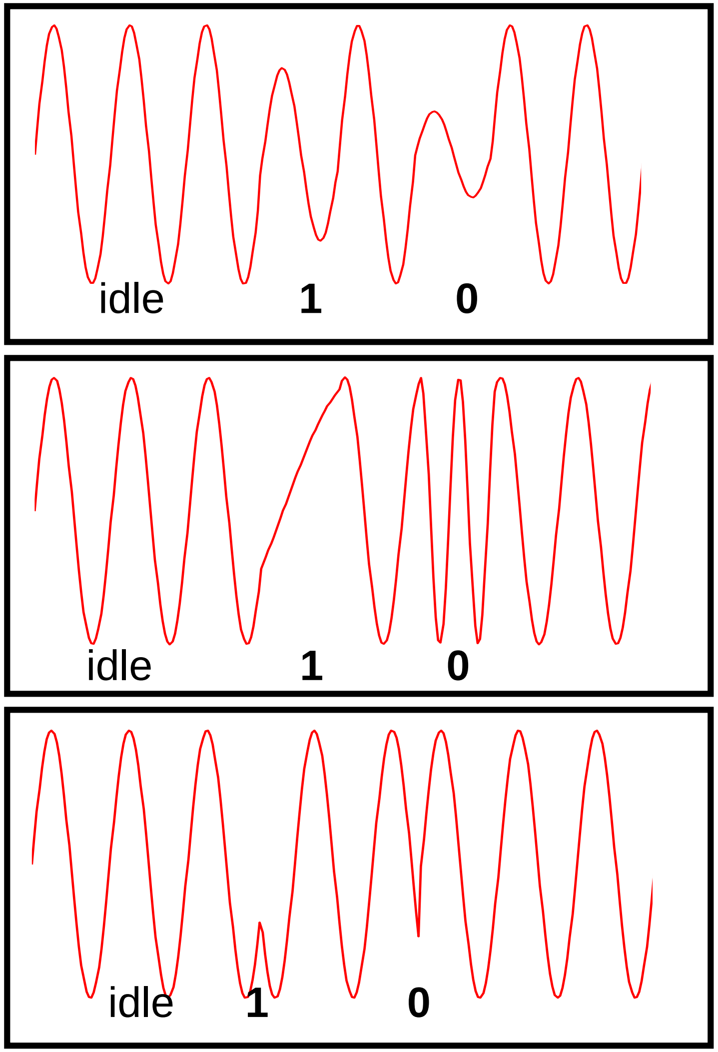


(d) $A = 1, f = 1, \phi = \pi/4$

- note: 2π radians = 360° = 1 period

Signal Modulation

- Amplitude modulation (AM)
  - Change the strength of the signal
  - High values -> stronger signal
- Frequency modulation (FM)
  - Change the frequency of the signal
- Phase modulation (PM)
  - Change the phase of the signal

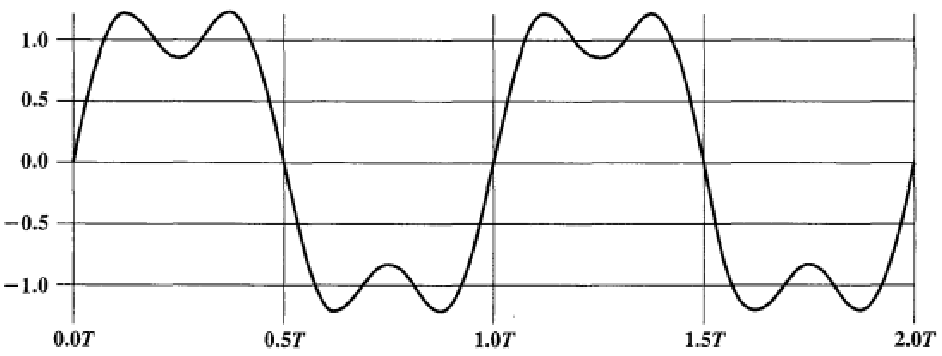


Frequency-Domain Concepts

- Electromagnetic signal
  - 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

Frequency-Domain Concepts

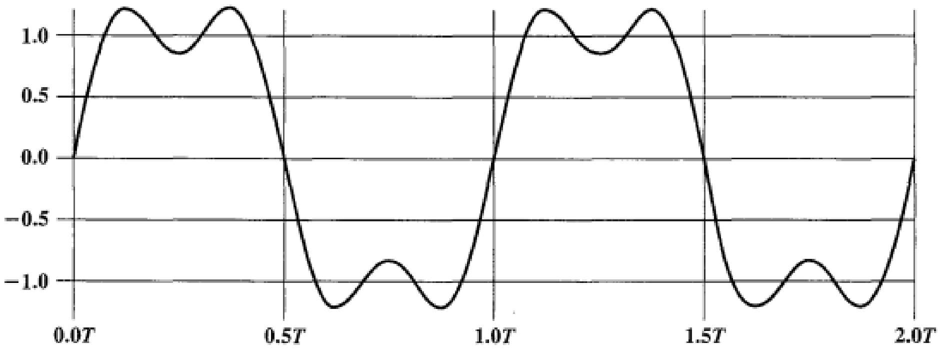
- A (periodic) signal
  - A sum of sine waves of different strengths
  - Example: *f* and *3f*
    - Note that *3f* is an integer multiple of *f*
- Fundamental frequency
  - All frequency components are integer multiples of one frequency



$(4/\pi)[\sin 2\pi ft) + (1/3)\sin(2\pi 3ft)]$

Frequency-Domain Concepts

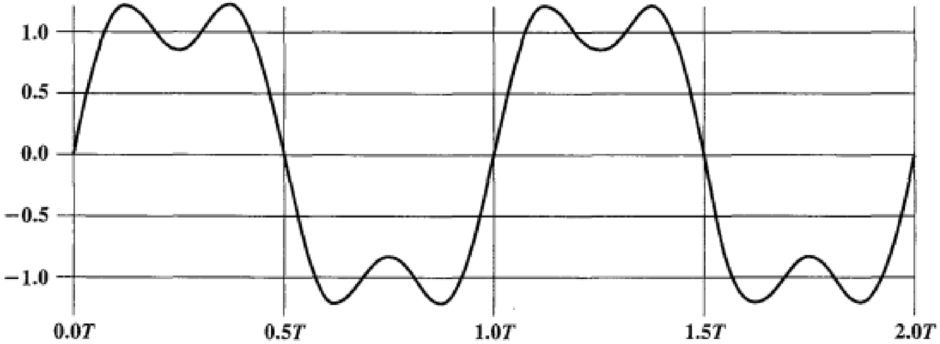
- A (periodic) signal
  - A sum of sine waves of different strengths
  - Example: *f* and *3f*
    - Note that *3f* is an integer multiple of f
- Fundamental frequency
  - Period of the signal = the period of the fundamental frequency



