Chapter 3 — Data Transmission

COSC 3213
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Terminology (1)

- Transmitter
- Receiver
- Medium
  - Guided medium
    - e.g. twisted pair, optical fiber
  - Unguided medium
    - e.g. air, water, vacuum

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3.1.1

Terminology (2)

- Direct link
  - No intermediate devices (except amplifiers, repeaters)
- Point-to-point
  - Direct link
  - Only 2 devices share link
- Multi-point
  - More than two devices share the link

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Terminology (3)

ANSI (USA) definitions:

- Simplex
  - One direction
    - e.g. Television
- Half duplex
  - Either direction, but only one way at a time
    - e.g. police radio
- Full duplex
  - Both directions at the same time
    - e.g. 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
- 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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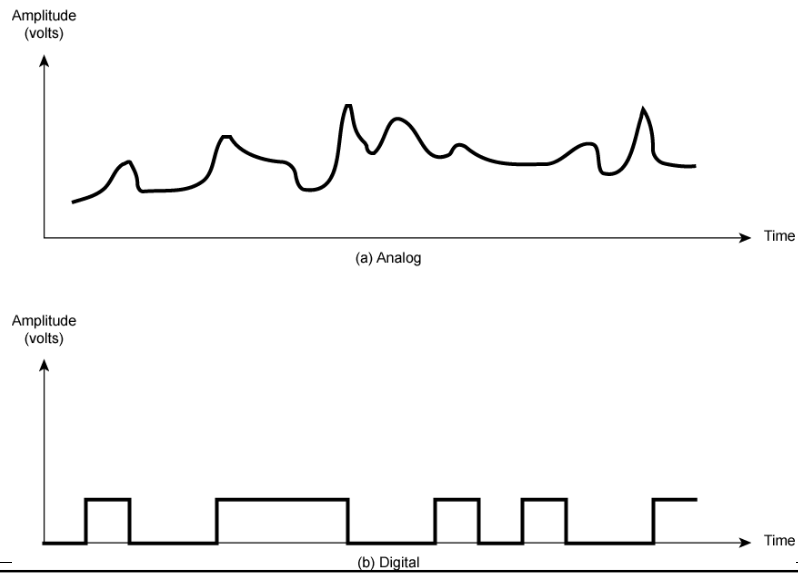
Analogue and Digital Signals



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Terminology

- Data: conveying information (data ≠ information)
- Signal: electric or electronic representation of data
- Signaling: physical propagation of the signal along a medium
- Transmission: communication of data by the propagation and processing of signals

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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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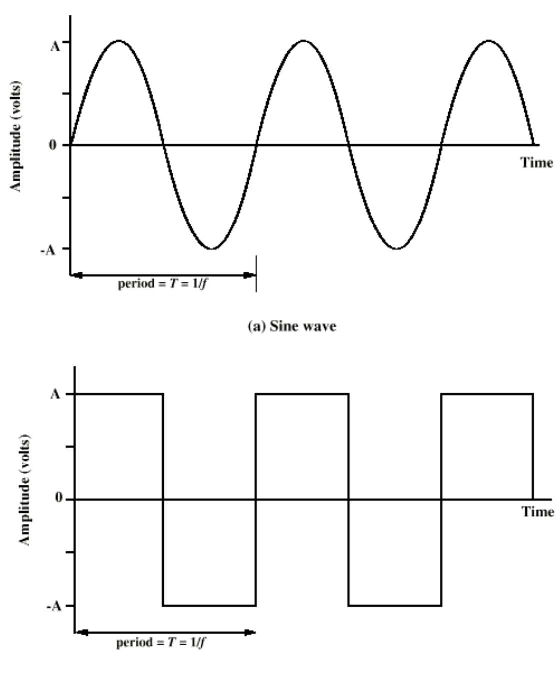
3.1.2

