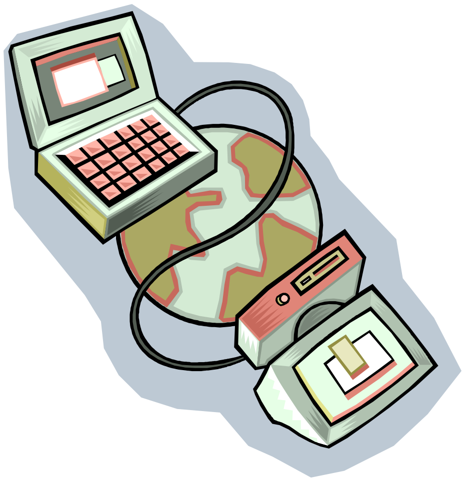
Chapter 3 — Data Transmission

CSE 3213

Data Transmission



- quality of the signal being transmitted

The successful transmission of data depends on two factors:

- characteristics of the transmission medium

Transmission Terminology

Data transmission occurs between transmitter and receiver over some transmission medium.

Communication is in the form of electromagnetic waves.

Guided media

- twisted pair, coaxial cable, optical fiber

Unguided media (wireless)

- air, vacuum, seawater

Transmission Terminology (2)

Direct link

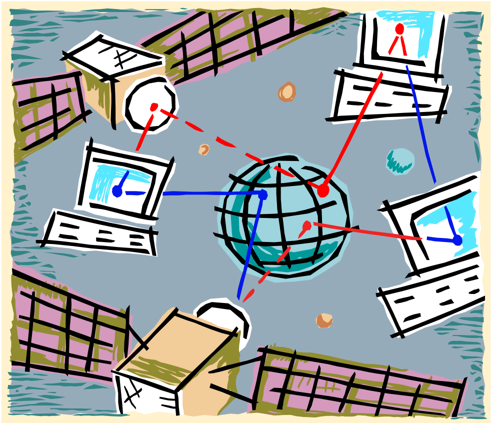
- no intermediate devices

Point-to-point

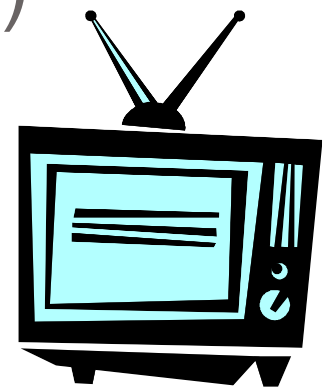
- direct link
- only 2 devices share link

Multi-point

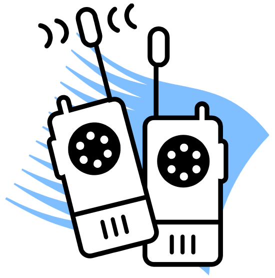
- more than two devices share the link



Transmission Terminology (3)



- **Simplex**
  - signals transmitted in one direction
    - eg. television



- **Half duplex**
  - both stations transmit, but only one at a time
    - eg. police radio

- **Full duplex**
  - simultaneous transmissions
    - eg. telephone

Note: elsewhere, half duplex is called "simplex";
full duplex is called "duplex" (ITU-T definitions)

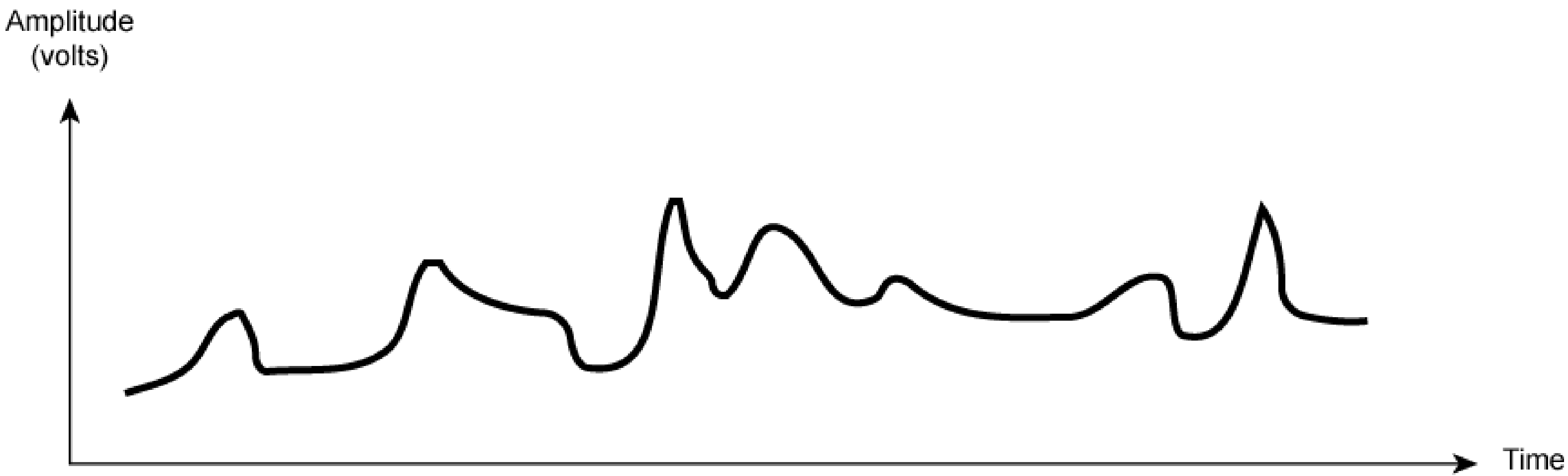
Analog and Digital Data Transmission

- Data
  - Entities that convey meaning, or information (data $\neq$ info)
- Signals
  - Electric or electromagnetic representations of data
- Signaling
  - Physical propagation of the signal along a medium
- Transmission
  - Communication of data by propagation and processing of signals

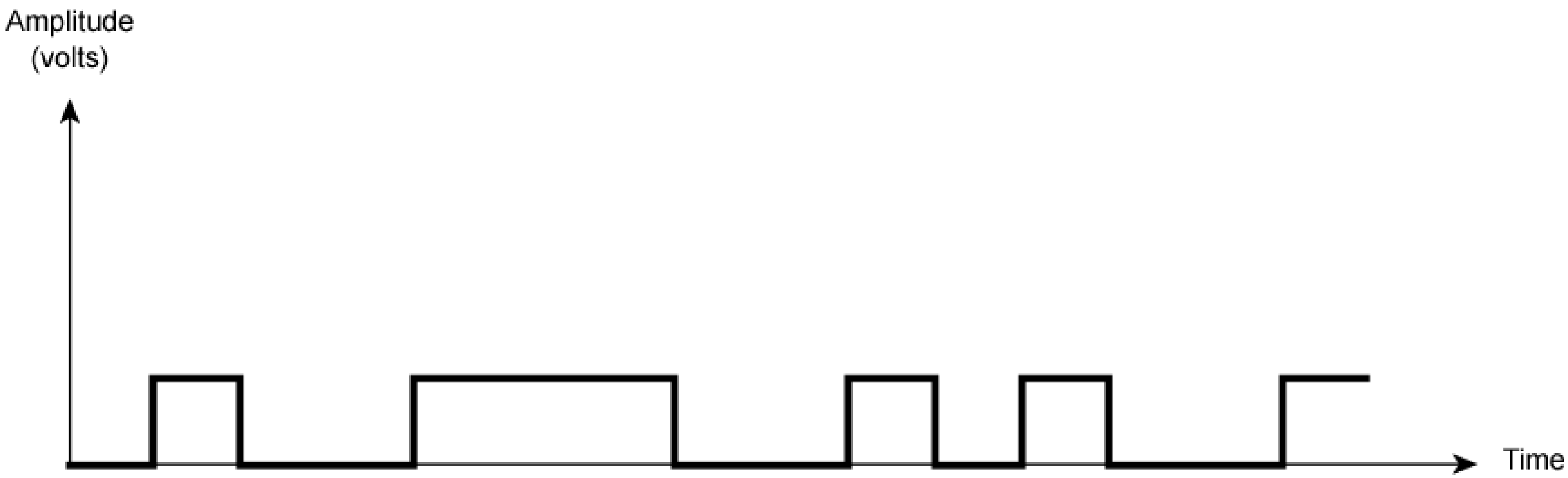
Analog and Digital Data

- Analog
  - Continuous values within some interval
  - e.g. sound, video
- Digital
  - Discrete values
  - e.g. text, integers