$(4/\pi)[\sin 2\pi ft) + (1/3)\sin(2\pi 3ft)]$

Frequency-Domain Concepts

- Spectrum
  - Range of frequencies
  - From *f* to *3f*
- Absolute bandwidth
  - Width of the spectrum
  - *3f – f = 2f*
- Effective bandwidth
  - Narrow band of frequencies that most of the signal's energy is contained in

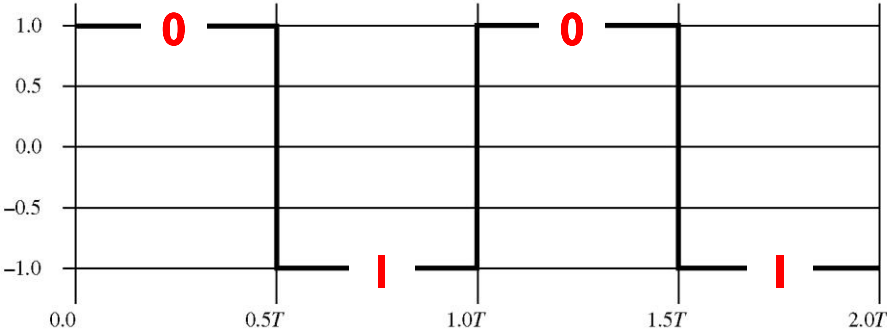


$(4/\pi)[\sin 2\pi ft) + (1/3)\sin(2\pi 3ft)]$

Relationship between Data Rate and Bandwidth

- Bandwidth translates to bits
  - The greater the (spectral) bandwidth, the higher the information-carrying capacity of the signal (data bandwidth)
  - Intuition: if a signal can change faster, it can be modulated in a more detailed way and can carry more data
- 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

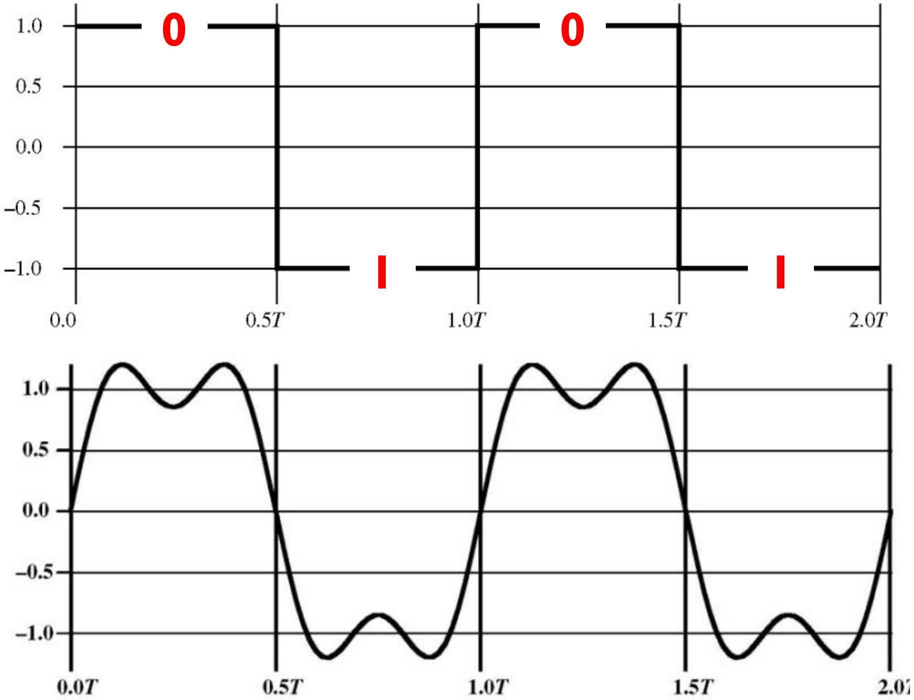
Signals to bits



- Each pulse lasts *1/2f*
  - Data rate = *2f bps*

What are the frequency components of the signal?

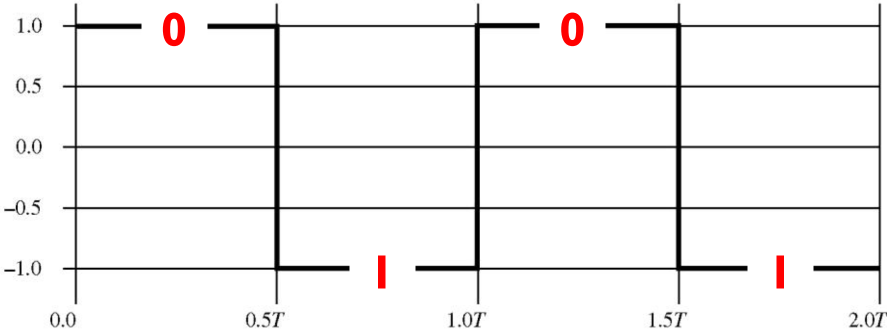
Signals to bits

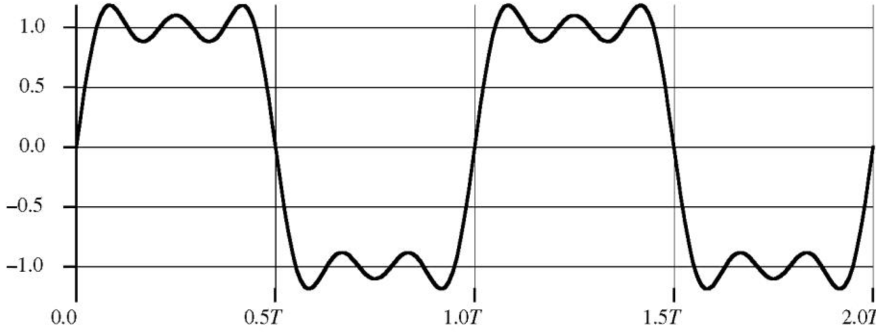


- Each pulse lasts $1/2f$
  - Data rate = $2f$ *bps*
- Add two sine waves

$(4/\pi)[\sin 2\pi ft) + (1/3)\sin(2\pi 3ft)]$

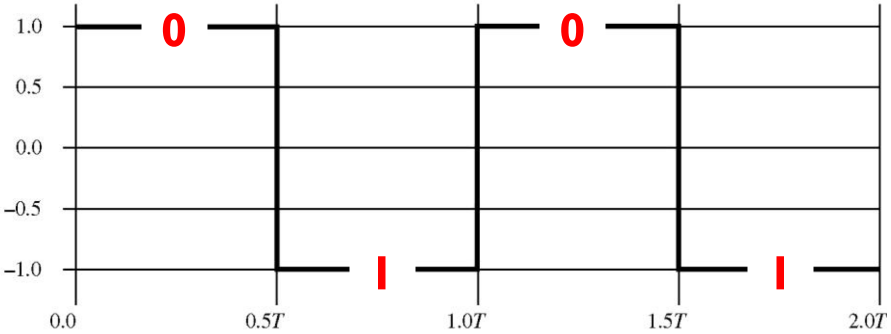
Signals to bits

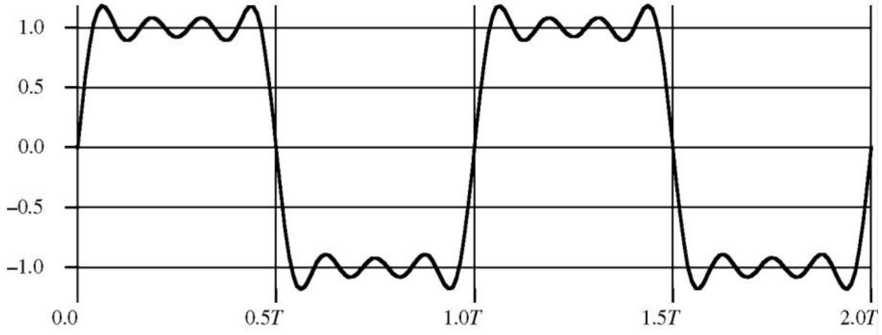




- Each pulse lasts *1/2f*
  - Data rate = *2f bps*
- Add a sine wave with frequency *5f*

