Chapter 3 — Data Transmission

CSE 3213

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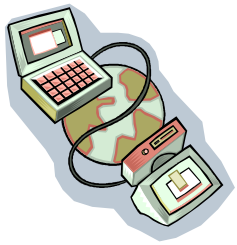
Data Transmission



The successful transmission of data depends on two factors:

- quality of the signal being transmitted
- characteristics of the transmission medium

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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

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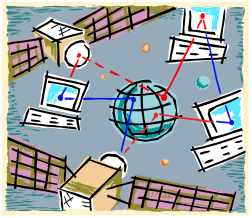
Transmission Terminology (2)

Direct link
- no intermediate devices

Point-to-point
- direct link
- only 2 devices share link

Multi-point
- more than two devices share the link



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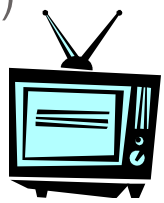
Transmission Terminology (3)



- **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)

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Analog and Digital Data Transmission

- Data
  - Entities that convey meaning, or information (data ≠ 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

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Analog and Digital Data

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

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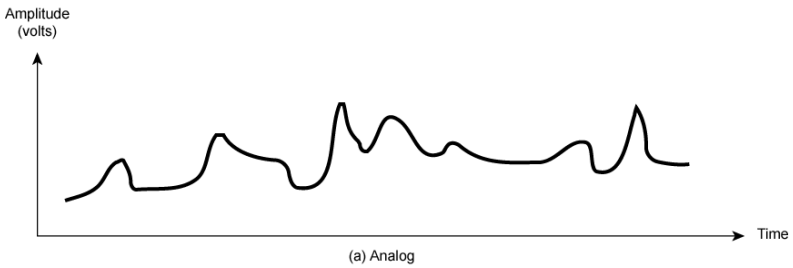
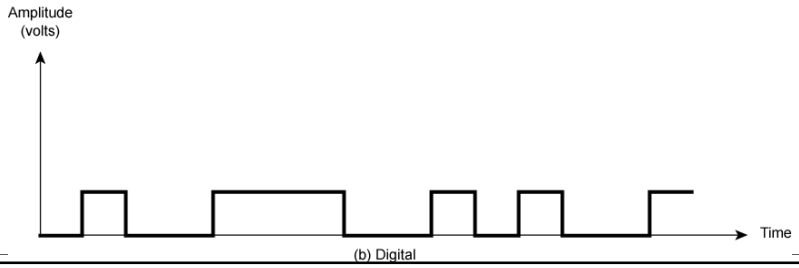
Analogue and Digital Signals



(a) Analog



(b) Digital

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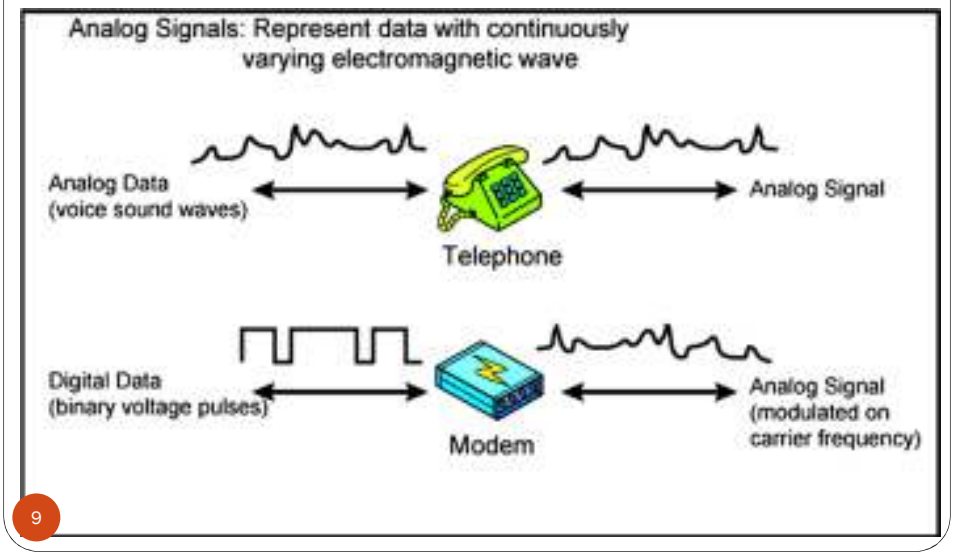
Analog Signals