Analogue and Digital Signals

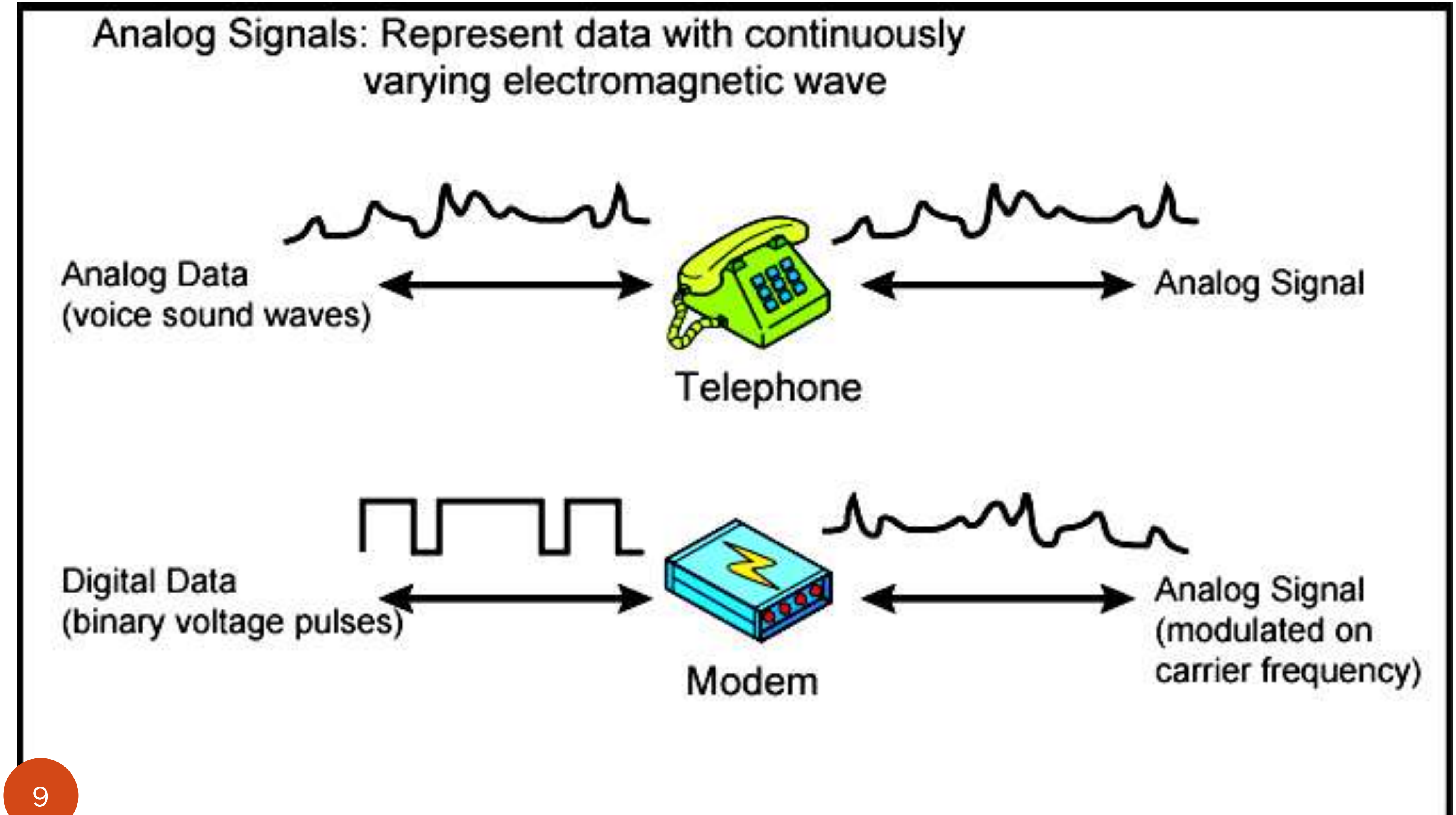


(a) Analog

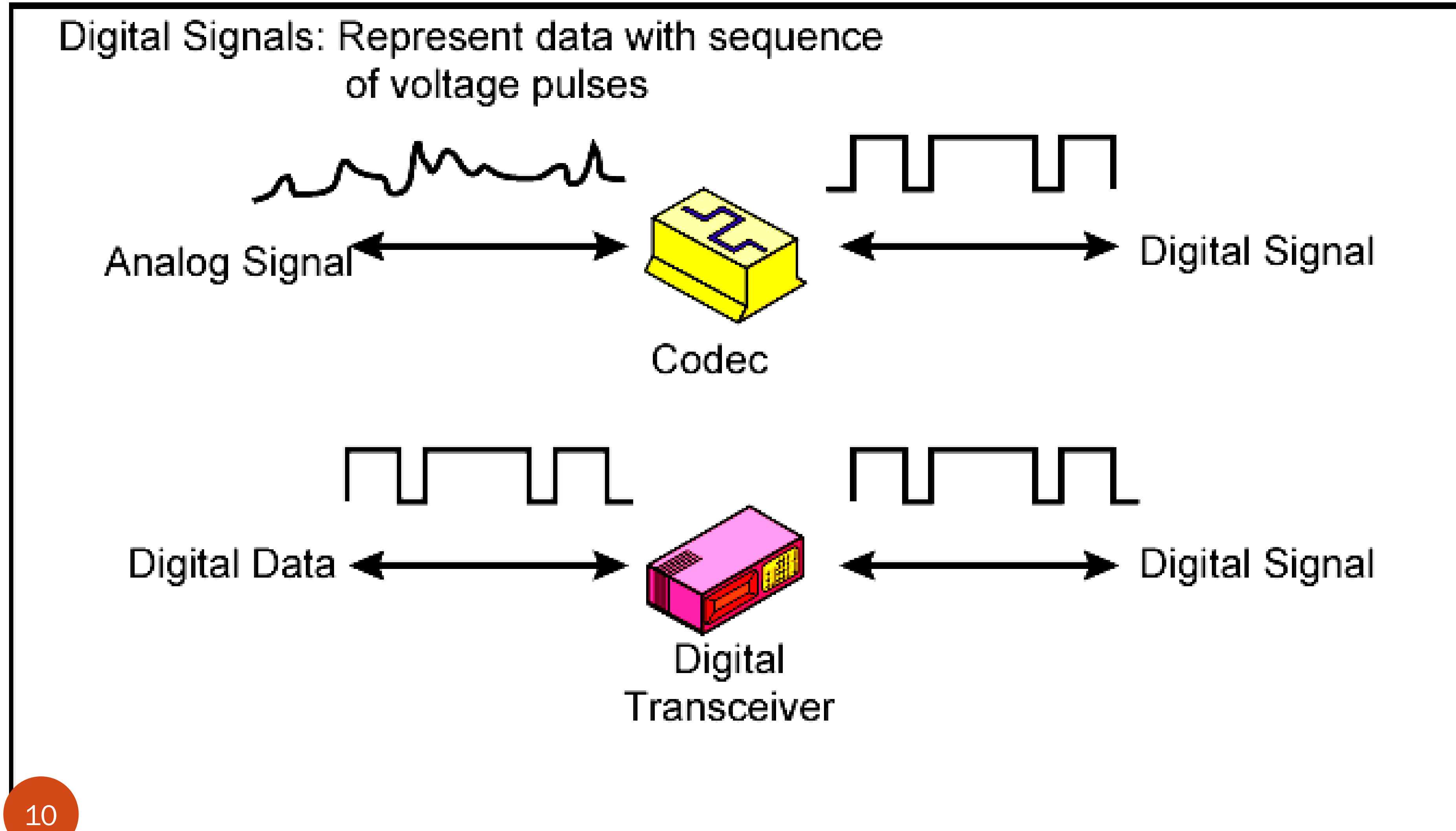


(b) Digital

Analog Signals

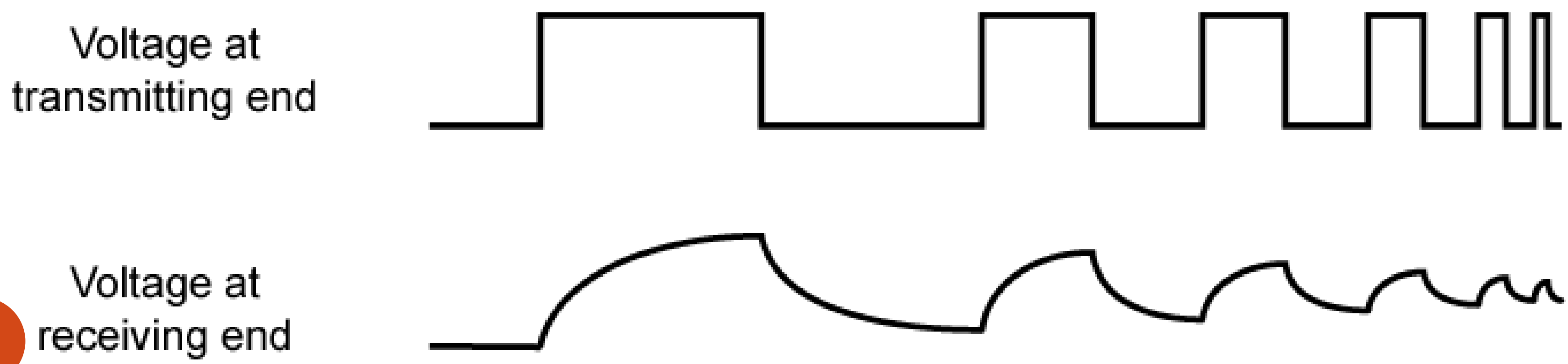


Digital Signals



Advantages & Disadvantages of Digital Signals

- cheaper
- less susceptible to noise
- but greater attenuation
- digital now preferred choice