Signals to bits



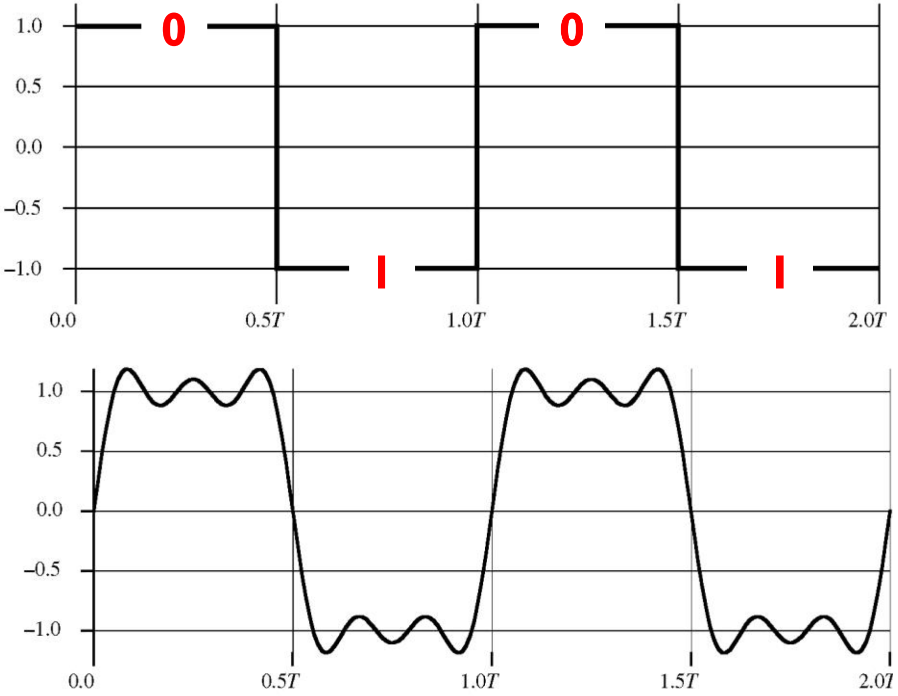


- Each pulse lasts *1/2f*
  - Data rate = *2f bps*
- Add a sine wave with frequency *7f*
  - And so on …

Infinite frequencies = infinite bandwidth!

not quite …

Data rate

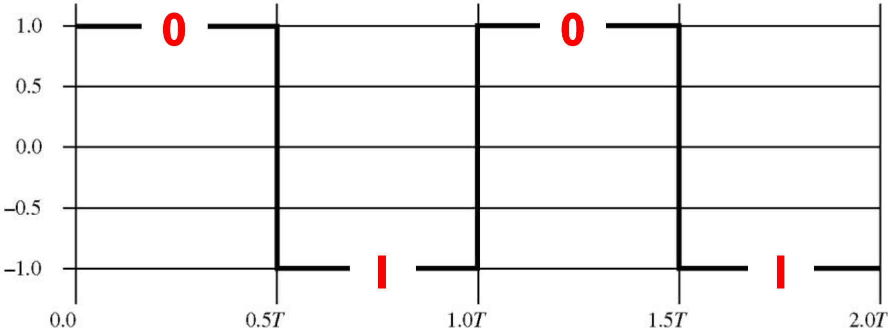


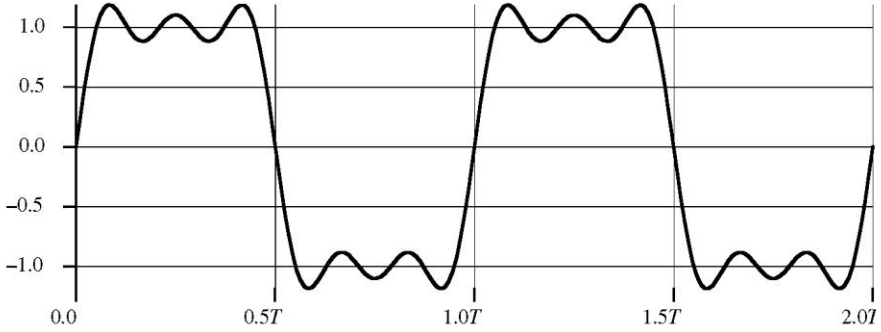
Close enough to square wave to distinguish 0 and 1

- Available bandwidth of bandwidth of 4MHz

- If $f = 10^6$ cycles/sec = 1MHz
  - Signal bandwidth = 4MHz
  - T = 1 bit/0.5 µsec
  - Data rate = 2 Mbps

Data rate





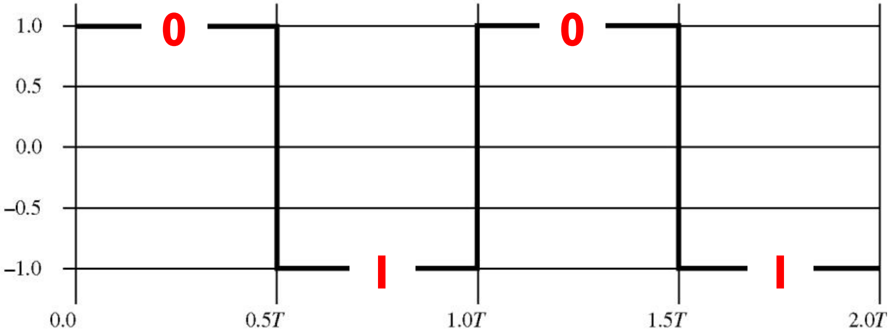
Close enough to square wave to distinguish 0 and 1

