CS/ECE 439: Wireless Networking

Physical Layer

Limitation (of Wireless) Communication

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)

30 km	.3 km	3 m	3 cm

VLF	LF	MF	HF	VHF	UHF	SHF	EHF

AM Broadcast →   FM Broadcast →   Radar Bands

Sonics → ← Ultra-sonics →   ← Microwaves →

10 kHz	1 MHz	100 MHz	10 GHz
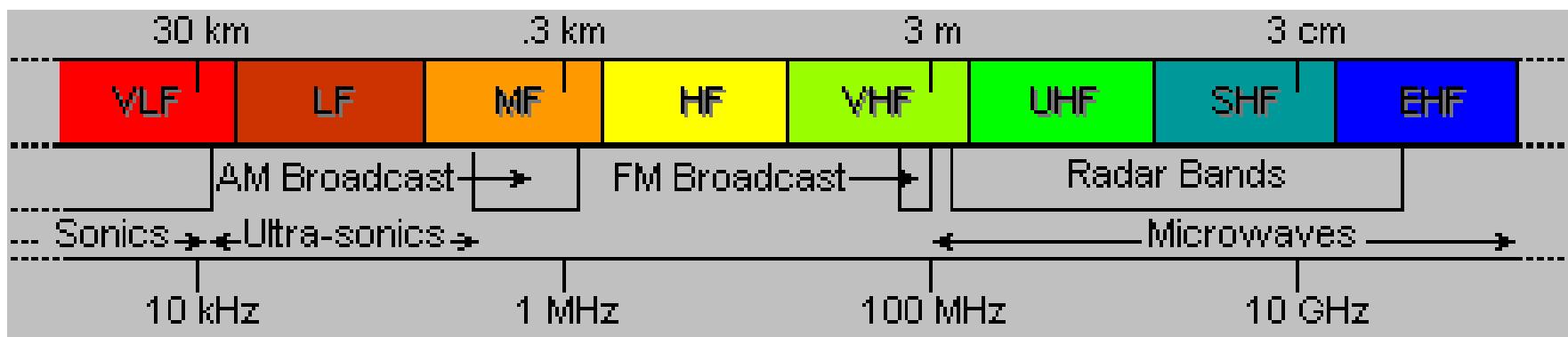
▸ Travels at the speed of light
▸ Can take both a time and a frequency view

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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

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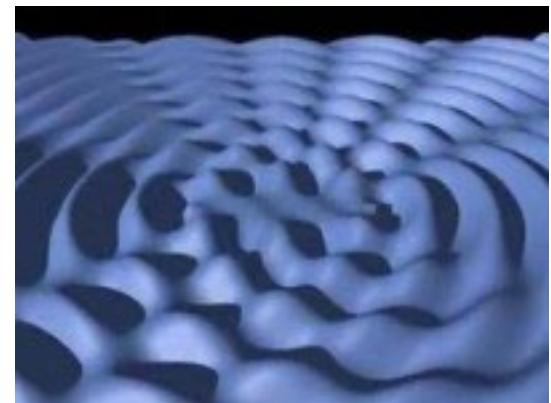
Cartoon View 2 – Rays of Energy

▶ Can also view it as a "ray" that propagates between two points

  ▶ Rays can be reflected etc.

  ▶ Can provide connectivity without line of sight

▶ A channel can also include multiple "rays" that take different paths

  ▶ Known as multipath

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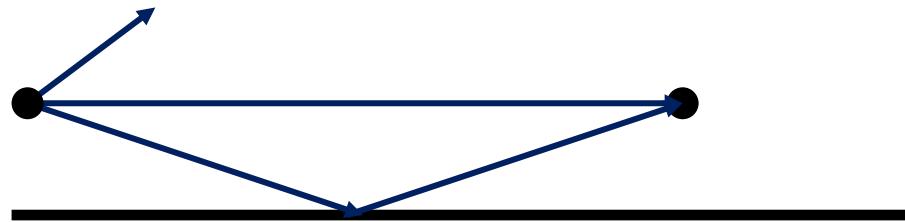
But how can two hosts communicate?
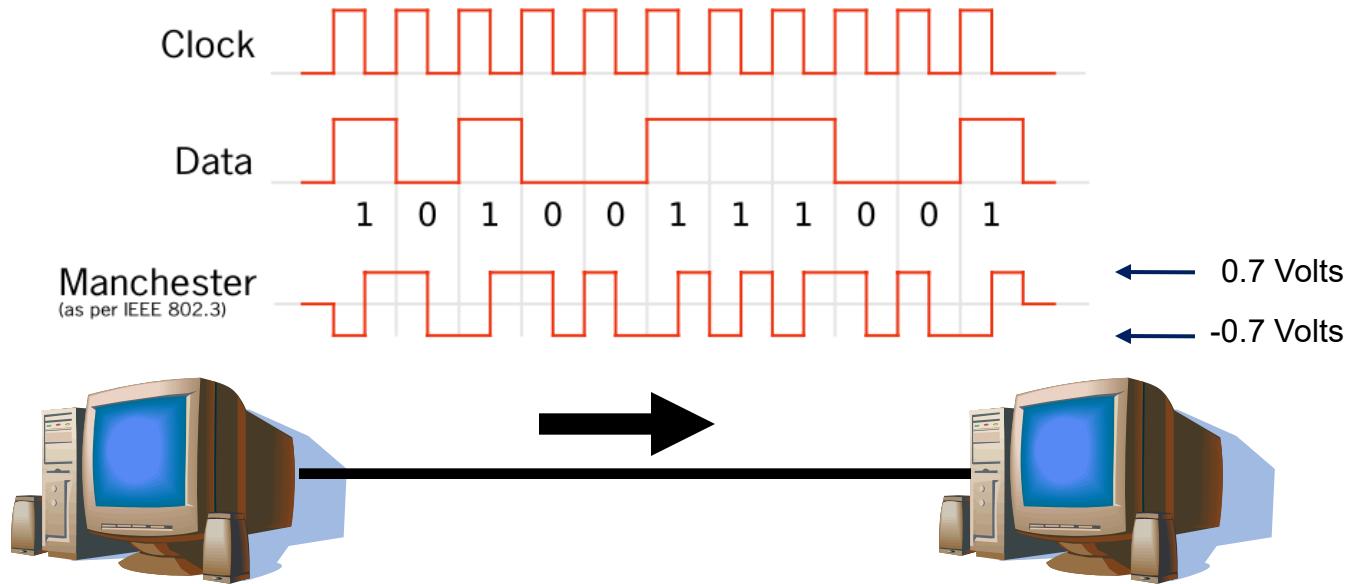
- ▸ Encode information on modulated "Carrier signal"
    - ▸ Phase, frequency, and/or amplitude modulation