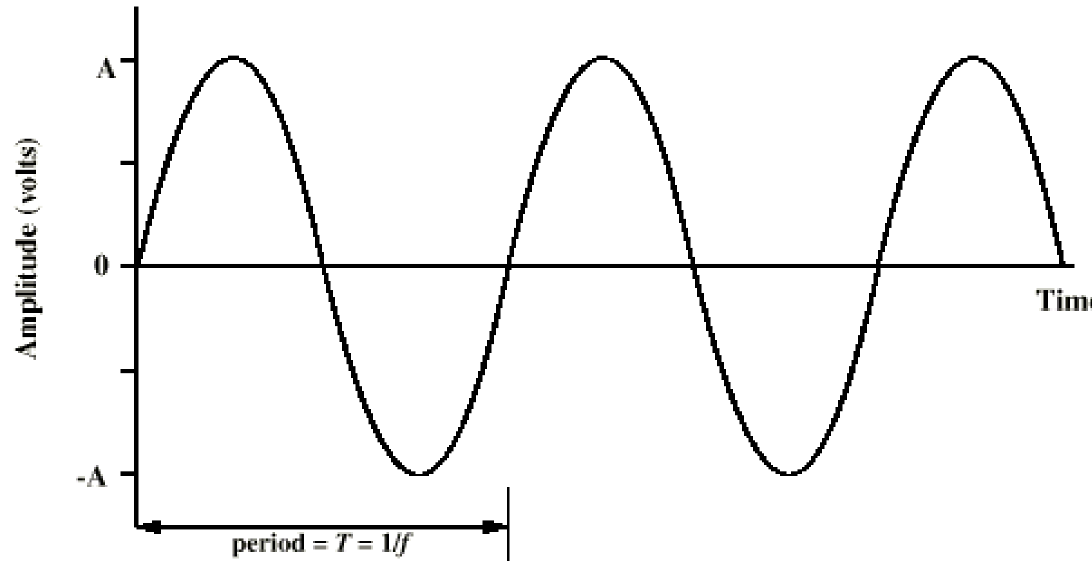
Frequency, Spectrum and Bandwidth

- Time domain
  - Example: a sine wave, a square wave
- Frequency domain
  - Signal usually made up of many components of different frequencies
  - Components are sine waves
  - More important than time domain

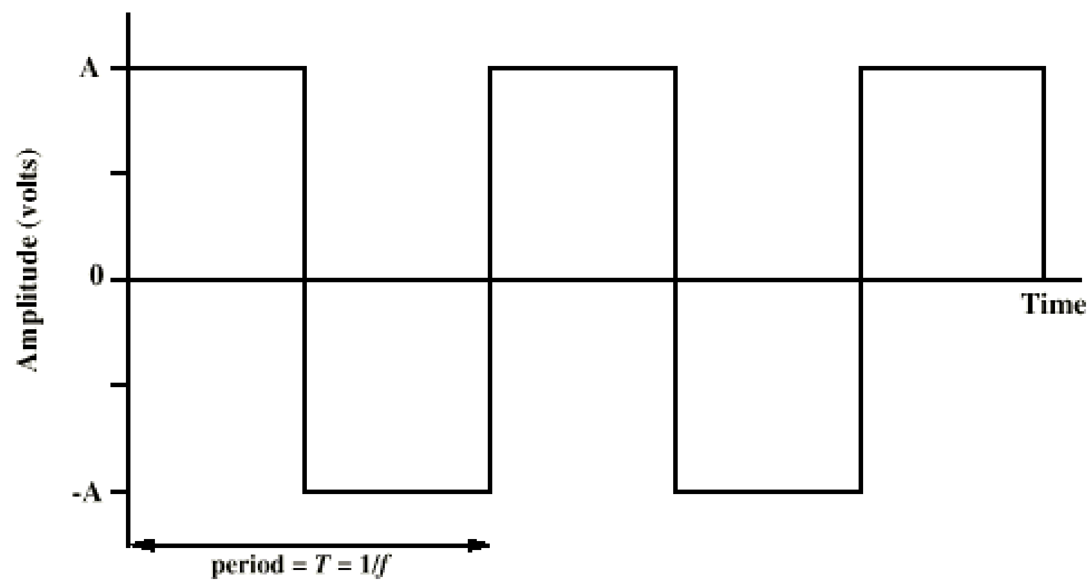
Time Domain Concepts

- Analog signal
  - Various in a smooth way over time (continuous)
- Digital signal
  - Maintains a constant level then changes to another constant level (discrete)
- Periodic signal
  - Pattern repeated over time
- Aperiodic signal
  - Pattern not repeated over time