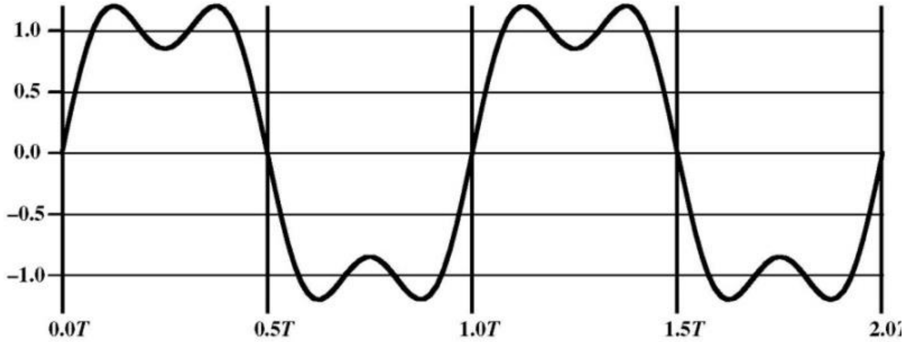
- Available bandwidth of bandwidth of 8MHz

- If f = 2MHz
  - Signal bandwidth = 8MHz
  - T = 1 bit/0.25 μsec
  - Data rate = 4 Mbps

2X BW = 2X data rate

Data rate





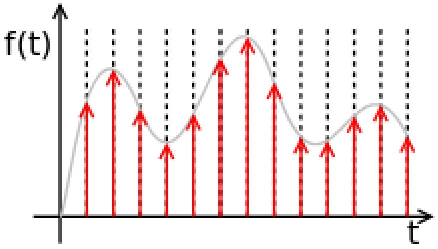
What if this is good enough?

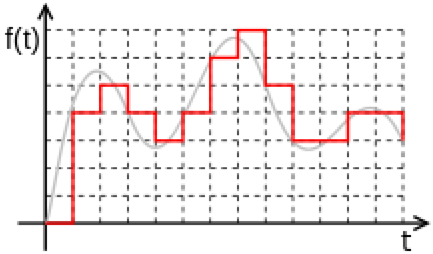
- Available bandwidth of bandwidth of 4MHz
- If *f* = 2MHz
  - Signal bandwidth = 4MHz
  - *T* = 1 bit/0.25 μsec
  - Data rate = 4 Mbps

IF the receiver can distinguish between 0 and 1!

Signals: Back to Analog and Digital

- Goal
  - Sender changes the signal, e.g. the amplitude, in a way that 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: discreet changes in the signal that correspond to a digital signal
  - Less susceptible to noise but can suffer from attenuation
  - Can regenerate signal along the path (repeater versus amplifier)

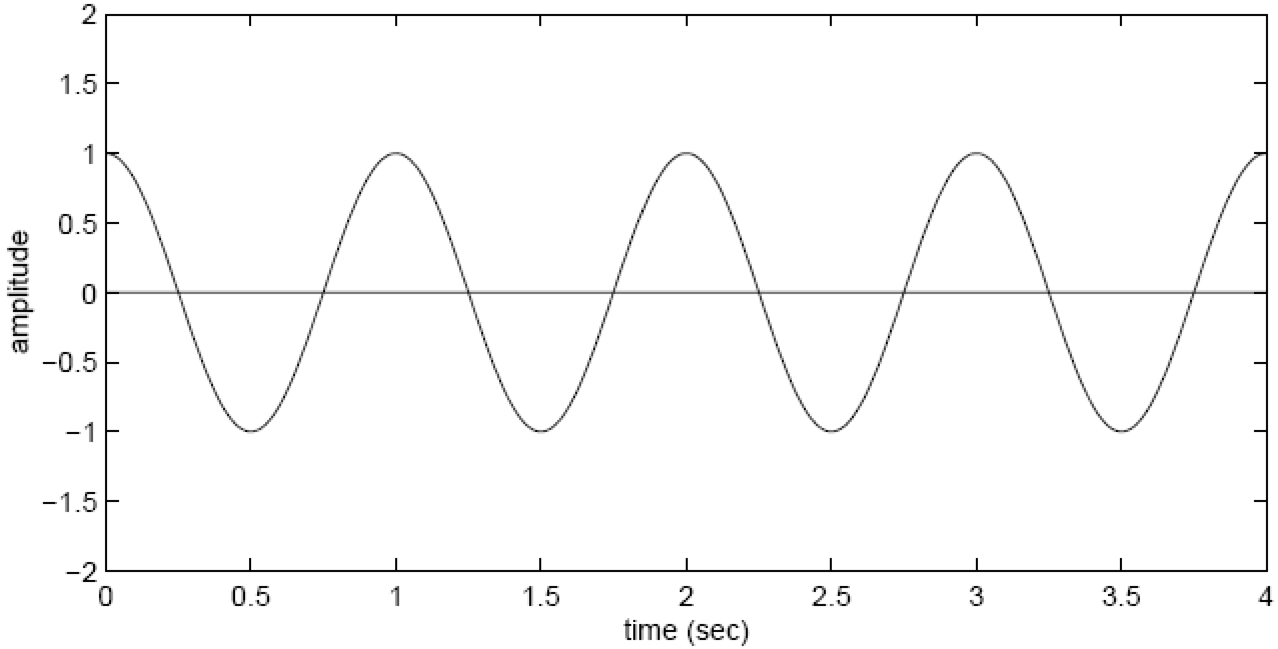




Channel Capacity

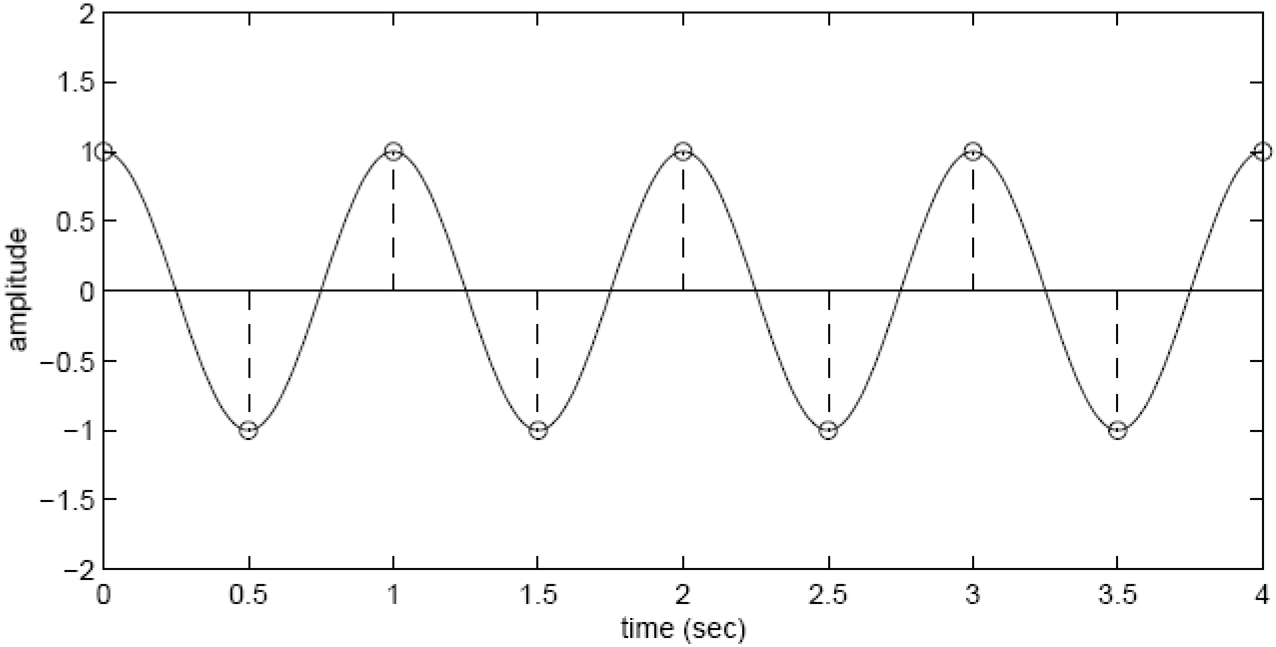
- Data rate
  - Rate at which data can be communicated (bps)
- Channel Capacity
  - Maximum rate at which data can be transmitted over a given channel, under given conditions
- Bandwidth
  - Bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (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