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(2πft + ϕ)*

▸ Effect of parameters
  ▸ *A = 1, f = 1 Hz,*
    ϕ = 0; thus *T = 1s*

(a) A = 1, f = 1, ϕ = 0
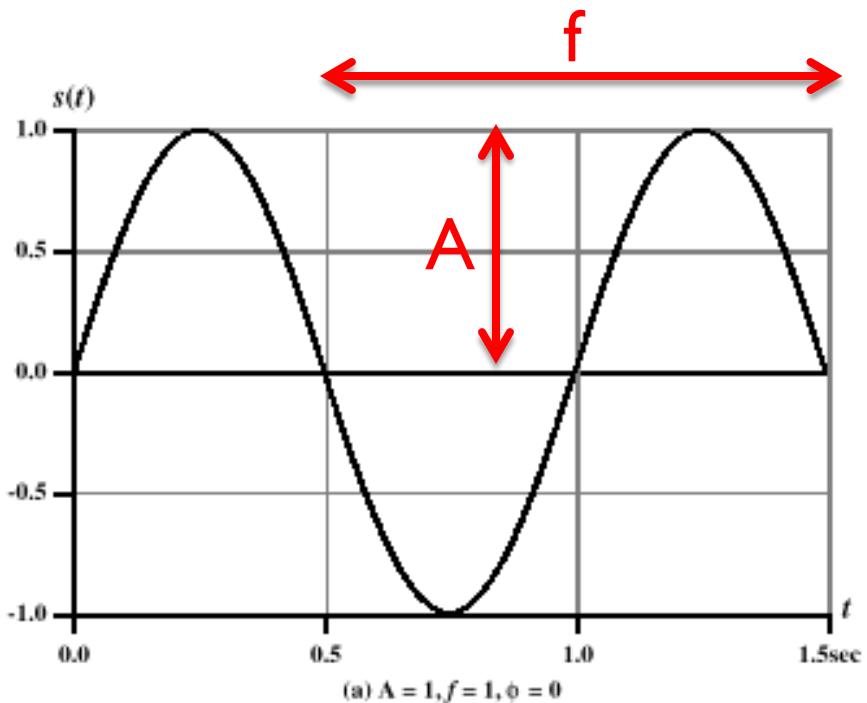
▸ note: *2π radians = 360° = 1 period*

Sine Wave Parameters

▸ **General sine wave**

  ▸ **If x-axis = time**

   ▸ *y-axis* = value of a signal at a given point in *space*

  ▸ **If x-axis = space**

    ▸ *y-axis* = value of a signal at a given point in *time*
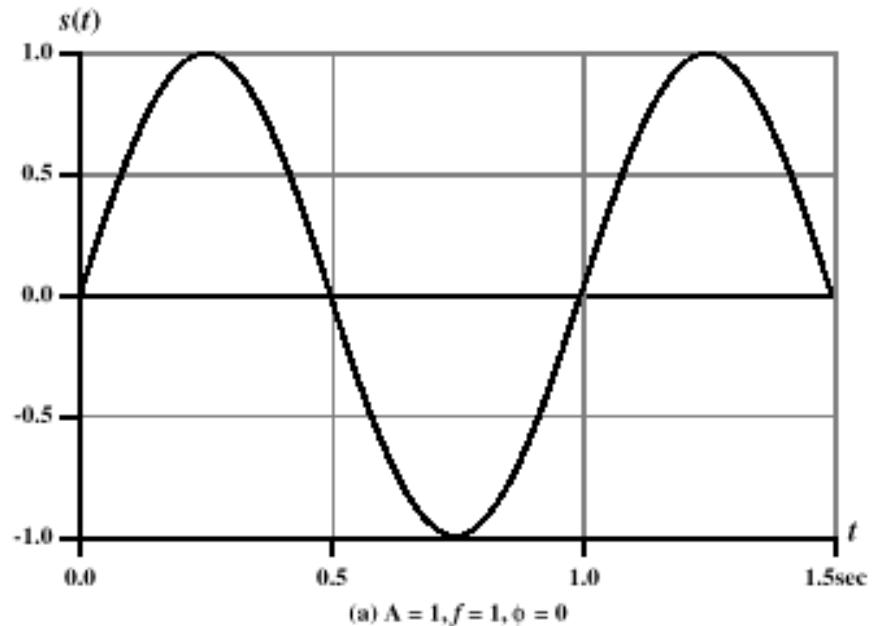
(a) $A = 1, f = 1, \phi = 0$

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

Sine Wave Parameters

▸ **General sine wave**
  ▸ *s(t) = A sin(2πft + φ)*
▸ **Effect of parameters**
  ▸ Reduced peak amplitude; *A=0.5*
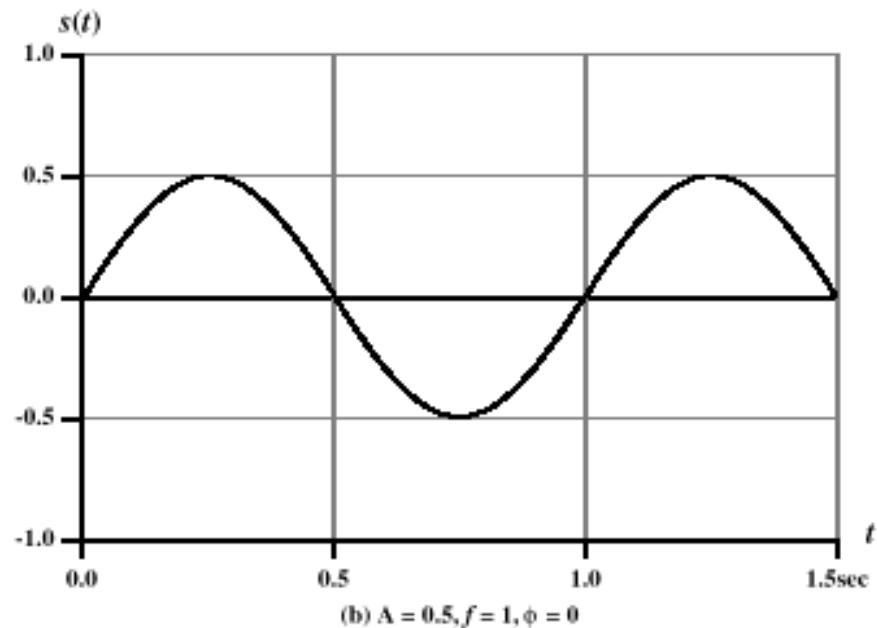
(b) A = 0.5, f = 1, φ = 0

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

Sine Wave Parameters

▸ **General sine wave**
  ▸ *s(t) = A sin(2πft + φ)*
▸ **Effect of parameters**
  ▸ Increased frequency; *f* = 2, thus *T* = ½
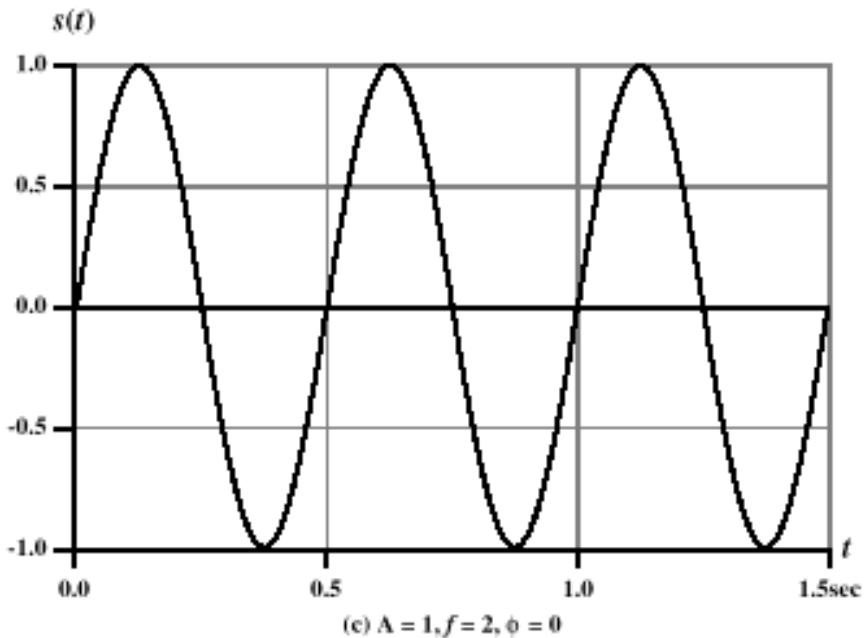
(c) A = 1, *f* = 2, φ = 0