Periodic Signals



(a) Sine wave



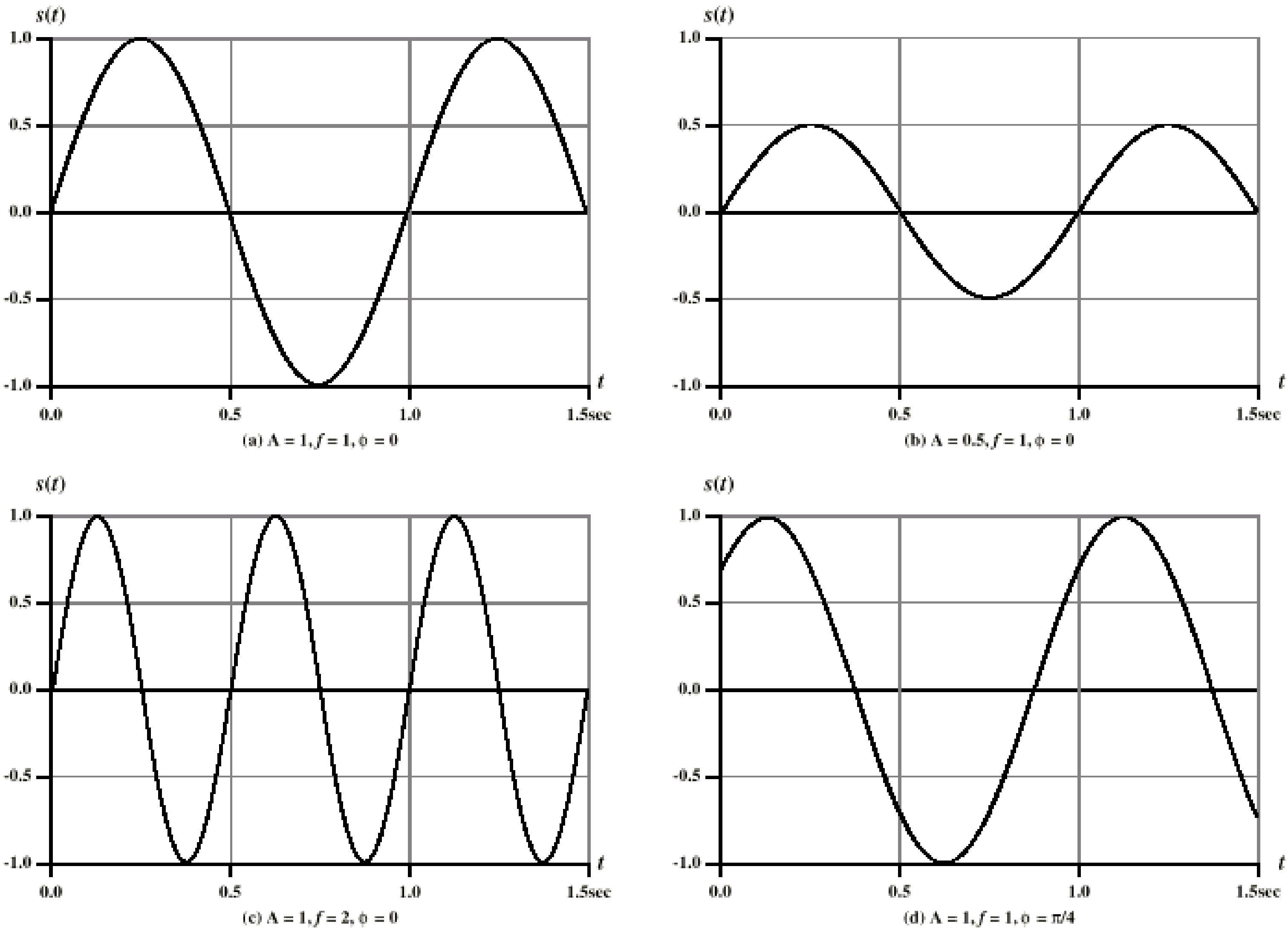
(b) Square wave

Sine Wave

Periodic continuous signal

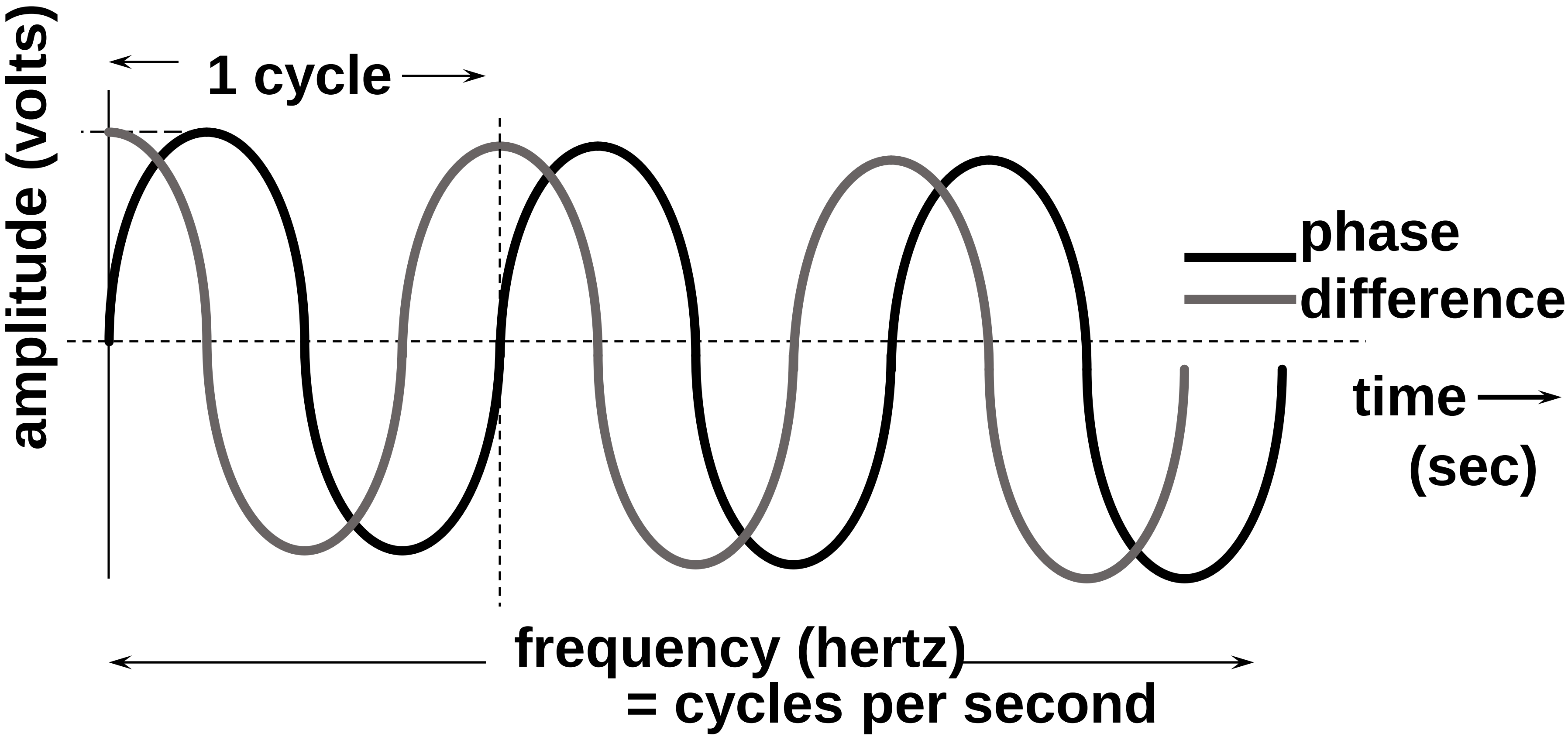
- Peak Amplitude (A)
  - maximum strength of signal
  - volts
- Frequency (f)
  - rate of change of signal
  - Hertz (Hz) or cycles per second
  - period = time for one repetition (T)
  - $T = 1/f$
- Phase (ϕ)
  - relative position in time

Examples of Sine Waves
$s(t) = A \sin(2\pi ft + \Phi)$



Analog Signaling

- Frequency and peak amplitude are the most important.



Wavelength (λ)

the wavelength of a signal is the distance occupied by a single cycle

can also be stated as the distance between two points of corresponding phase of two consecutive cycles

assuming signal velocity v, then the wavelength is related to the period as

$\lambda = vT$

especially when $v = c$

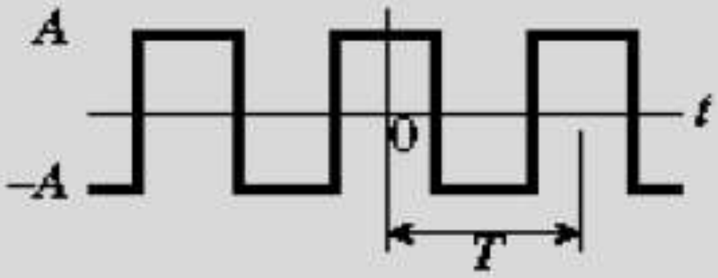
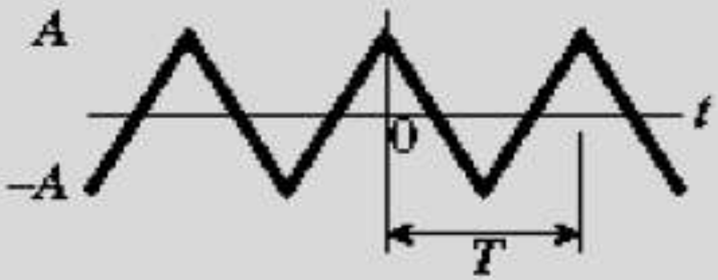
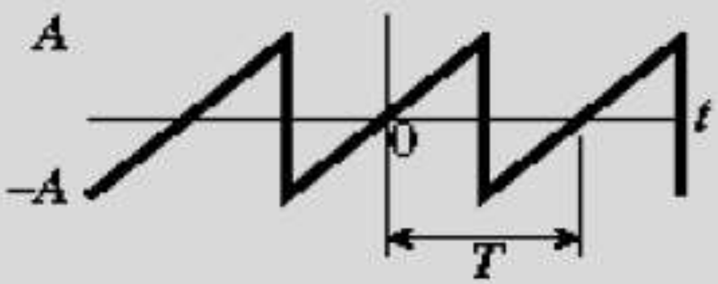
- $c = 3 \times 10^8$ m/s (speed of light in free space)

or equivalently

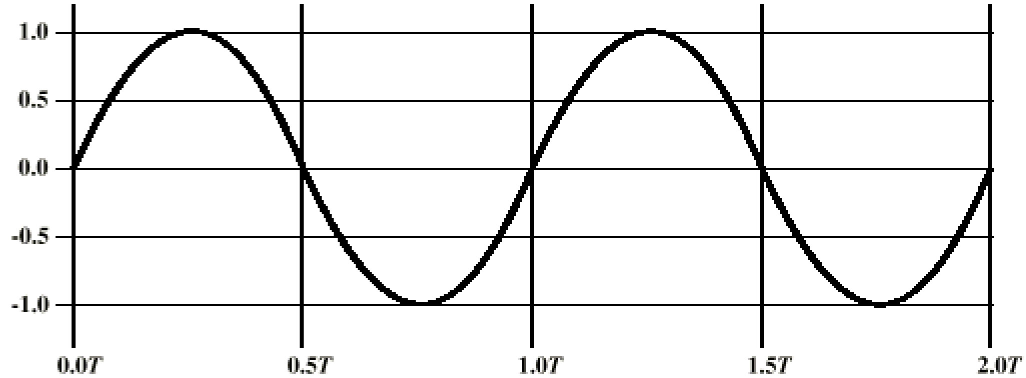
$\lambda f = v$

Frequency Domain Concepts

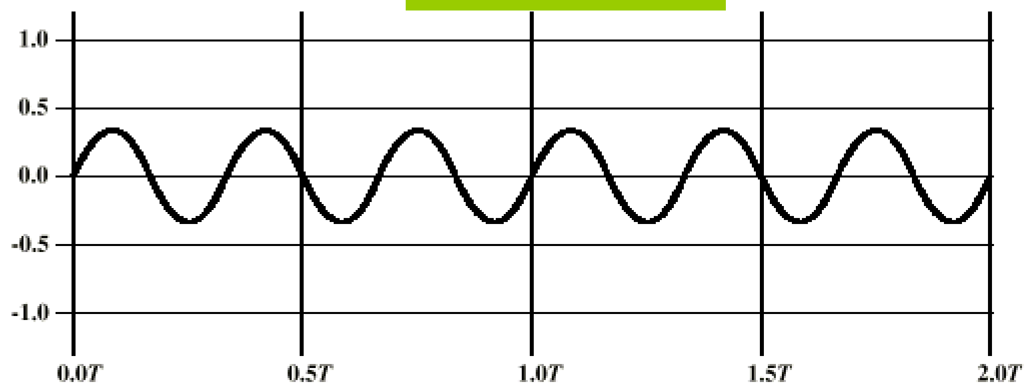
- Signal usually made up of many frequencies
- Components are sine waves
- Can be shown (Fourier analysis) that any signal is made up of components at various frequencies; each component is a sine wave
  - fundamental frequency
  - period of total signal = period of fundamental frequency
  - harmonic frequency = a multiple of fundamental frequency
- Can plot frequency domain functions