Sampling



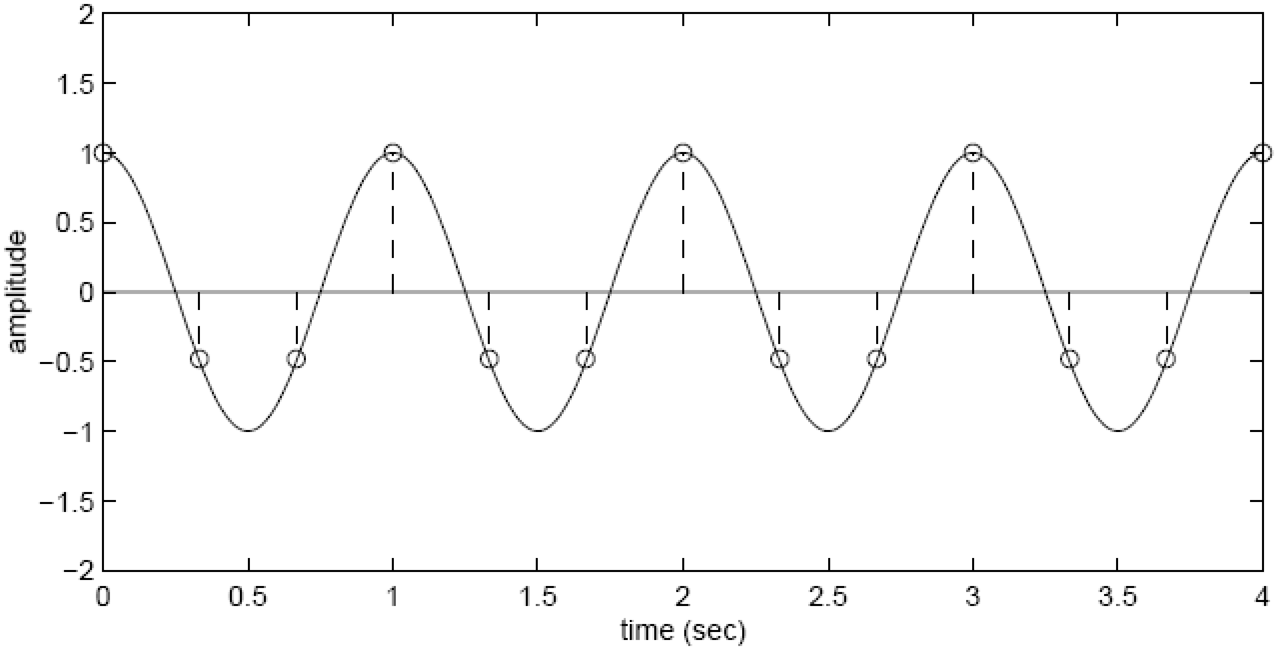
- Suppose you have the following 1Hz signal being received
- How fast do you need to sample, to capture the signal?

Sampling



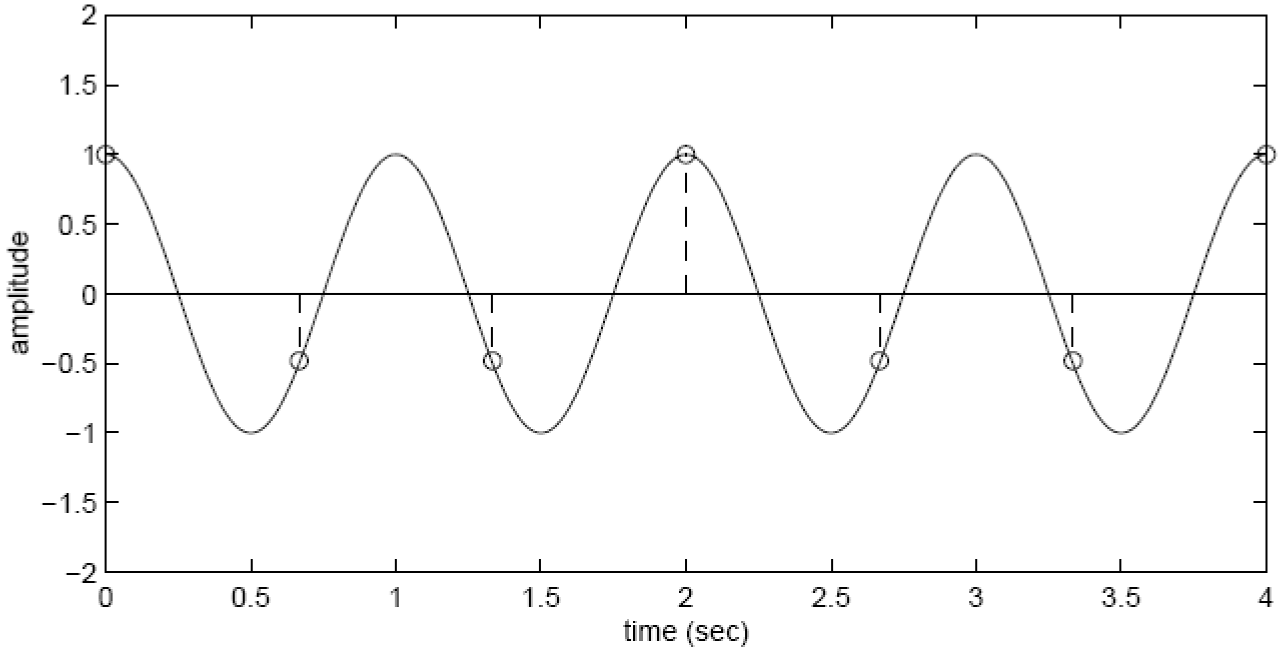
- Sampling a 1 Hz signal at 2 Hz is enough
  - Captures every peak and trough