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

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Sine Wave Parameters

▸ **General sine wave**

  ▸ *s(t) = A sin(2πft + φ)*

▸ **Effect of parameters**

  ▸ Phase shift
    φ = π/4 radians
    (45 degrees)

(d) A = 1, f = 1, φ = π/4
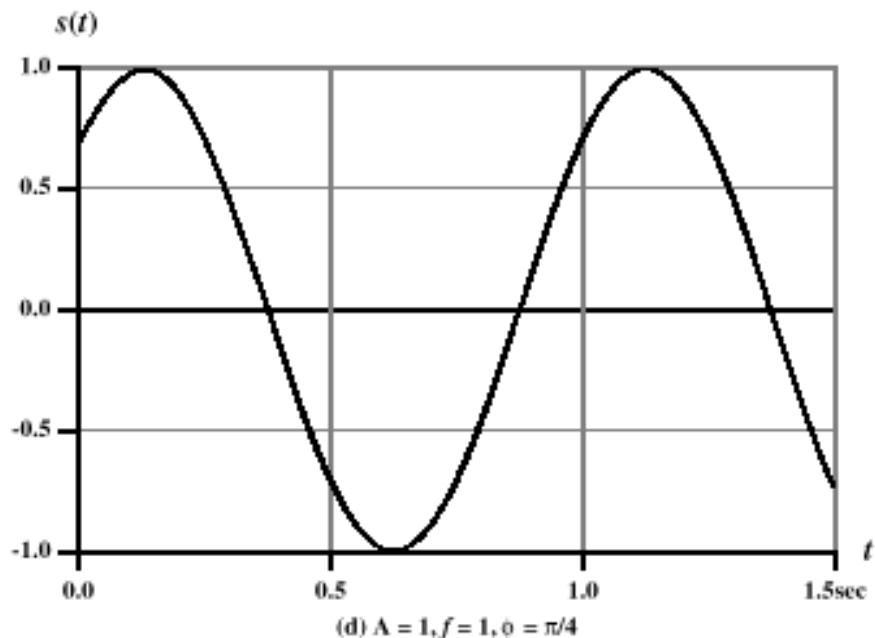
▸ note: *2π radians = 360° = 1 period*

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

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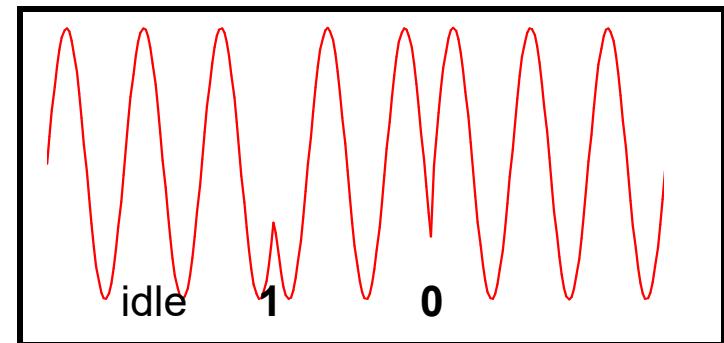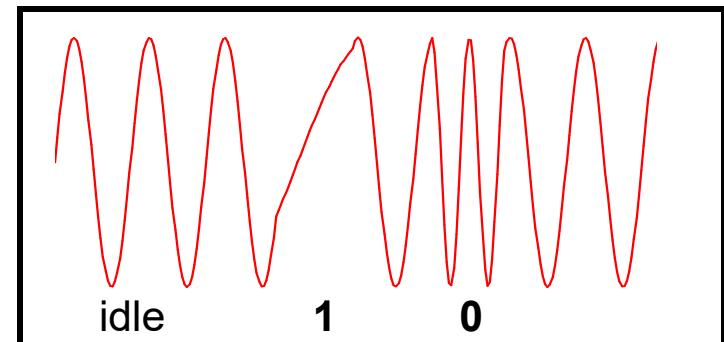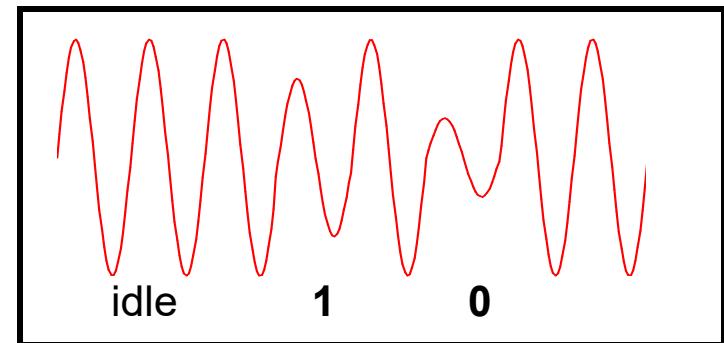
Relationship between Data Rate and Bandwidth

▸ **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
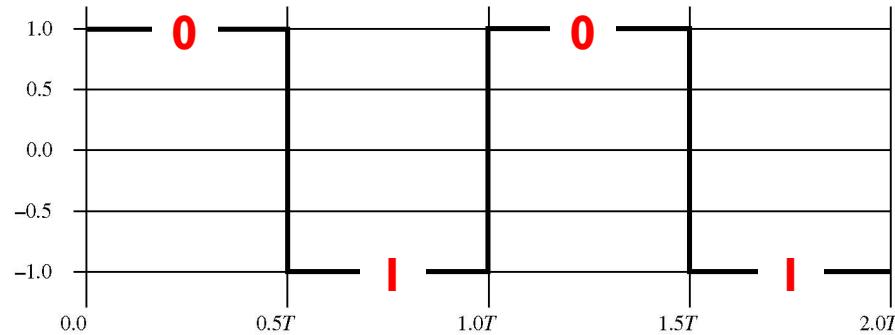
▸ Each pulse lasts *1/2f*