Periodic Signals



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Sine Wave

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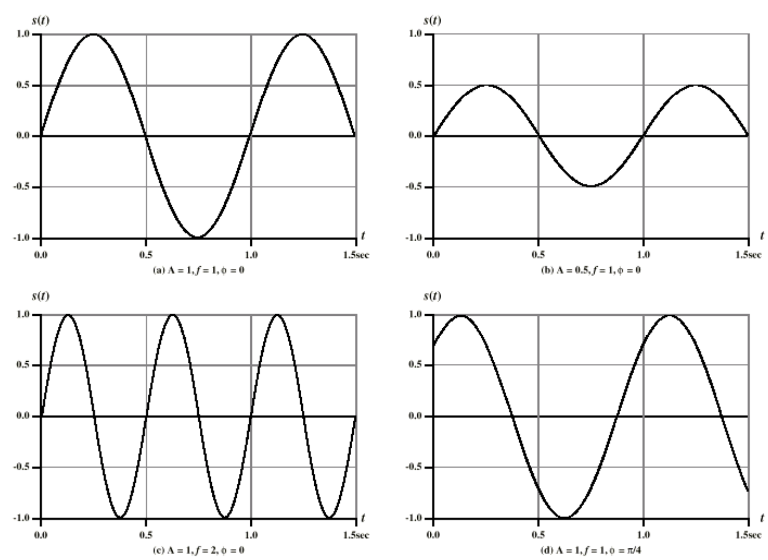
Varying Sine Waves $s(t) = A \sin(2\pi ft + \Phi)$



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

(b) $A = 0.5, f = 1, \phi = 0$

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

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

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Wavelength

- Distance occupied by one cycle
- Distance between two points of corresponding phase in two consecutive cycles
- λ
- Assuming signal velocity *v*
  - $\lambda = vT$
  - $\lambda f = v$
  - $c = 3 * 10^8$ m/sec (speed of light in free space)

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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
- Can plot frequency domain functions

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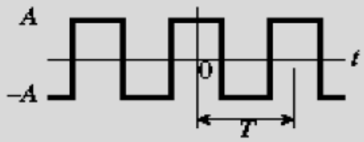
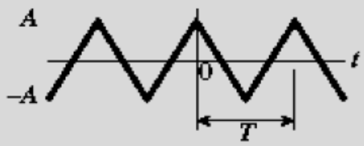
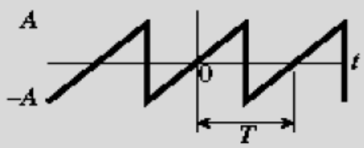
Signal	Fourier Series
Square wave 	$(4A/\pi) \times [\cos(2\pi f_1 t) - (1/3)\cos(2\pi(3f_1)t) + (1/5)\cos(2\pi(5f_1)t) - (1/7)\cos(2\pi(7f_1)t) + \ldots]$
Triangular wave 	$(8A/\pi^2) \times [\cos(2\pi f_1 t) + (1/9)\cos(2\pi(3f_1)t) + (1/25)\cos(2\pi(5f_1)t) + \ldots]$
Sawtooth wave 	$(2A/\pi) \times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

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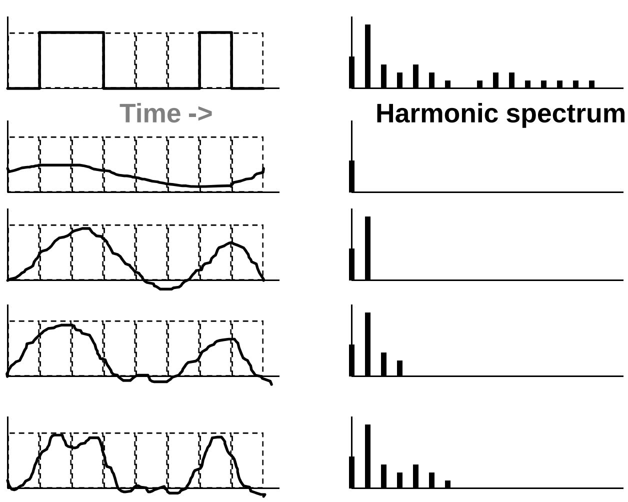

Original

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

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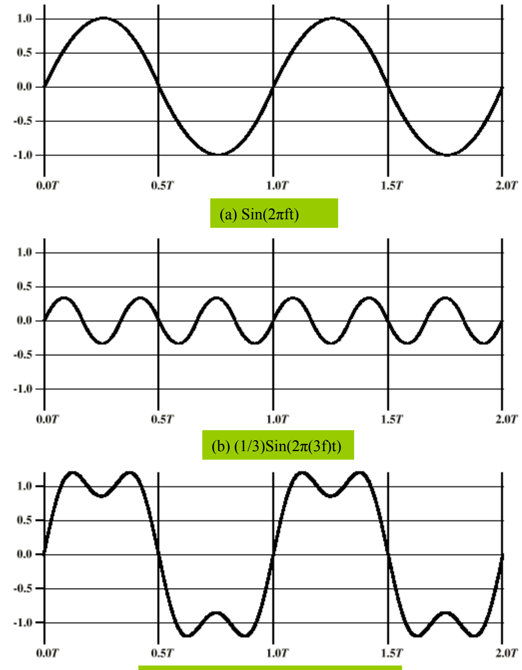
Addition of Frequency Components