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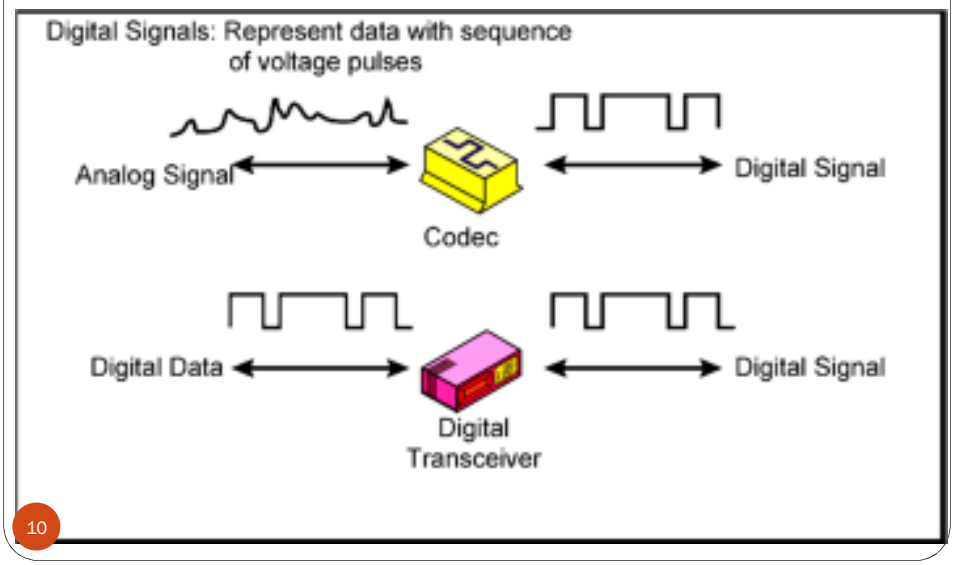
Digital Signals



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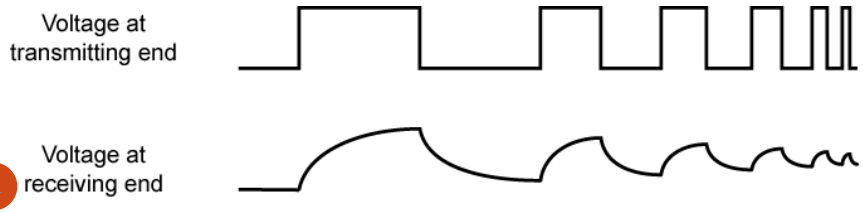
Advantages & Disadvantages of Digital Signals

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



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Frequency, Spectrum and Bandwidth

- Time domain concepts
  - Analog signal
    - Various in a smooth way over time
  - Digital signal
    - Maintains a constant level then changes to another constant level
  - Periodic signal
    - Pattern repeated over time
  - Aperiodic signal
    - Pattern not repeated over time

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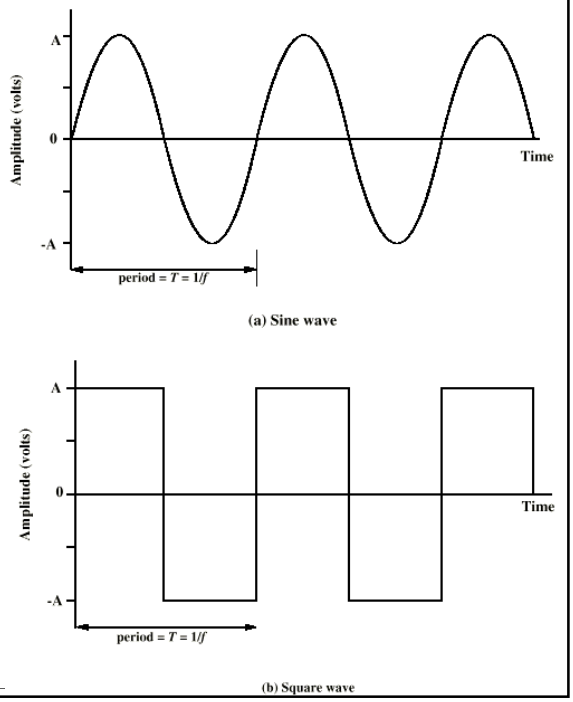
Periodic Signals