   ▸ Data rate = *2f bps*

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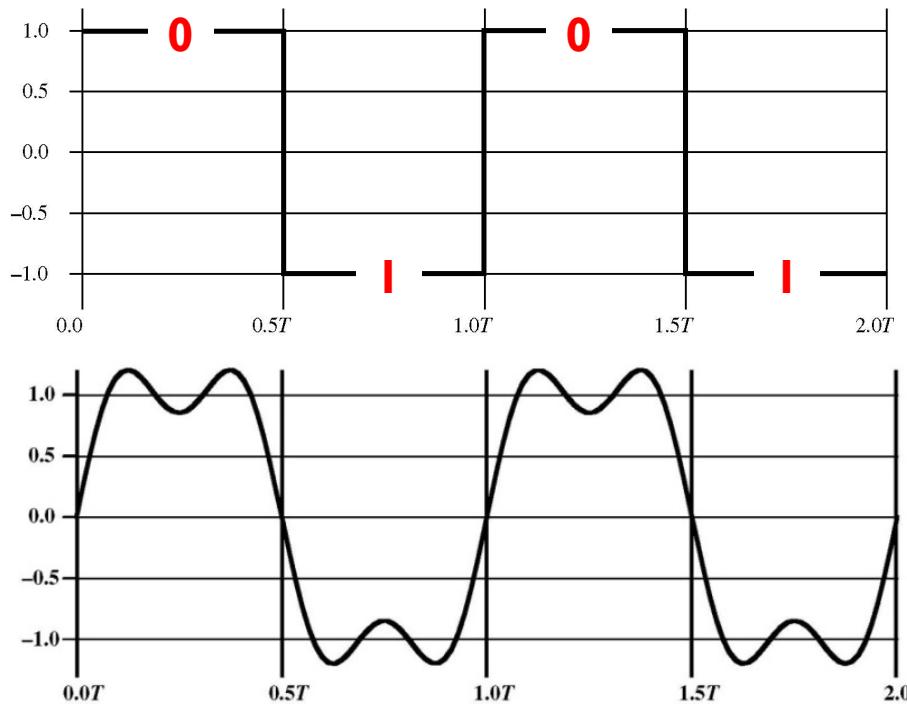
Signals to bits

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

▸ Add two sine waves
  (4/π)[sin2πft) + (1/3)sin(2π3ft)]

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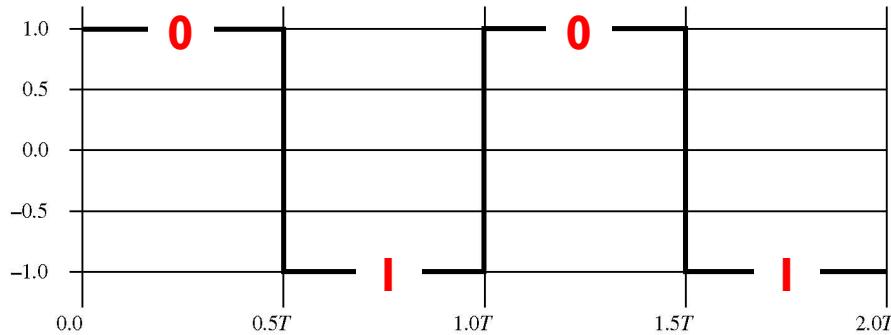
- ▶ Each pulse lasts *1/2f*
  - ▶ Data rate = *2f bps*
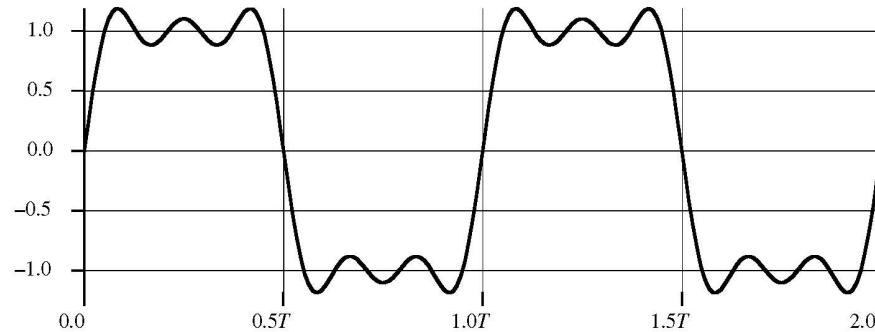
- ▶ Add a sine wave with frequency *5f*

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Signals to bits
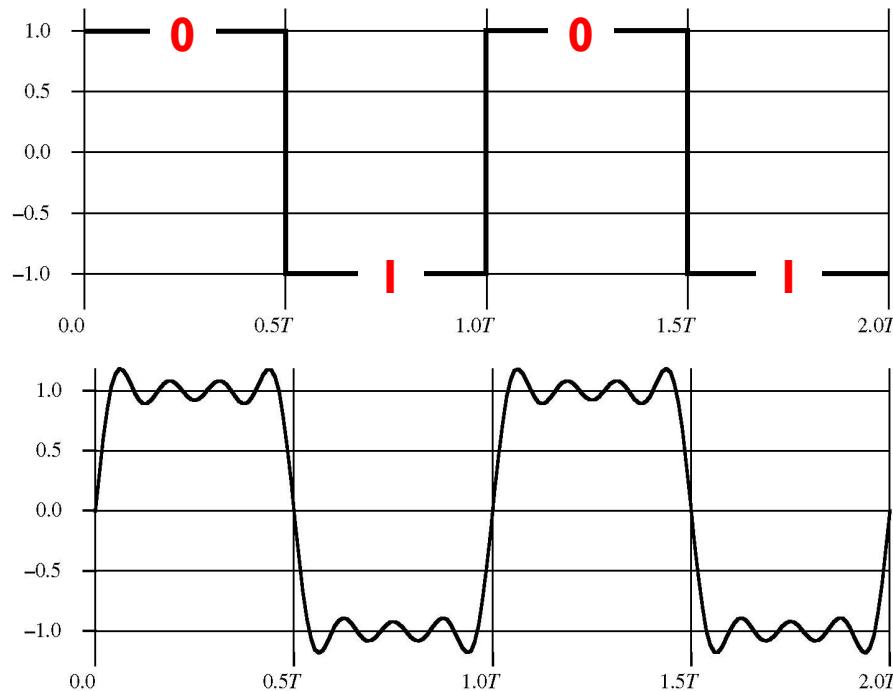
- ▸ Each pulse lasts *1/2f*
  - ▸ Data rate = *2f bps*

- ▸ Add a sine wave with frequency *7f*
  - ▸ And so on …

Infinite frequencies = infinite bandwidth!

not quite …
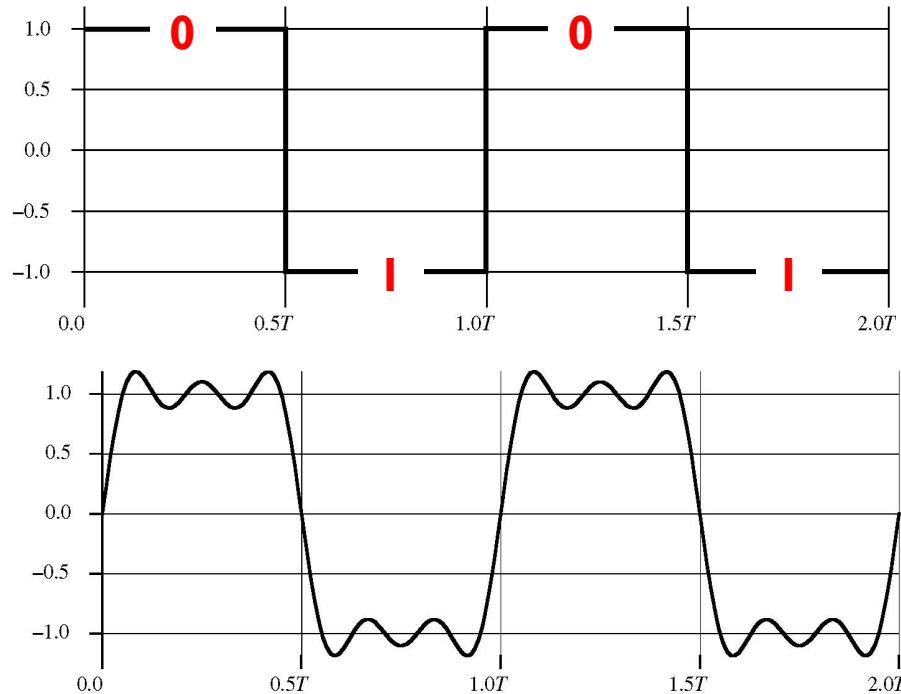
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Data rate