Sampling



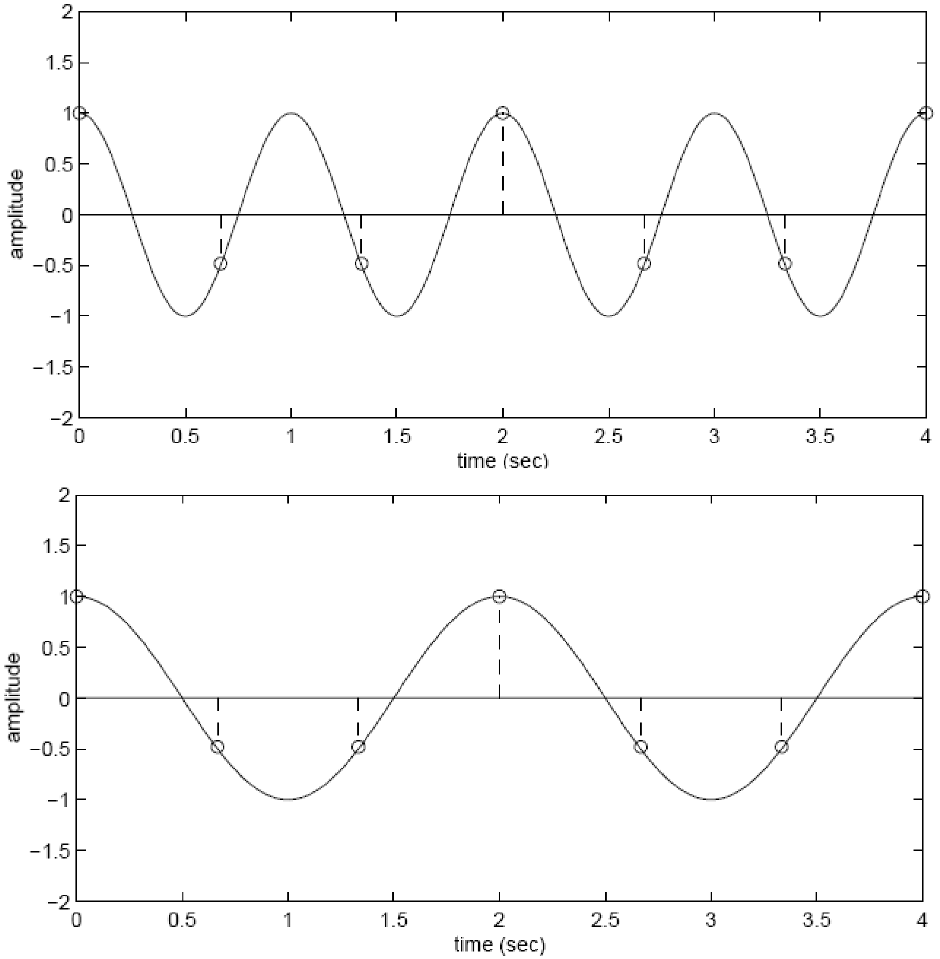
- Sampling a 1 Hz signal at 3 Hz is also enough
  - In fact, more than enough samples to capture variation in signal

Sampling



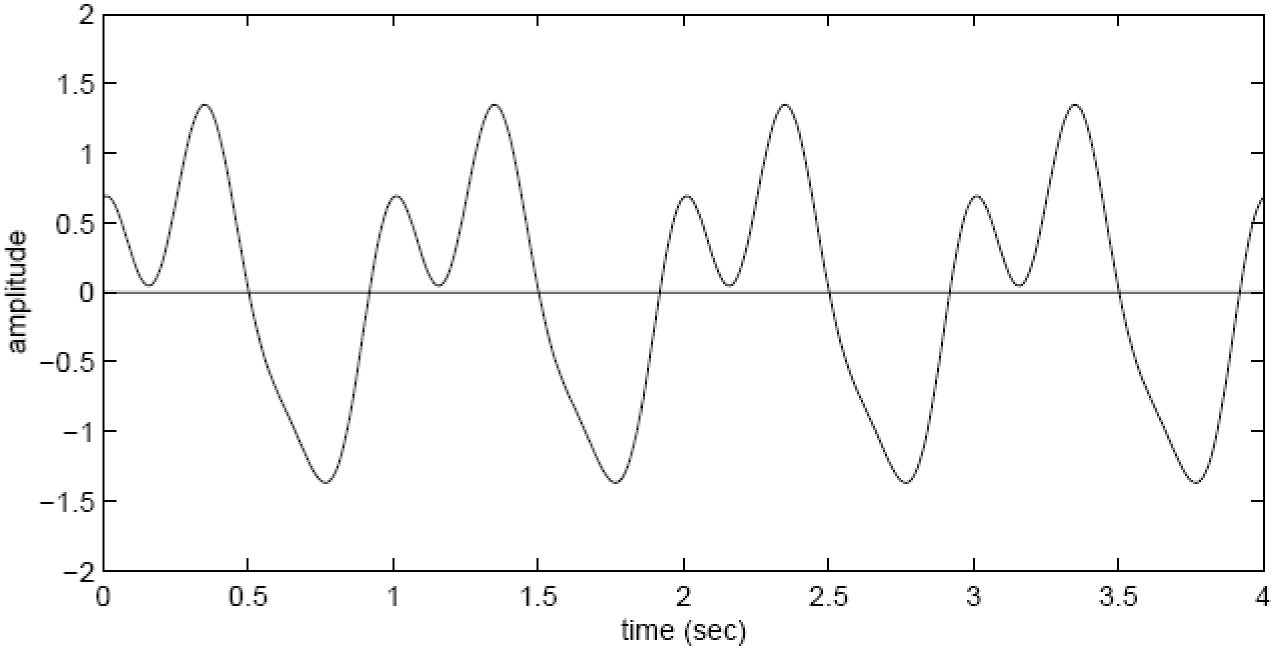
- Sampling a 1 Hz signal at 1.5 Hz is not enough
  - Why?

Sampling



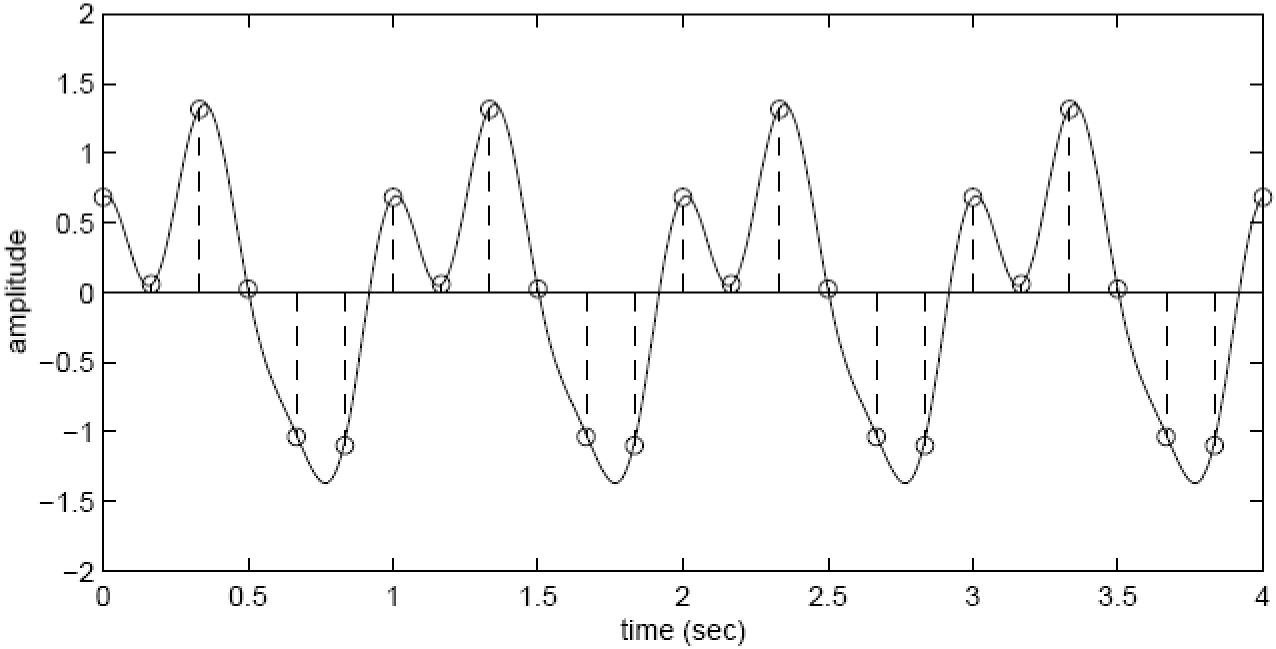
- Sampling a 1 Hz signal at 1.5 Hz is not enough
  - Can't distinguish between multiple possible signals
  - Problem known as **aliasing**