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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

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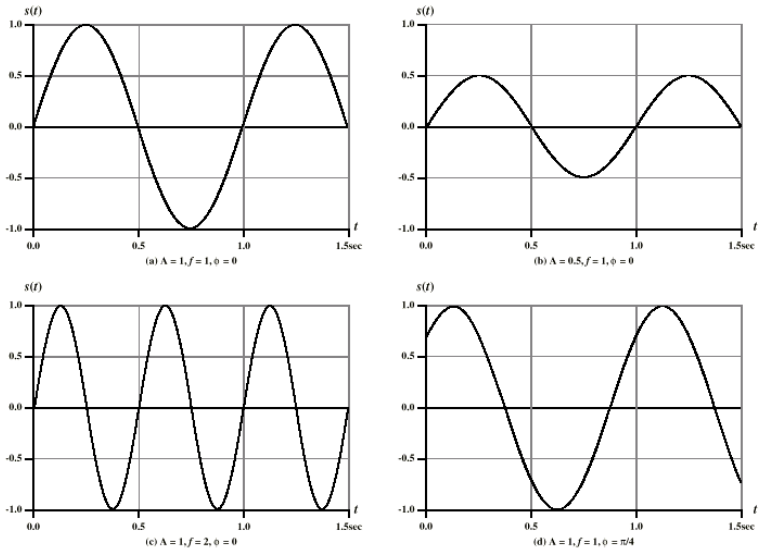
Examples of Sine Waves

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



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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

especially when $v = c$

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

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

$\lambda = vT$

or equivalently

$\lambda f = v$

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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

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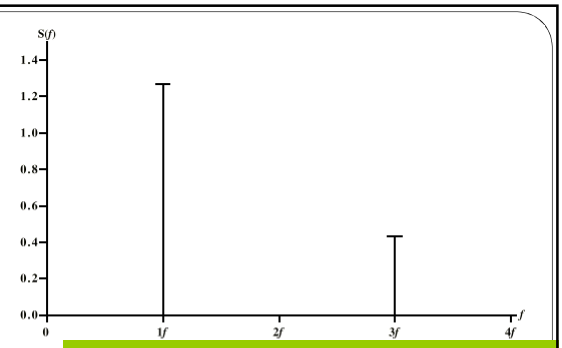
Frequency Domain Examples

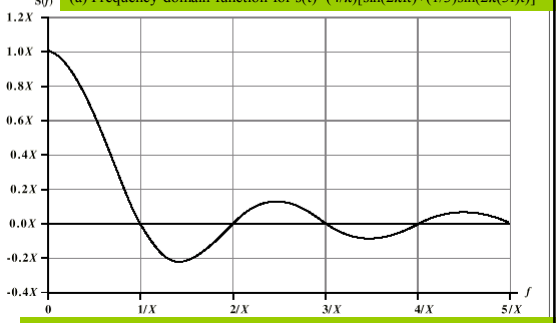
S(f) is discrete

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

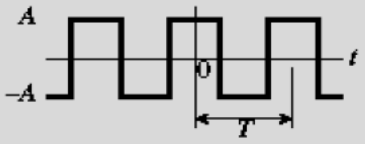
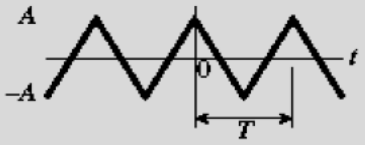
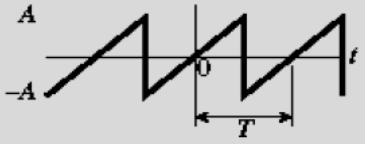
Single square pulse
S(f) is continuous