Signal	Fourier Series
Square wave 	$(4A/\pi) \times [\cos(2\pi f_1 t) - (1/3)\cos(2\pi(3f_1)t) + (1/5)\cos(2\pi(5f_1)t) - (1/7)\cos(2\pi(7f_1)t) + \ldots]$
Triangular wave 	$(8A/\pi^2) \times [\cos(2\pi f_1 t) + (1/9)\cos(2\pi(3f_1)t) + (1/25)\cos(2\pi(5f_1)t) + \ldots]$
Sawtooth wave 	$(2A/\pi) \times [\sin(2\pi f_1 t) - (1/2)\sin(2\pi(2f_1)t) + (1/3)\sin(2\pi(3f_1)t) - (1/4)\sin(2\pi(4f_1)t) + \ldots]$

Addition of Frequency Components (T = 1/f)

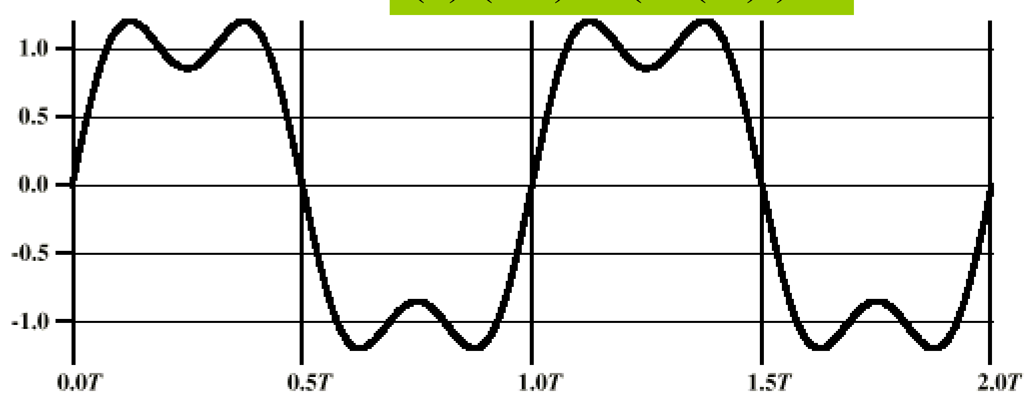


(a) sin(2πft)



(b) (1/3)sin(2π(3f)t)

(c) is the sum of *f* and 3*f*



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

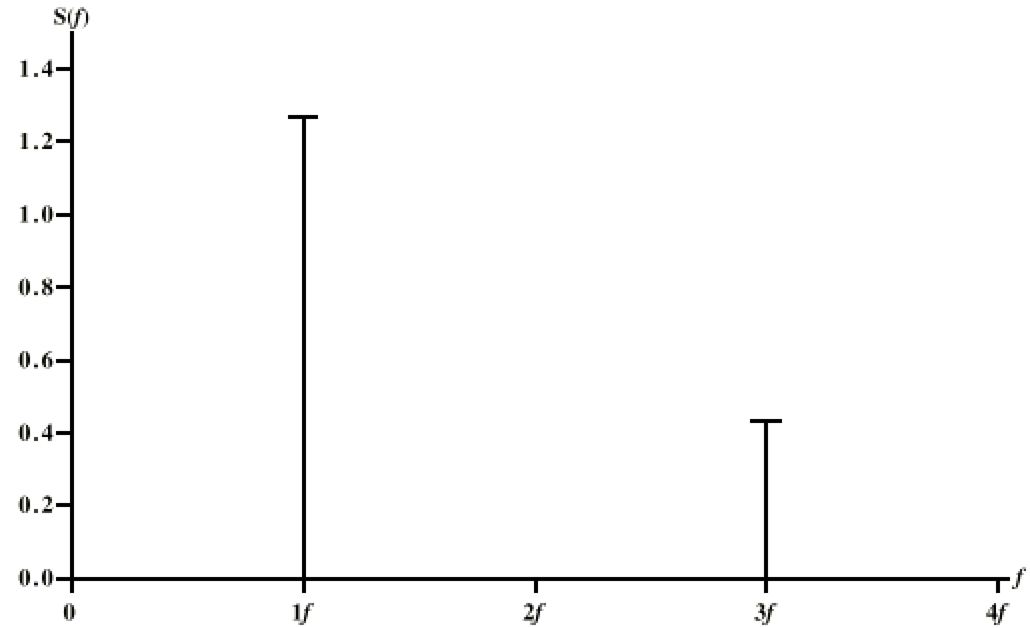
(c) (4/π)[sin(2πft)+(1/3)sin(2π(3f)t)]

Frequency Domain

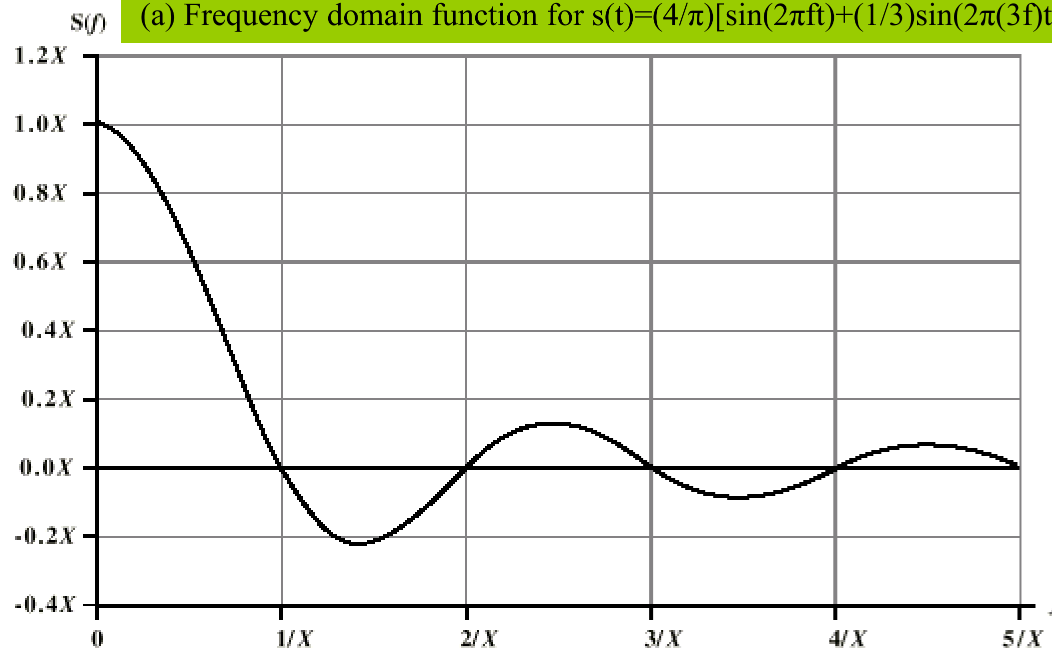
S(f) is discrete

Figure a is discrete because the time domain function is periodic. Figure b is continuous because the time domain function is aperiodic.