What about more complex signals?



- Fourier’s theorem
  - Any continuous signal can be decomposed into a sum of sines and cosines at different frequencies
- Example: Sum of 1 Hz, 2 Hz, and 3 Hz sines
  - How fast to sample?

What about more complex signals?



- Fourier's theorem
  - Any continuous signal can be decomposed into a sum of sines and cosines at different frequencies
- Example: Sum of 1 Hz, 2 Hz, and 3 Hz sines
  - How fast to sample? **--> answer: 6 Hz**

Generalizing the Examples

- What data rate can a channel sustain?
- How is data rate related to bandwidth?
- How does noise affect these bounds?
- What else can limit maximum data rate?

What Data Rate can a Channel Sustain? How is Data Rate Related to Bandwidth?

- Transmitting N distinct signals over a noiseless channel with bandwidth B, we can achieve at most a data rate of

Number of signals per second

2B log2 N

Number of bits per signal

  - ex.: a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second

- Nyquist's Sampling Theorem (H. Nyquist, 1920's)

What Data Rate can a Channel Sustain? How is Data Rate Related to Bandwidth?

- Transmitting N distinct signals over a noiseless channel with bandwidth B, we can achieve at most a data rate of

Number of signals per second

$\boxed{2B}\boxed{\log 2\ N}$

Number of bits per signal

  - ex.: a 300(ate of at most 6000 bits/

- Nyquist's S 20's)

Baud rate

Number of **physical symbols** transmitted per second

Bit rate

Actual number of **data bits** transmitted per second

Relationship

Depends on the number of **bits** encoded in each **symbol**

Noiseless Capacity

- Nyquist' s theorem: $2B \log_2 N$
- Example 1: sampling rate of a phone line
  - B = 4000 Hz
  - 2B = 8000 samples/sec.
    - sample every 125 microseconds

Noiseless Capacity

- Nyquist's theorem: $2B \log_2 N$
- Example 2: noiseless capacity
  - B = 1200 Hz
  - N = each pulse encodes 16 symbols
  - C =

Noiseless Capacity

- Nyquist' s theorem: $2B \log_2 N$
- Example 2: noiseless capacity
  - $B = 1200$ Hz
  - $N =$ each pulse encodes 16 symbols
  - $C = 2B \log_2 (N) = D \times \log_2 (N)$

    $= 2400 \times 4 = 9600$ bps

How does Noise affect these Bounds?

- Noise
  - Blurs the symbols, reducing the number of symbols that can be reliably distinguished
- Claude Shannon (1948)
  - Extended Nyquist's work to channels with additive white Gaussian noise (a good model for thermal noise)

$$\text{channel capacity } C = B \log_2 (1 + S/N)$$

N is noise

where

C is the maximum supportable bit rate

B is the channel bandwidth

S/N is the ratio between signal power and in-band noise power

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channel capacity $C = B \log_2 (1 + S/N)$

- Represents error free capacity
  - also used to calculate the noise that can be tolerated to achieve a certain rate through a channel
- Result is based on many assumptions
  - Formula assumes white noise (thermal noise)
  - Impulse noise is not accounted for
  - Various types of distortion are also not accounted for

Noisy Capacity

- Telephone channel
  - 3400 Hz at 40 dB SNR

$$\mathrm{SNR(dB)} = 10 \log_{10} \left(\frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}} \right)$$

decibels (dB) is a logarithmic unit of measurement that expresses the magnitude of a physical quantity (usually power or intensity) relative to a specified or implied reference level

Decibels

- A ratio between signal powers is expressed in decibels

$$\text{decibels (db)} = 10\log_{10}(P_1 / P_2)$$

- Used in many contexts
  - The loss of a wireless channel
  - The gain of an amplifier
- Note that dB is a relative value
  - Can be made absolute by picking a reference point
    - Decibel-Watt – power relative to 1W
    - Decibel-milliwatt – power relative to 1 milliwatt

Signal-to-Noise Ratio

- Signal-to-noise ratio (SNR, or S/N)
  - Ratio of
    - the power in a signal

      to
    - the power contained in the noise
  - Typically measured at a receiver

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

- A high SNR
  - High-quality signal
- Low SNR
  - May be hard to "extract" the signal from the noise
- SNR sets upper bound on achievable data rate

Noisy Capacity

- Telephone channel
  - 3400 Hz at 40 dB SNR
  - $C = B \log_2 (1+S/N)$ bits/s
  - SNR = 40 dB

    $40 = 10 \log_{10} (S/N)$

    $S/N = 10{,}000$
  - $C = 3400 \log_2 (10001) = 44.8$ kbps

$$\mathrm{SNR(dB)} = 10 \log_{10} \left(\frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}} \right)$$

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

More examples of Nyquist and Shannon Formulas

- Spectrum of a channel between 3 MHz and 4 MHz ; $\text{SNR}_{\text{dB}} = 24$ dB

$$B =$$

$$\text{SNR} =$$

- Using Shannon's formula

$$C = B \log_2 (1 + S/N)$$

More examples of Nyquist and Shannon Formulas

- Spectrum of a channel between 3 MHz and 4 MHz ; SNR_{dB} = 24 dB

$$B = 4\,\text{MHz} - 3\,\text{MHz} = 1\,\text{MHz}$$

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

$$\text{SNR} = 251$$

- Using Shannon's formula

$$C = B \log_2 (1 + S/N)$$

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

More examples of Nyquist and Shannon Formulas

- How many signaling levels are required?

$$C = 2B\log_2 M$$

More examples of Nyquist and Shannon Formulas

- How many signaling levels are required?