(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

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 	$(2A/\pi) \times [\sin(2\pi f_1 t) - (1/2)\sin(2\pi(2f_1)t) + (1/3)\sin(2\pi(3f_1)t) - (1/4)\sin(2\pi(4f_1)t) + \ldots]$

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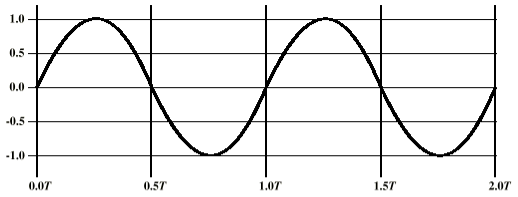
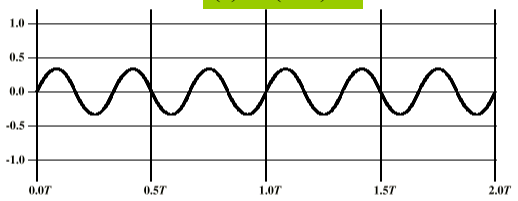
Addition of Frequency Components (T = 1/f)

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

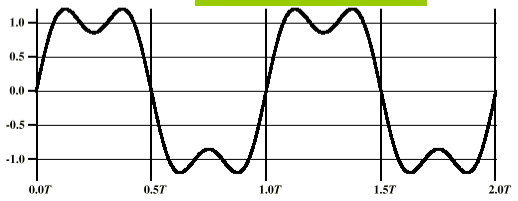
(c) (4/π)[sin(2πft)+(1/3)sin(2π(3f)t)]



(a) sin(2πft)



(b) (1/3)sin(2π(3f)t)



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

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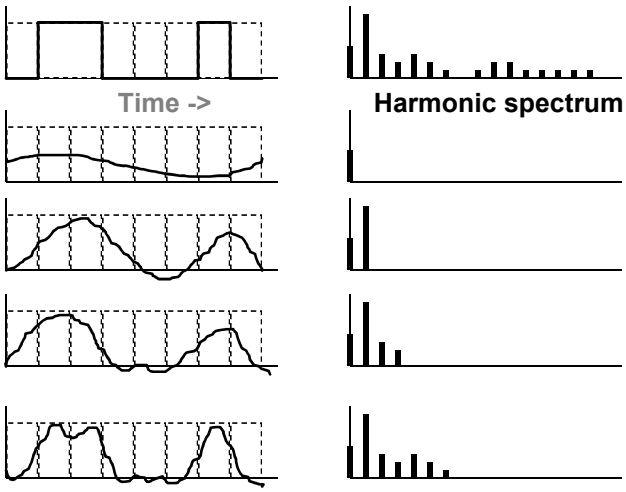

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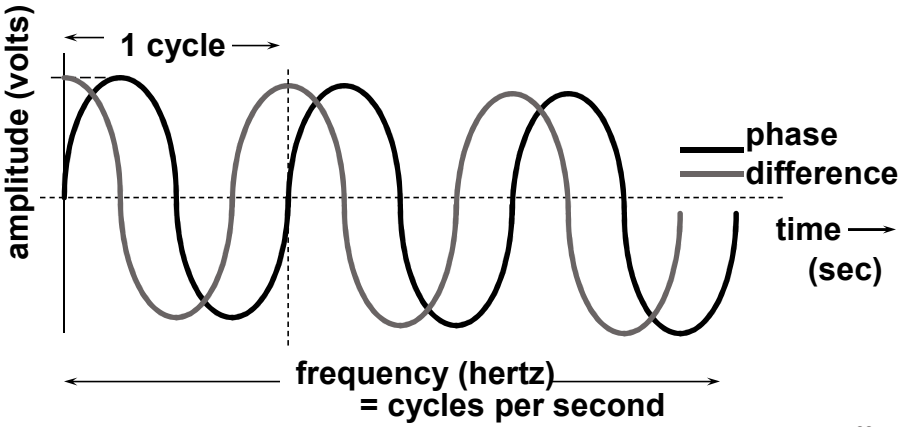
Analog Signaling

- Frequency and peak amplitude are the most important.