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
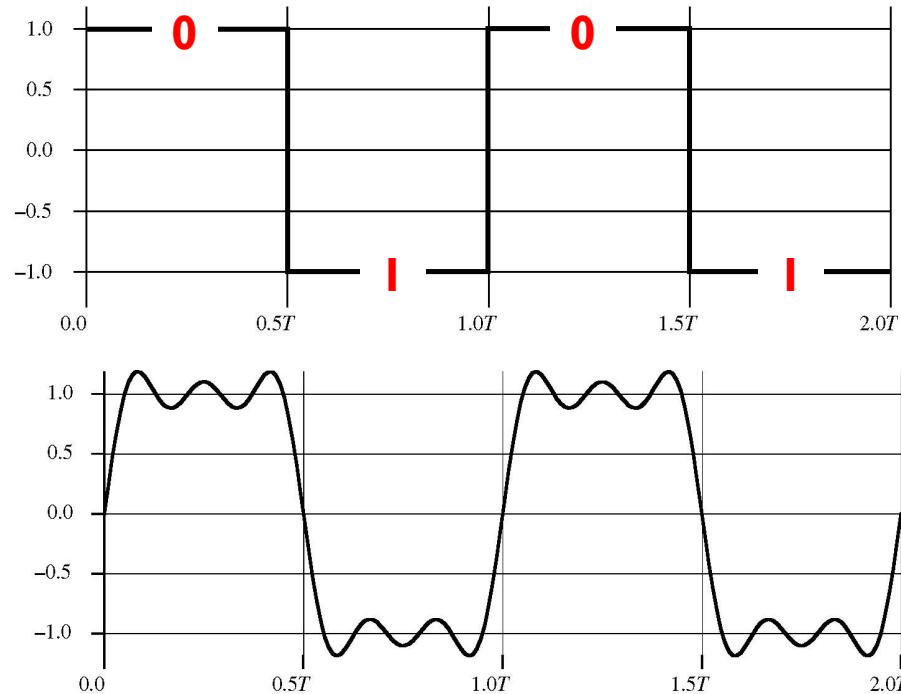
▸ **Available bandwidth of bandwidth of 8MHz**

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

2X BW = 2X data rate

Data rate
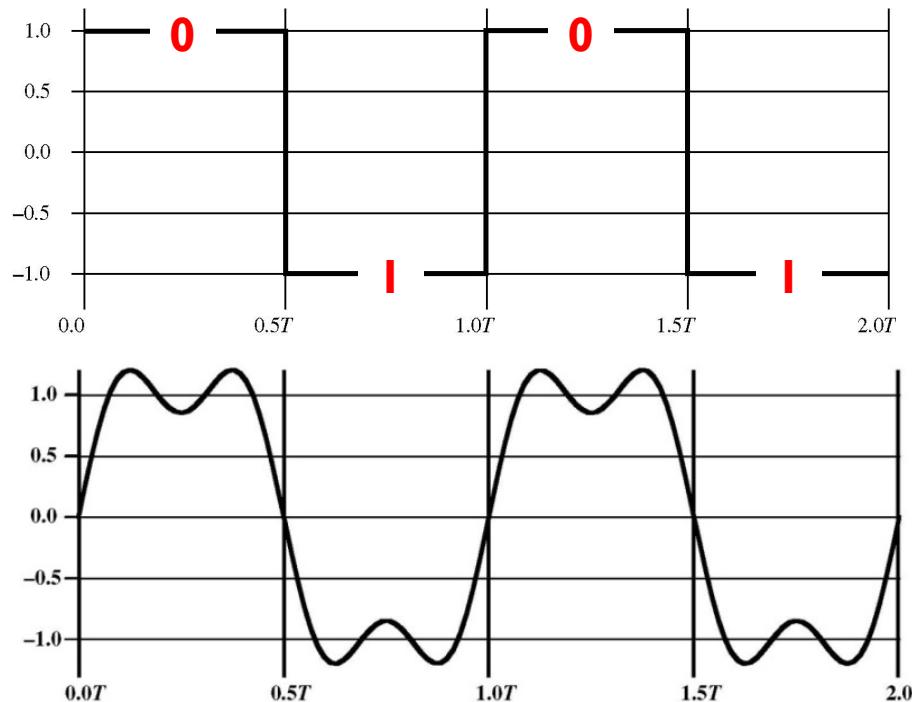
What if this is good enough?

- ▸ 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!

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
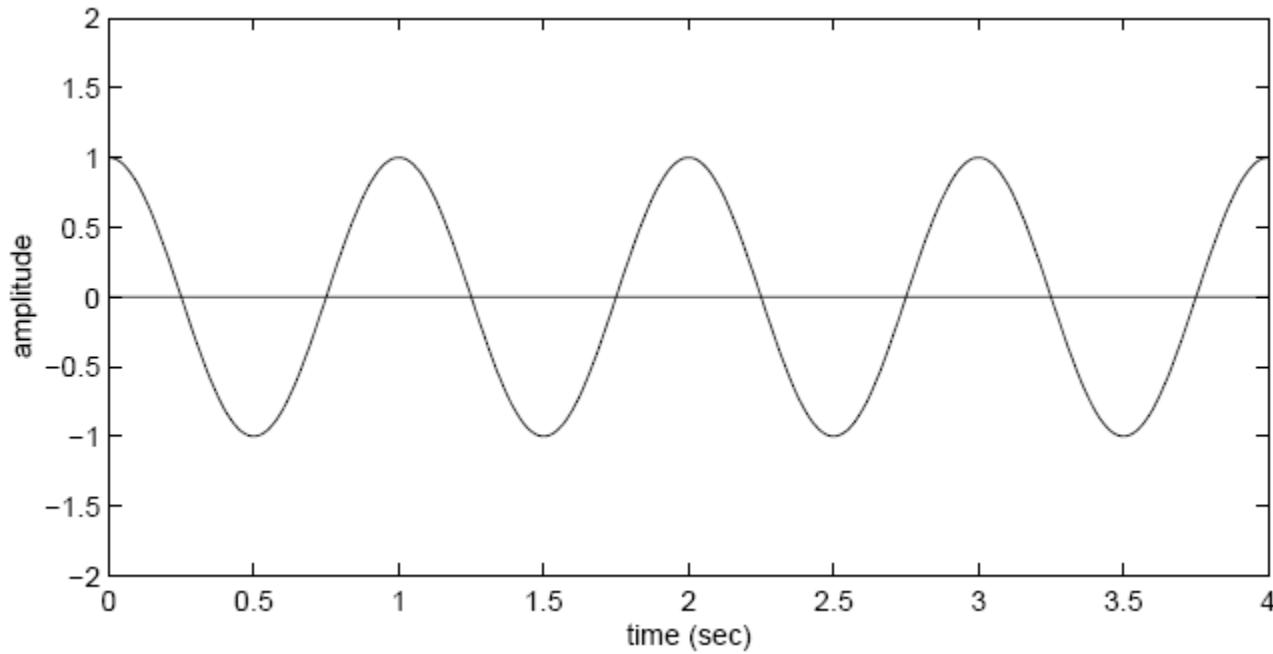
▸ Suppose you have the following 1Hz signal being received

▸ How fast do you need to sample, to capture the signal?