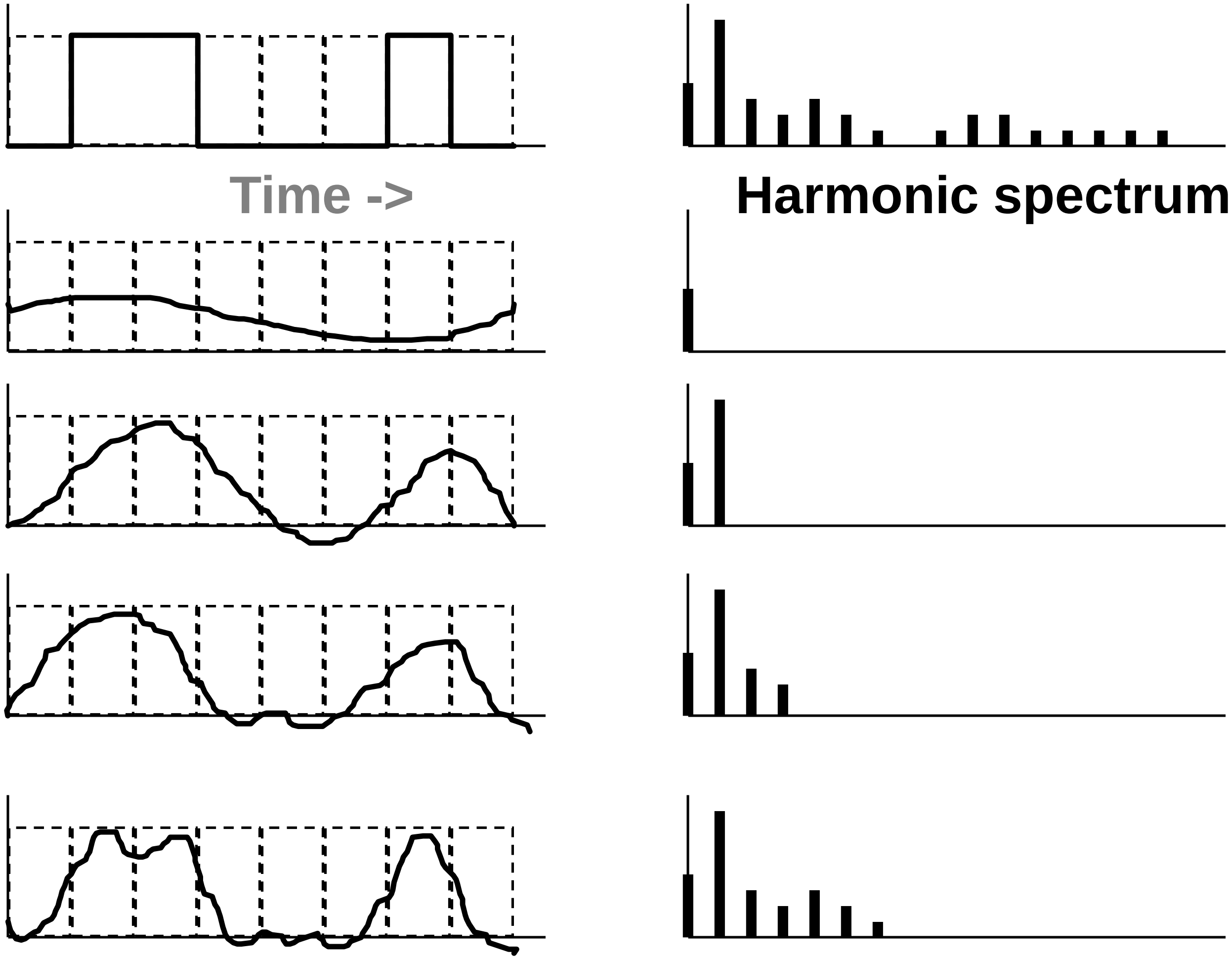
Single square pulse
S(f) is continuous



(a) Frequency domain function for s(t)=(4/π)[sin(2πft)+(1/3)sin(2π(3f)t)]



(b) Frequency domain function for a single square pulse s(t)=1 for -X/2<t<X/2



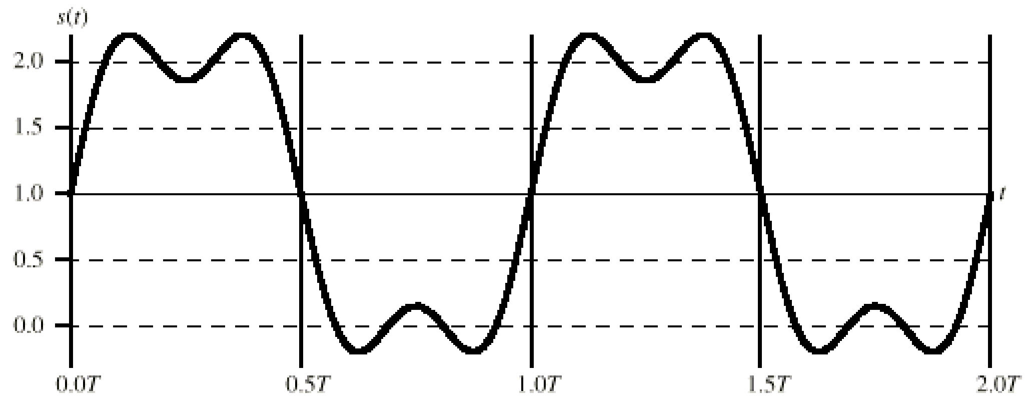
Original

As we add more harmonics the signal reproduces the original more closely

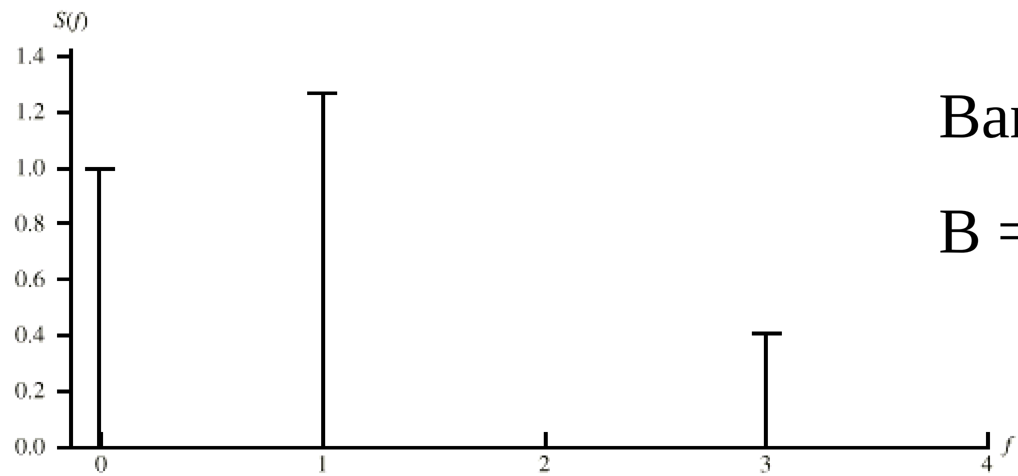
Spectrum and Bandwidth

- Spectrum
  - range of frequencies contained in signal
- Absolute bandwidth
  - width of spectrum
- Effective bandwidth (or just *bandwidth*)
  - narrow band of frequencies containing most of the energy
- DC Component
  - Component of zero frequency
  - No DC component $\Rightarrow$ average amplitude $= 0$
  - DC component is undesirable (avg amplitude $\neq 0$)

Signal with DC Component



(a) $s(t)=1+(4/\pi)[\mathrm{Sin}(2\pi ft)+(1/3)\mathrm{Sin}(2\pi(3f)t)]$



(b) S(f)

Bandwidth

$B = 3f - f = 2f$

Data Rate and Bandwidth

- Data rate
  - In bits per second
  - Rate at which data can be communicated
- Bandwidth
  - In cycles per second, or Hertz
  - Constrained by transmitter and medium
- Channel: a communication path

Data Rate and Bandwidth

any transmission system has a limited band of frequencies

this limits the data rate that can be carried on the transmission medium

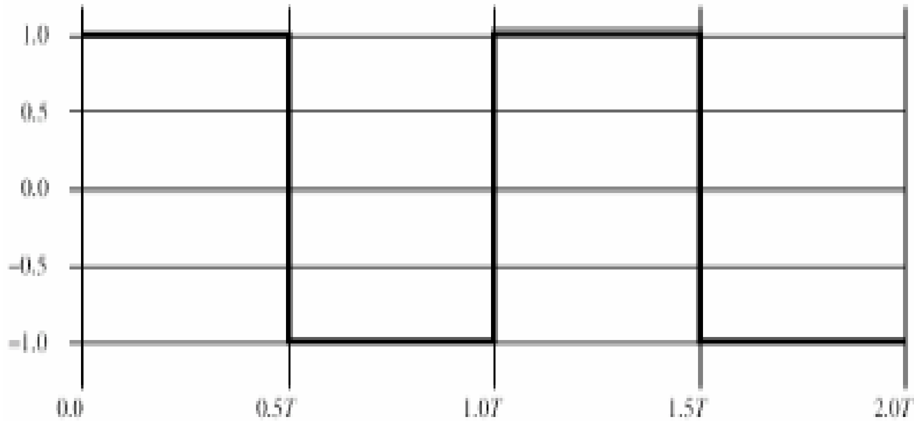
square waves have infinite components and hence an infinite bandwidth

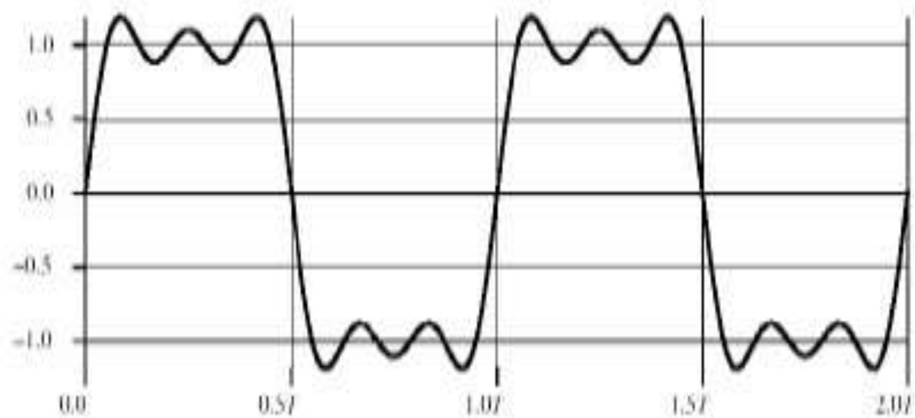
most energy in first few components

limiting bandwidth creates distortions

There is a direct relationship between data rate and bandwidth.