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Frequency Domain

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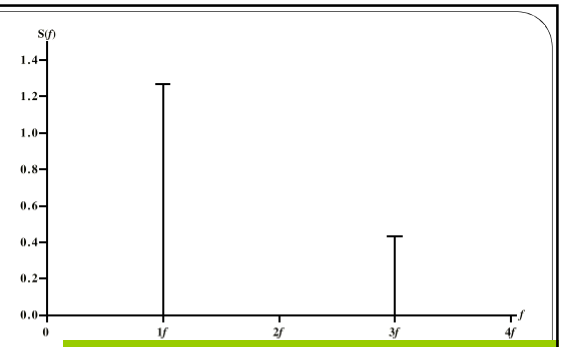
Single square pulse
S(f) is continuous



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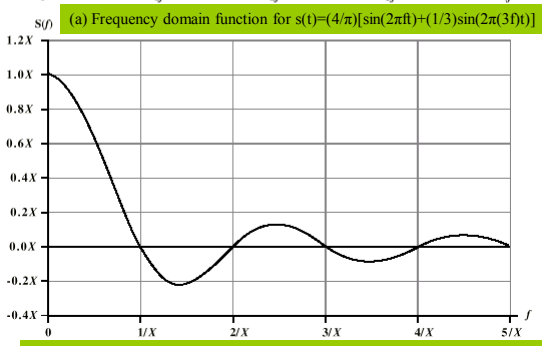

(b) Frequency domain function for a single square pulse s(t)=1 for -X/2<t<X/2

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)

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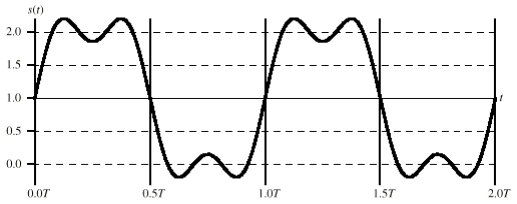
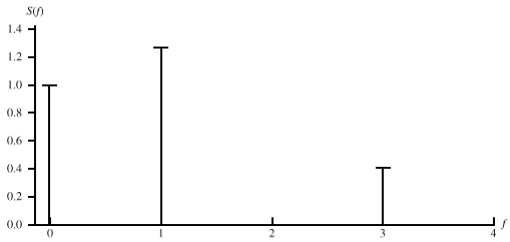
Signal with DC Component



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



(b) S(f)

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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.

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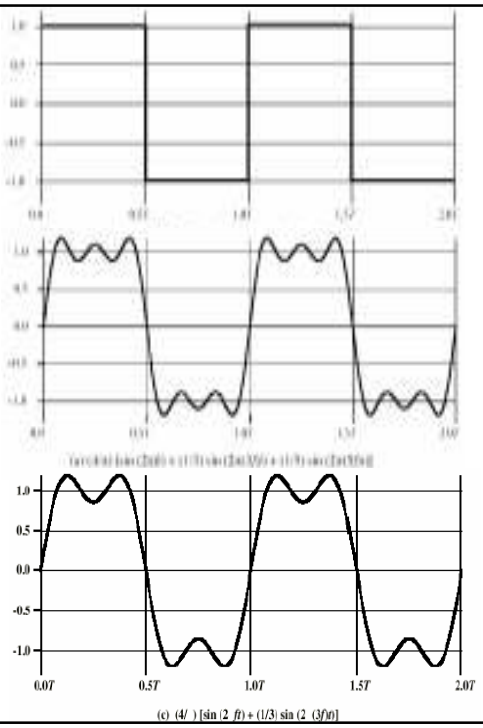

Example

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

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

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

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Data Rate and Bandwidth (2)

- Any transmission system has a limited band of frequencies
- This limits the data rate that can be carried
- 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

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Data Rate and Bandwidth (4)

Consider a square wave

- Data rate $R = 2 \times f$ (f: fundamental frequency)
- Double the bandwidth ⇒ 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).