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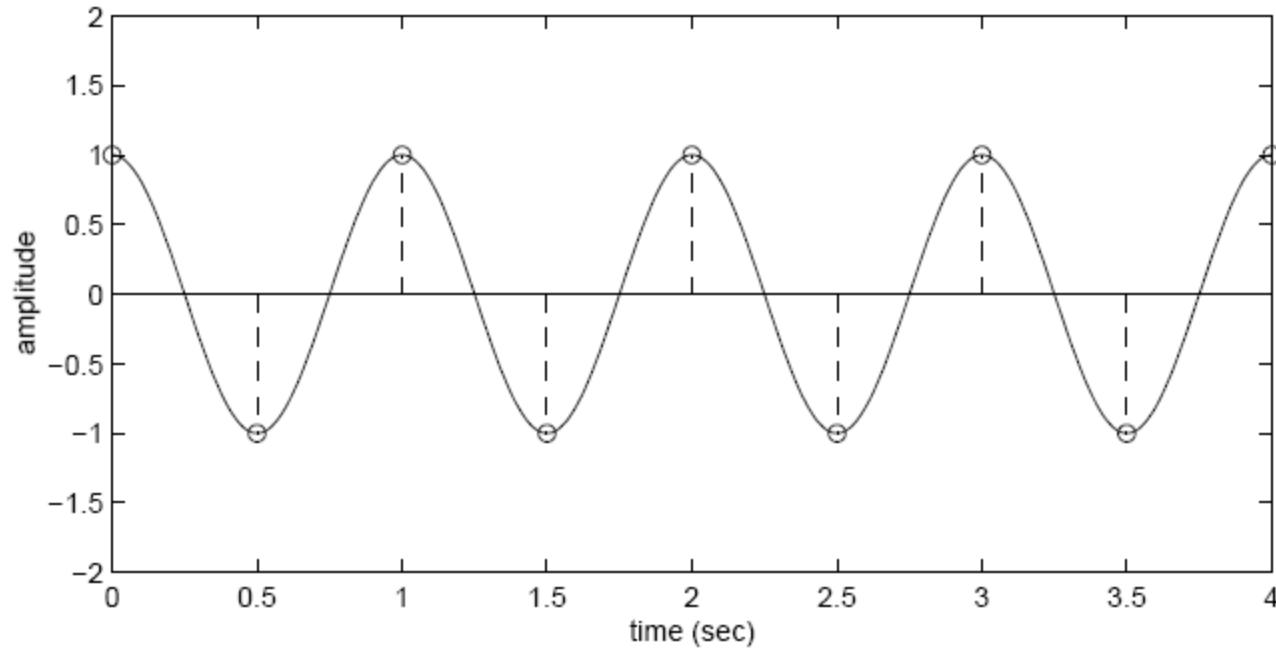
Sampling

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

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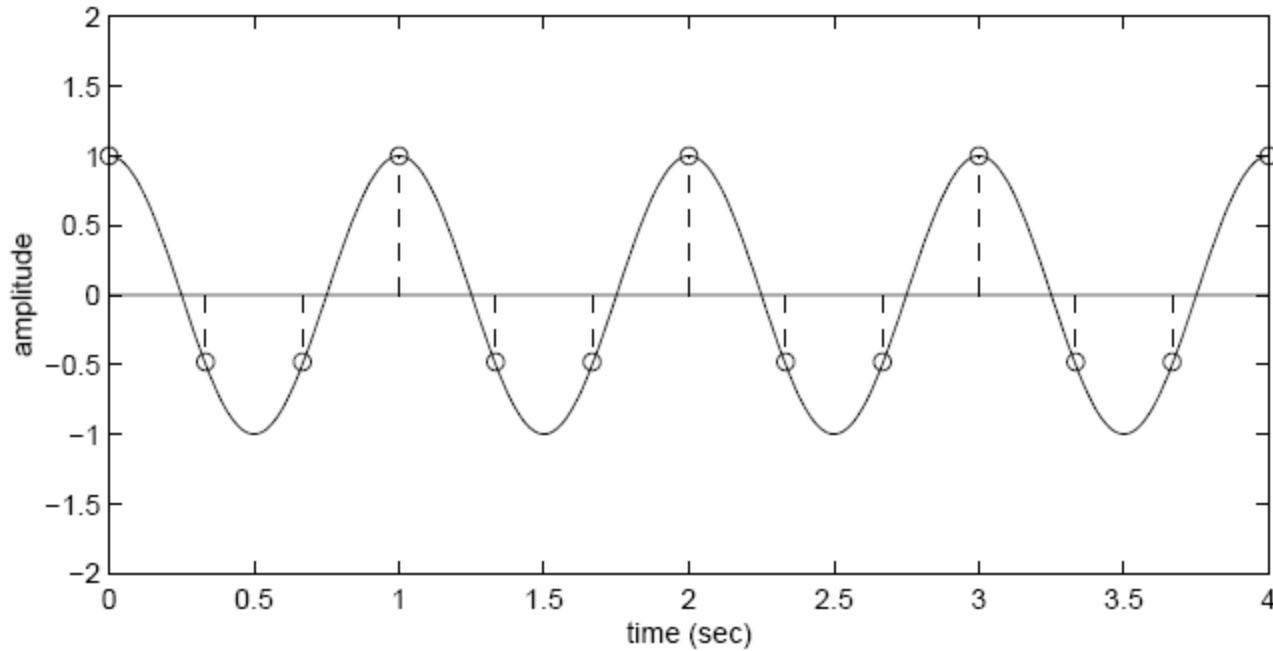
Sampling

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

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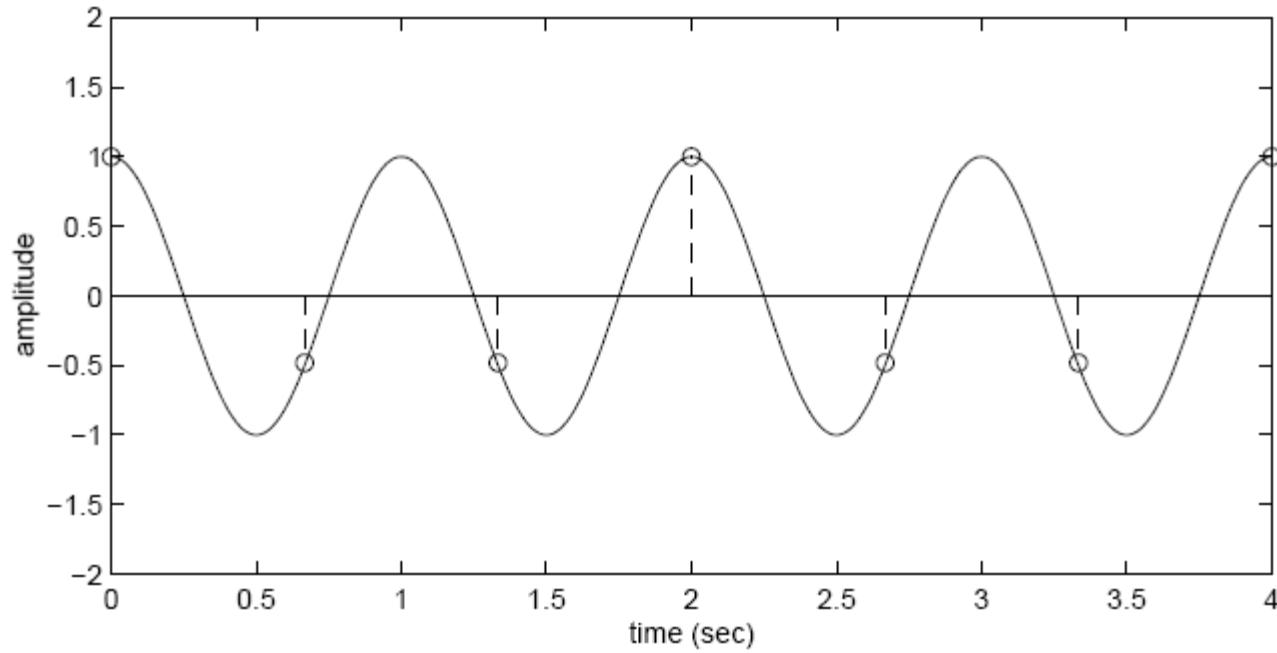
Sampling