Example

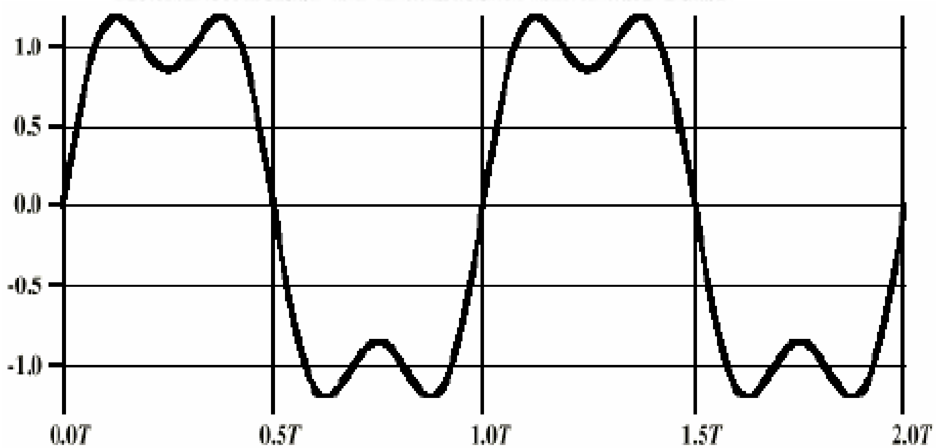




(a) (4/π) [sin (2πft) + (1/3) sin (2π(3f)t) + (1/5) sin (2π(5f)t)]

Case 1:
f = 1 MHz
R = ? Mbps
B = ? MHz

Case 2:
f = ? MHz
B = 8 MHz
R = ? Mbps



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

Case 3:
f = ? MHz
B = 4 MHz
R = ? Mbps

Data Rate and Bandwidth (3)

Consider a square wave

- Data rate $R = 2 \text{ x } f$ (f: fundamental frequency)
- Double the bandwidth $\Rightarrow$ double the data rate (other things being equal)
- A given bandwidth can support different data rates (e.g., by removing the component with the highest frequency). However, it's harder for the receiver to interpret the received signal if R is high (i.e., more chances for errors).

Data Rate and Bandwidth (4)

In general,

- The greater the bandwidth $\Rightarrow$ the higher the data rate
- The higher the data rate $\Rightarrow$ The greater the required effective bandwidth
- Keeping the same data rate:

  Greater bandwidth $\Rightarrow$ better quality of the received signal, but greater cost
- The higher center frequency $\Rightarrow$ the higher the potential bandwidth

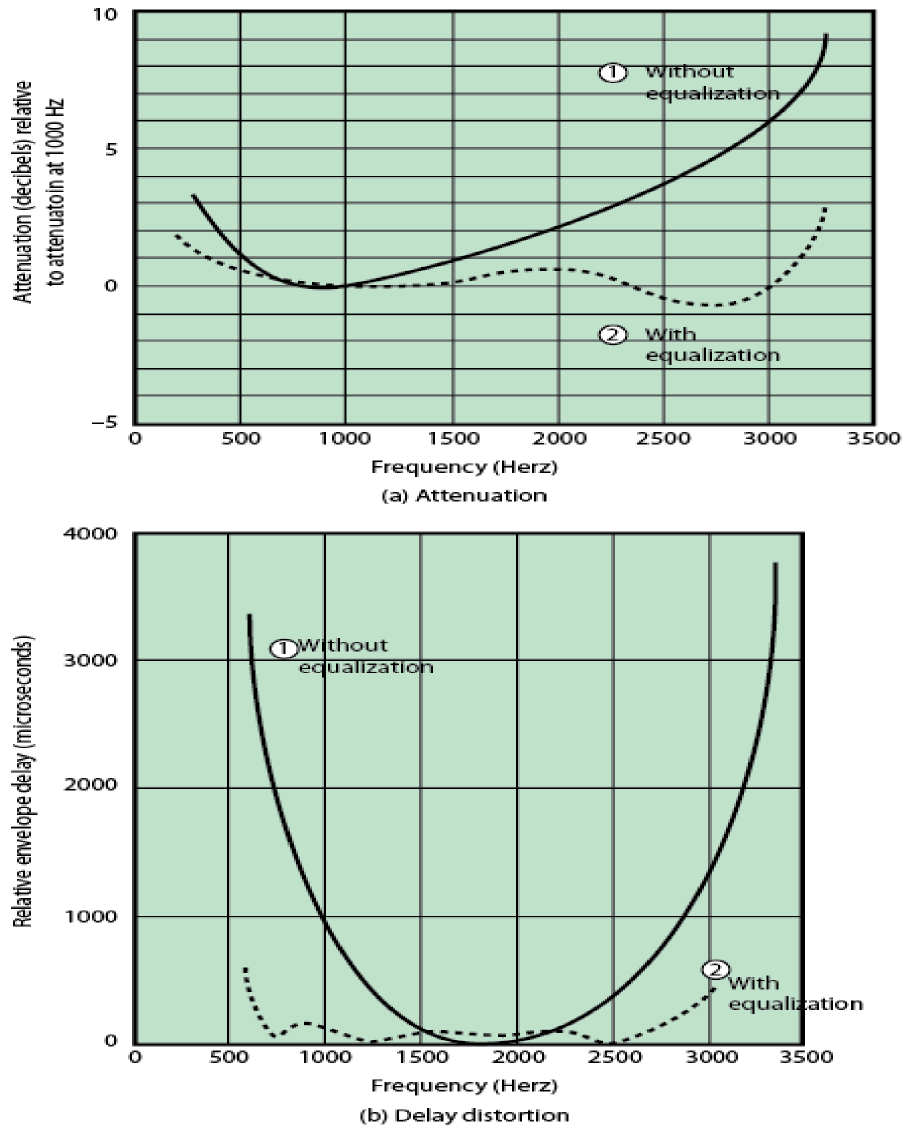
Transmission Impairments (3.3)

- Signal received may differ from signal transmitted
- Analog - degradation of signal quality
- Digital - bit errors
- Caused by
  - Attenuation and attenuation distortion
  - Delay distortion
  - Noise

Attenuation

- Signal strength falls off with distance
- Solutions: use repeaters, amplifiers
- Depends on medium
- Received signal strength:
  - must be enough to be detected
  - must be sufficiently higher than noise to be received without error
- Attenuation distortion
  - Attenuation is an increasing function of frequency.
  - Solution: equalization (amplifying high frequencies more than low frequencies)
- Less of a problem with digital signals (why?)

Attenuation and Delay Distortion



Delay Distortion

- occurs because propagation velocity of a signal through a guided medium varies with frequency
  - highest velocity near the center frequency
- various frequency components arrive at different times resulting in phase shifts between the frequencies
- particularly critical for digital data since parts of one bit spill over into others causing inter-symbol interference
- solution: equalization

Noise

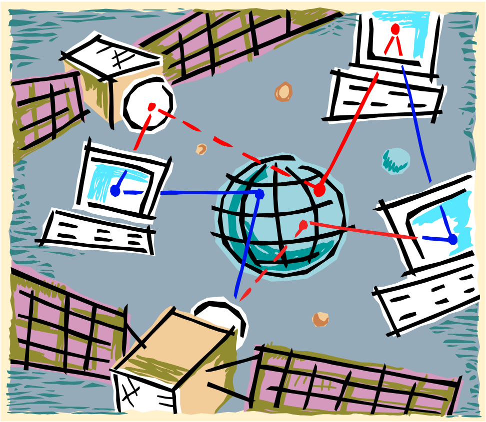
unwanted signals inserted between transmitter and receiver

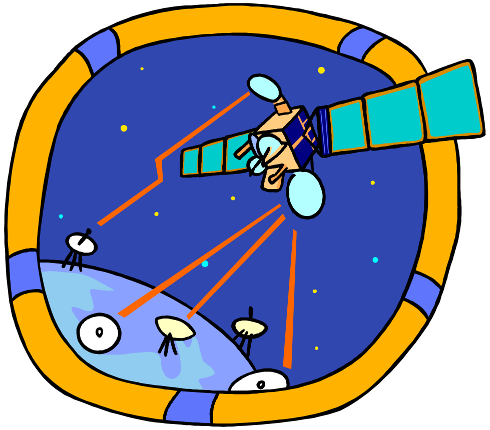
is the major limiting factor in communications system performance

Categories of Noise (1)

Thermal noise

- due to thermal agitation of electrons
- uniformly distributed across bandwidths
- referred to as white noise

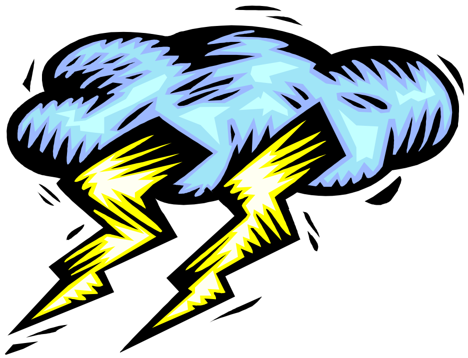




Intermodulation noise

- produced by nonlinearities in the transmitter, receiver, and/or intervening transmission medium
- effect is to produce signals at a frequency that is the sum or difference of the two original frequencies