$$C = 2B\log_2 M$$

$$8\times10^6 = 2\times\left(10^6\right)\times\log_2 M$$

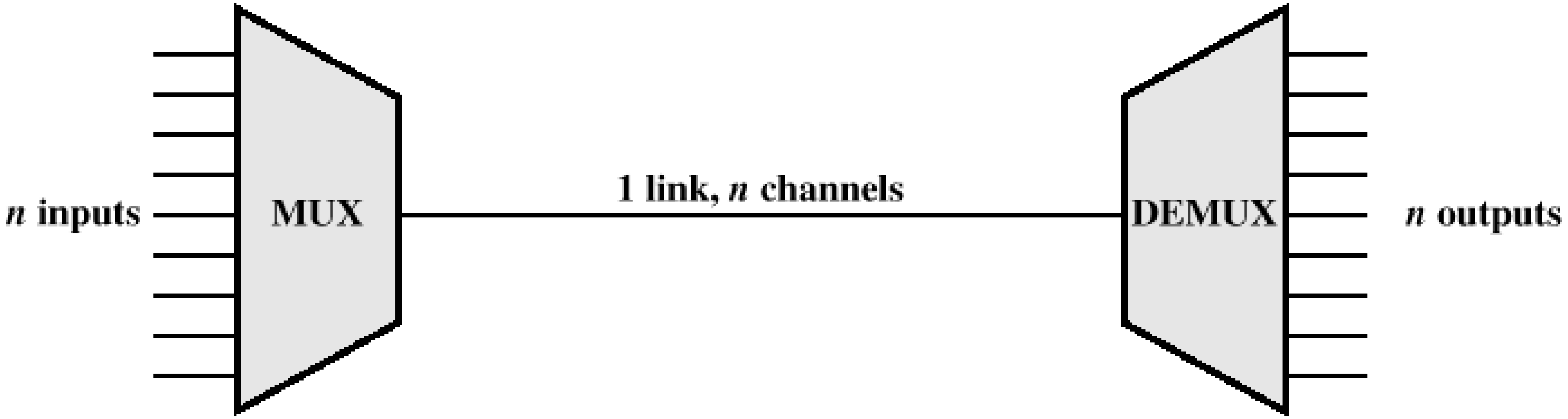
$$4 = \log_2 M$$

$$M = 16$$

- Look out for: dB versus linear values, $\log_2$ versus $\log_{10}$

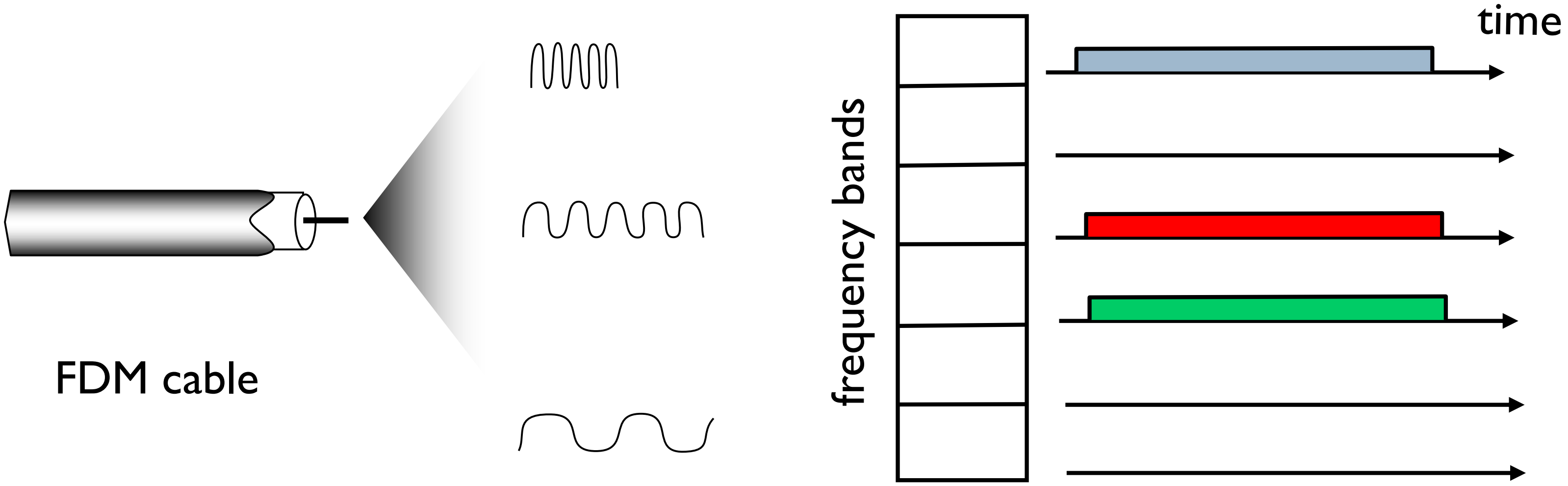
Multiplexing

- Capacity of transmission medium
  - May exceed capacity required for transmission of a single signal
- Multiplexing
  - Carrying multiple signals on a single medium
  - More efficient use of transmission medium



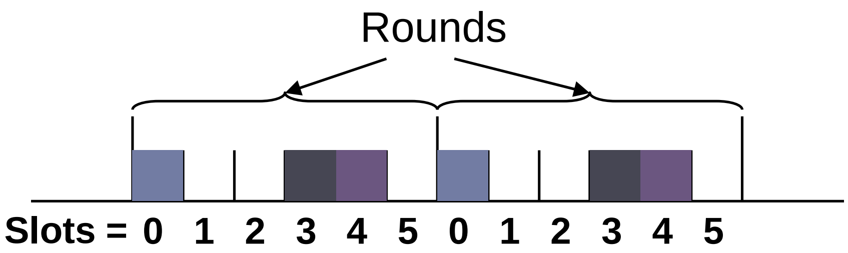
Multiplexing

- FDM: Frequency Division Multiplexing
  - Channel spectrum divided into frequency bands
  - Each assigned fixed frequency band/reduced rate
  - Unused transmission time in frequency bands go idle
  - Example: 6-station LAN, 1,3,4 transmit, frequency bands 2,5,6 idle



Multiplexing

- TDM: Time Division Multiplexing
  - Access in "rounds"
    - Each user/node/etc… gets fixed length slot in each round
    - Each user can sent at full speed some of the time
    - Unused slots go idle
  - Example: 6-slots with transmissions in slots 0, 3, and 4



FDM Example: AMPS

- US analog cellular system in early 80’s
- 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: GSM

- Global System for Mobile communication
  - First introduced in Europe in early 90s
- Uses a combination of TDM and FDM
- 25 MHz each for up and down links.
- Broken up in 200 KHz channels
  - 125 channels in each direction
  - Each channel can carry about 270 kbs
- Each channel is broken up in 8 time slots
  - Slots are 0.577 msec long
  - Results in 1000 channels, each with about 25 kbs of useful data; can be used for voice, data, control
- General Packet Radio Service (GPRS)
  - Data service for GSM, e.g. 4 down and 1 up channel

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, …