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

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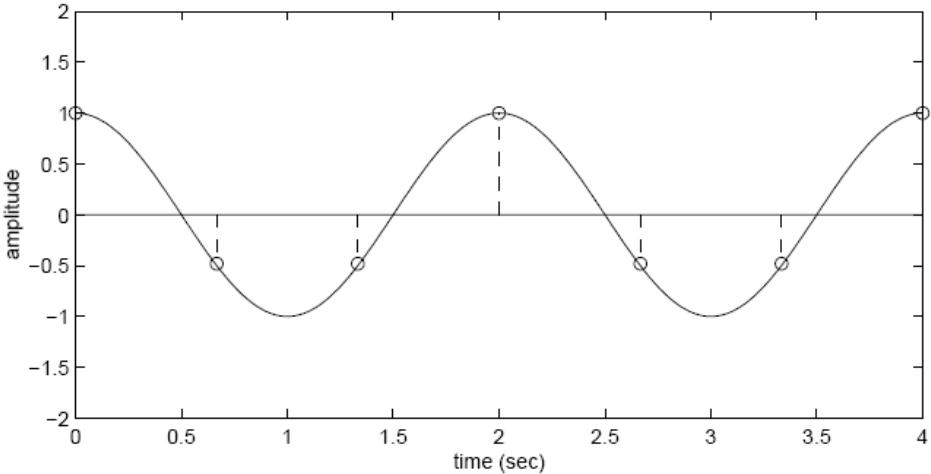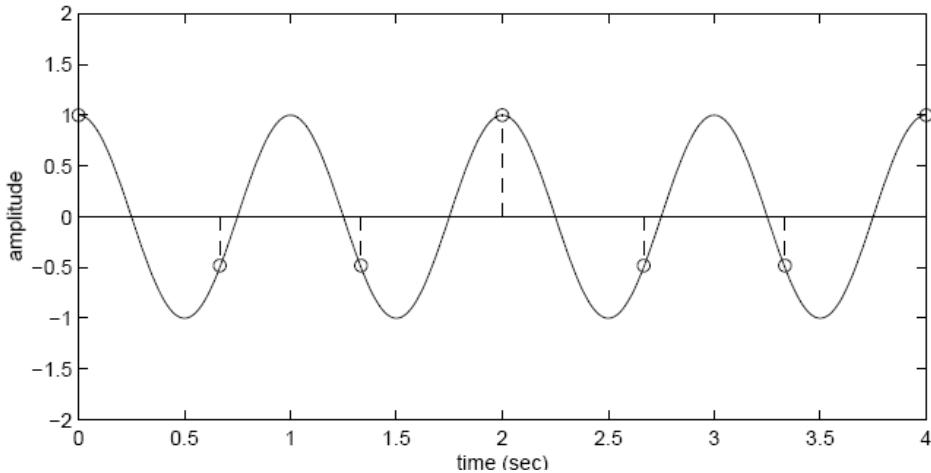
- ▸ **Sampling a 1 Hz signal at 1.5 Hz is not enough**
  - ▸ Can't distinguish between multiple possible signals
  - ▸ Problem known as **aliasing**

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Aliasing

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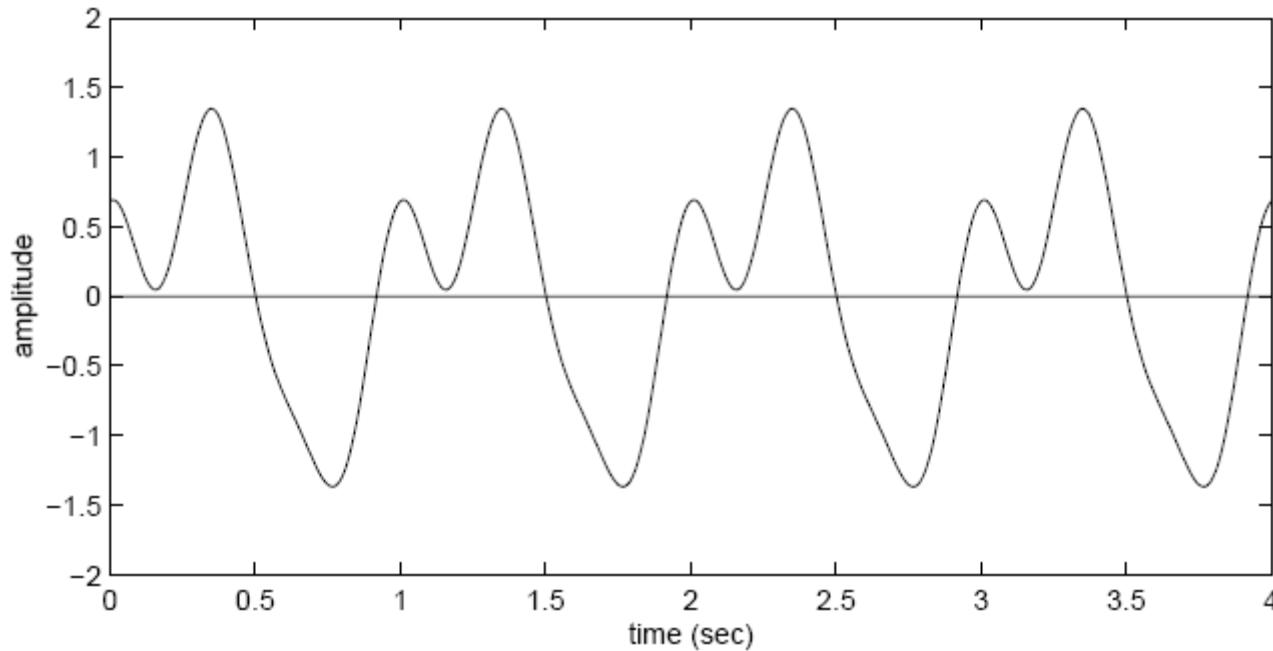
- Fourier's theorem
  - Any continuous signal can be decomposed into a sum of sines and cosines at different frequencies
- Example: Sum of 1 Hz, 2 Hz, and 3 Hz sines
  - How fast to sample?