Categories of Noise (2)



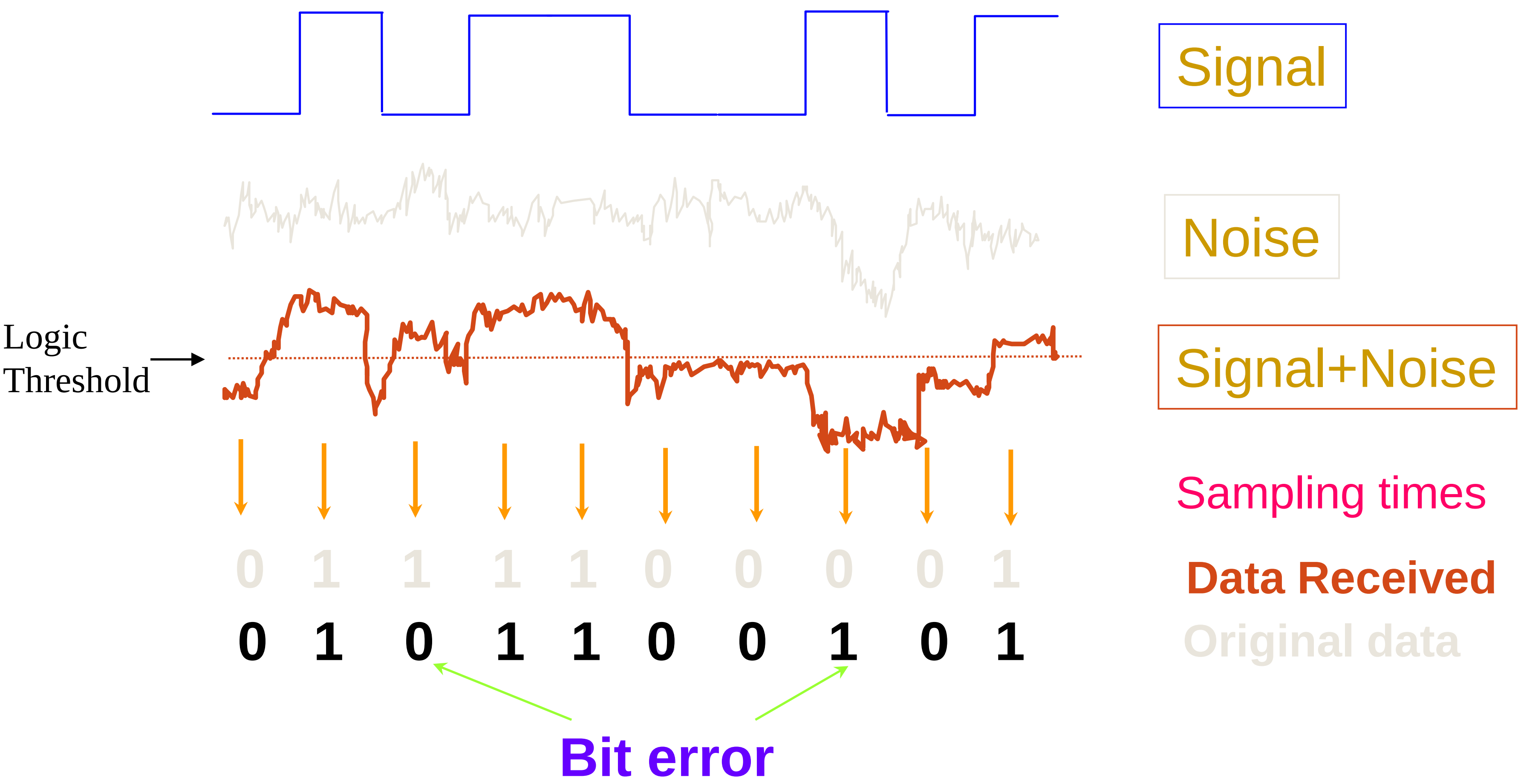
Impulse Noise:

- caused by external electromagnetic interferences
- noncontinuous, consisting of irregular pulses or spikes
- short duration and high amplitude
- minor annoyance for analog signals but a major source of error in digital data

Crosstalk:

- a signal from one line is picked up by another
- can occur by electrical coupling between nearby twisted pairs or when microwave antennas pick up unwanted signals

Effect of noise



Thermal (White) Noise

- Due to thermal agitation of electrons
- Uniformly distributed

$N = kTB$ (watts)

k = Boltzmann's constant = 1.38×10^{-23} J/K

T = kelvin degrees; B = bandwidth in Hz

Signal to Noise Ratio (SNR)

- **Noise effects**
  - distorts a transmitted signal
  - attenuates a transmitted signal

- **signal-to-noise ratio to quantify noise: S/N**
- **usually expressed using dB**

$$\mathbf{SNR_{dB} = 10 \log_{10} \frac{S}{N}}$$

S= average signal power

N= noise power

Channel Capacity (3.4)

- The maximum rate at which data can be transmitted over a given communication path, or channel, under given conditions.
- 4 related factors: data rate, bandwidth, noise, error rate (see next slide).
- Our goal: get as high a data rate as possible at a particular limit of error rate for a given bandwidth.
- The main constraint on achieving this efficiency is noise.

Channel Capacity (cont.)

- Data rate
  - In bits per second
  - Rate at which data can be communicated
- Bandwidth
  - In cycles per second of Hertz
  - Constrained by transmitter and medium
- Noise
  - Average level of noise over the communication path
- Error rate
  - Error: 1 becomes 0; 0 becomes 1
  - At a given noise level, higher data rate $\Rightarrow$ higher error rate (Fig 3.16)

Nyquist Bandwidth

- Assume noise-free channels
- Channel bandwidth limits the signal/data rate
- Given bandwidth B, highest signal rate is 2B: C = 2B
- If rate of signal transmission is 2B then signal with frequencies no greater than B is sufficient to carry signal rate
- Given binary signal, data rate supported by B Hz is 2B bps
- Can be increased by using M signal levels: $C = 2B \log_2 M$
  - however this increases burden on receiver
  - noise and other impairments limit the value of *M*

Nyquist Bandwidth: Example

Binary signals

- $B = 3,100$ Hz
- $C = 2B = 6,200$ bps

Multi-level signal

- $M = 8$
- $C = 2B \log_2 M = 2 \times 3100 \times 3 = 18,600$ bps
- Higher bit rate with the same bandwidth
- Drawback?

Shannon Capacity Formula

- Consider data rate, noise and error rate
- Higher data rate shortens each bit so burst of noise affects more bits
  - At given noise level, high data rate means higher error rate
- Capacity $C = B \log_2(1 + S/R)$
  - S/R = (signal power)/(noise power)
  - Typically measured at the receiver
- Assumes only thermal noise

  $\Rightarrow$ much lower rates are achieved in practice due to impulse noise, attenuation distortion, delay distortion, etc.
- Increase data rate by increasing S? Or increasing B?

decibel (dB)

- Normal ratio = P_{out}/P_{in}
- 1 bel (B) = $\log_{10}(P_{out}/P_{in})$

  (devised by engineers of Bell Telephone Lab, named after Alexander Graham Bell)
- 1 decibel (dB) = 10 B = 10 $\log_{10}(P_{out}/P_{in})$
- Note: this is dimensionless unit (a ratio)
- 3 dB ≈ doubling of power

  $10 \log_{10}(2) = 10 \times 0.3 = 3$
- 6 dB ≈ 4 times the power

Why dB and not simple ratio?

- Signal strength often falls off exponentially.
- Net gain/loss in a cascaded path can be calculated with simple addition/subtraction.
- Signal to noise ratio (in decibels)

  $SNR_{\mathbf{dB}} = 10 \log_{10} (\text{signal/noise})$
- Note: "S/R" in the Shannon capacity formula is a normal ratio, not dB.
  - See Example 3.6 in the textbook.

Exercises

- Calculate the thermal noise for an effective noise temperature of 27°C and a 10 MHz bandwidth.

- Given a channel for digital signals with a bandwidth of 1KHz, is it possible to transmit data at a rate of 6 Kbps along this channel? If so, describe a method and any conditions that must be satisfied. If not, explain why.

- Repeat the previous problem for a data rate of 1 Kbps

Exercises (2)

- Given a square wave signal represented by the following Fourier series:

  $$x(t) = \cos(2\pi ft) - (1/3)\cos(6\pi ft) + (1/5)\cos(10\pi ft) - (1/7)\cos(14\pi ft)$$

  The fundamental frequency of the signal is 5 KHz.

1. What is the effective bandwidth of the signal?
2. What is the data rate supported by the signal?

- Given a SNR of 20 dB, calculate the capacity of a channel with a bandwidth of 1 KHz.

Required Reading

- Chapter 3
- Reference: Appendix 3A (decibels)