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Data Rate and Bandwidth (5)

In general,

- The greater the bandwidth ⇒ the higher the data rate
- The higher the data rate ⇒ The greater the required effective bandwidth
- Keeping the same data rate:

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

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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

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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 is an increasing function of frequency

  Solutions:
  - equalization
  - amplifying high frequencies more than low frequencies
- Less of a problem with digital signals (why?)

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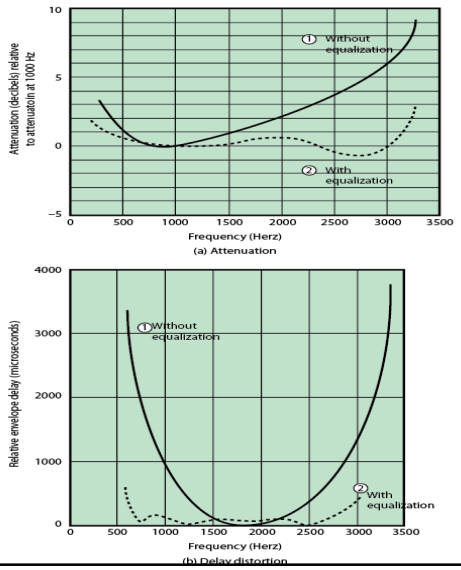
Attenuation and Delay Distortion



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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

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Noise

unwanted signals inserted between transmitter and receiver

is the major limiting factor in communications system performance

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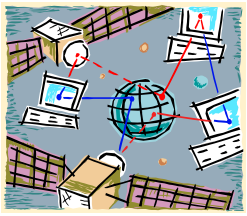
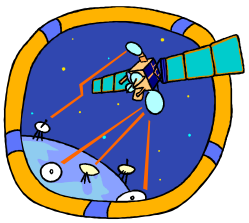
Categories of Noise

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

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Categories of Noise

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

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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

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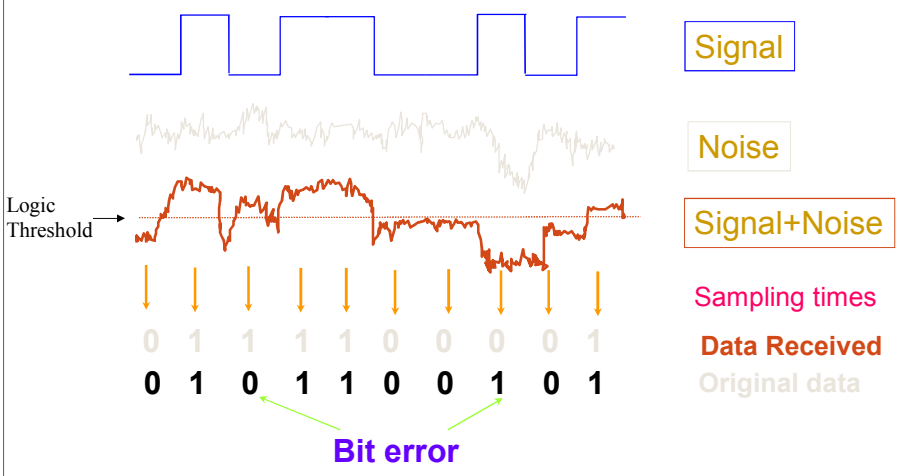
Effect of noise



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Signal to Noise Ratio (SNR)

- **Effect**
  - distorts a transmitted signal
  - attenuates a transmitted signal
- **signal-to-noise ratio to quantify noise**
- **usually expressed using dB**

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

S= average signal power

N= noise power

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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.

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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 ⇒ higher error rate (Fig 3.16)

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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*

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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?

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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?

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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 x 0.3 = 3
- 6 dB ≈ 4 times the power

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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)

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

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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

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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.

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Required Reading

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

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