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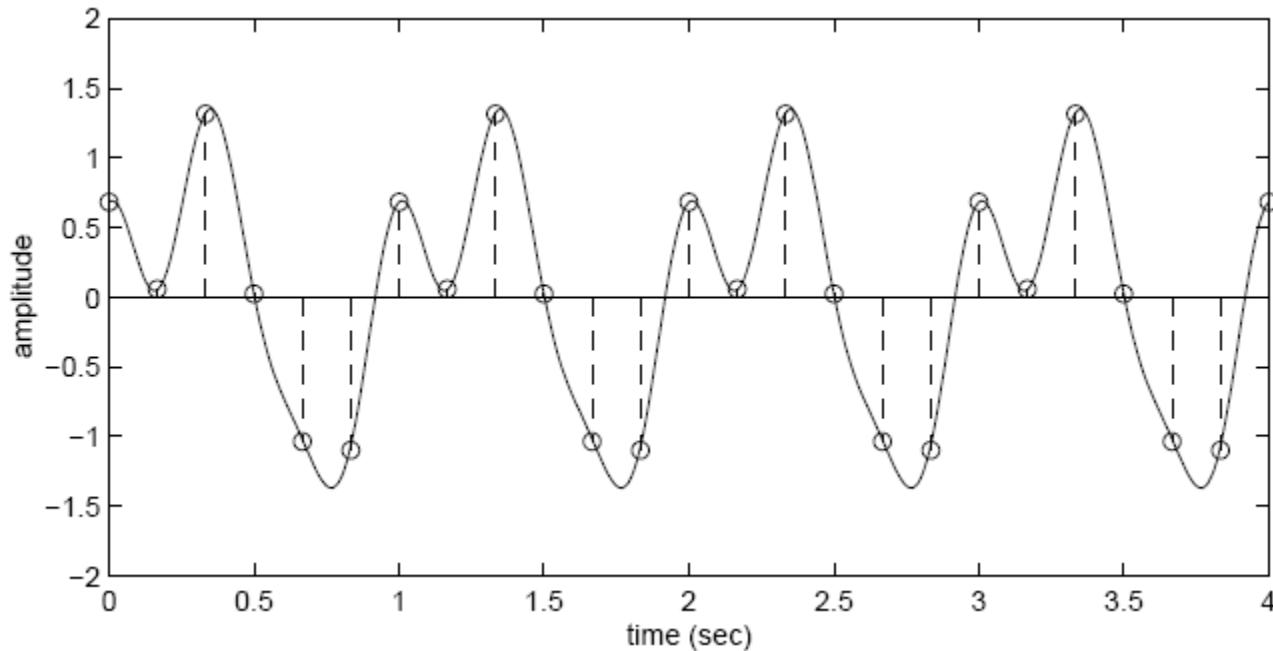
- Fourier's theorem
  - Any continuous signal can be decomposed into a sum of sines and cosines at different frequencies
- Example: Sum of 1 Hz, 2 Hz, and 3 Hz sines
  - How fast to sample? **--> answer: 6 Hz**

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 → $2B \log_2 N$ ← 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)

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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 ⟶ $2B \log_2 N$ ⟵ Number of bits per signal

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

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**

▸ Nyquist's S   '20's)

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

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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 x 4 = 9600 bps

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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)

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

where

      C is the maximum supportable bit rate

      B is the channel bandwidth

      N is noise

      S/N is the ratio between signal power
             and in-band noise power
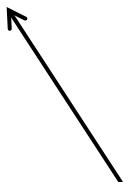
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How does Noise affect these Bounds?

▸ Noise
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▸ Claude Shannon (1948)
  ▸ Extended Nyquist's work to channels with additive white Gaussian noise (a good model for thermal noise)

<p style="color:red; text-align:center">channel capacity $C = B \log_2 (1 + S/N)$</p>

▸ 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

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

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

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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

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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

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

▶ **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

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

    $S/N = 10{,}000$

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

  - $C = 3400 \log_2 (10001) = 44.8$ kbps

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

FDM cable

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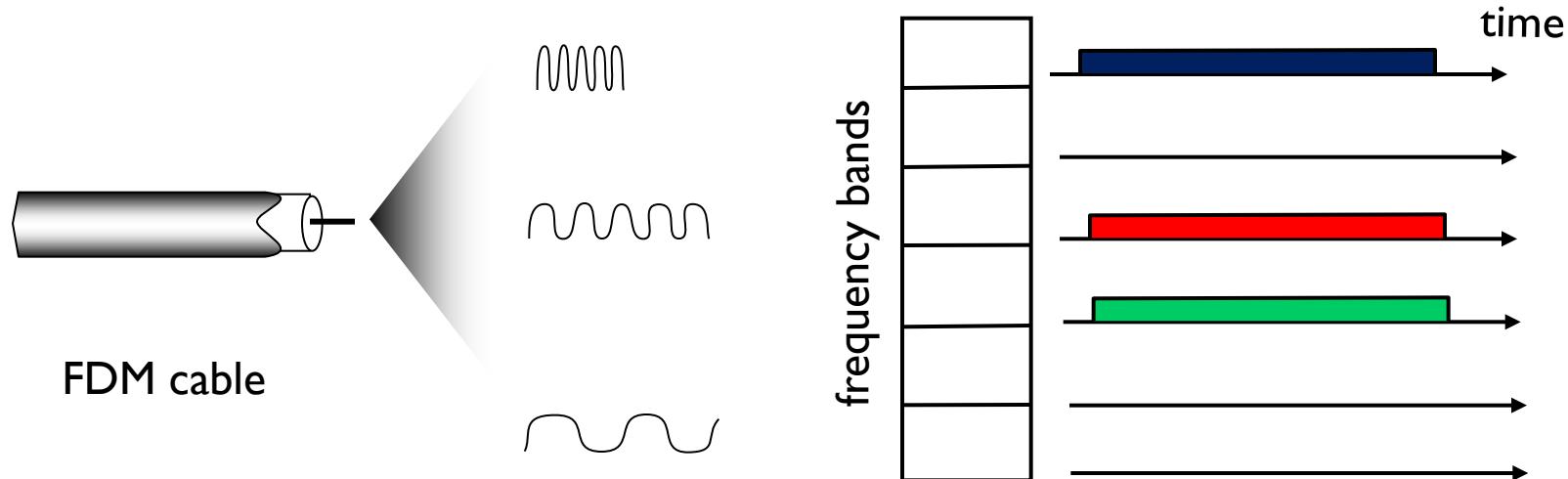
Multiplexing

▸ **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

Rounds

Slots = 0 1 2 3 4 5 0 1 2 3 4 5
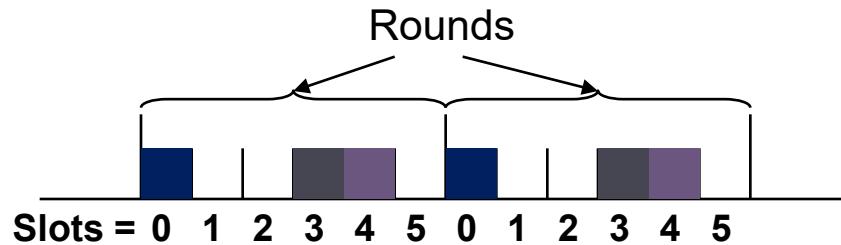
FDM Example: AMPS

▸ 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

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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, …