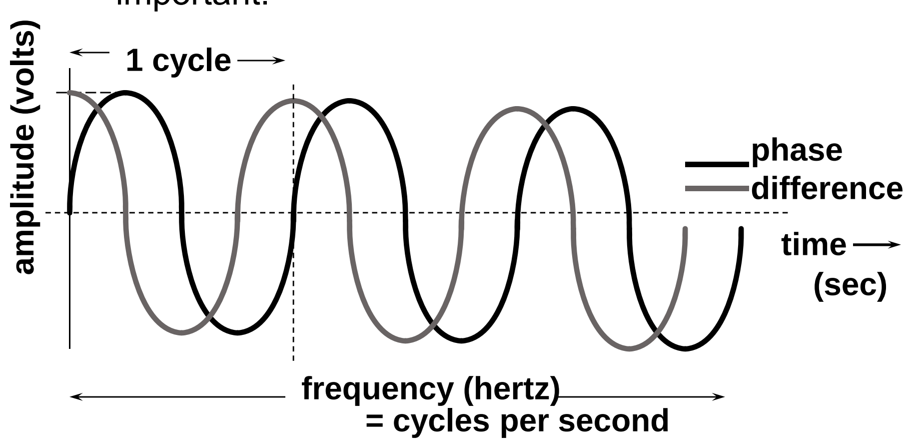
(a) Sin(2πft)

(b) (1/3)Sin(2π(3f)t)

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

Analog Signaling

- Frequency and peak amplitude are the most important.

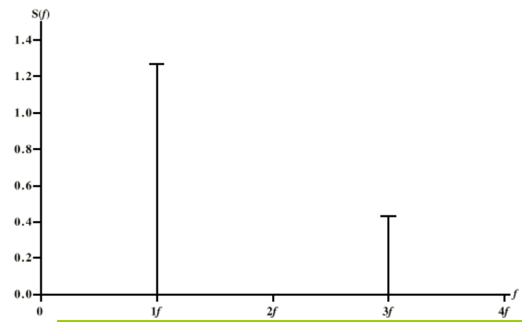


Frequency Domain

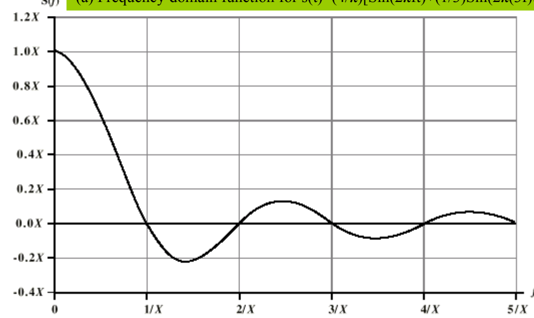
S(f) is discrete

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 $s(t)=(4/\pi)[\sin(2\pi ft)+(1/3)\sin(2\pi(3f)t)]$



(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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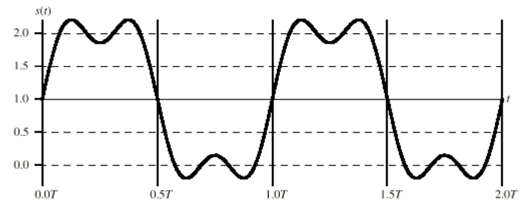
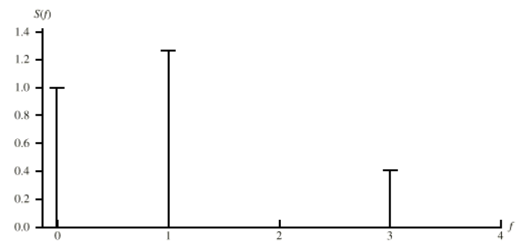
Signal with DC Component



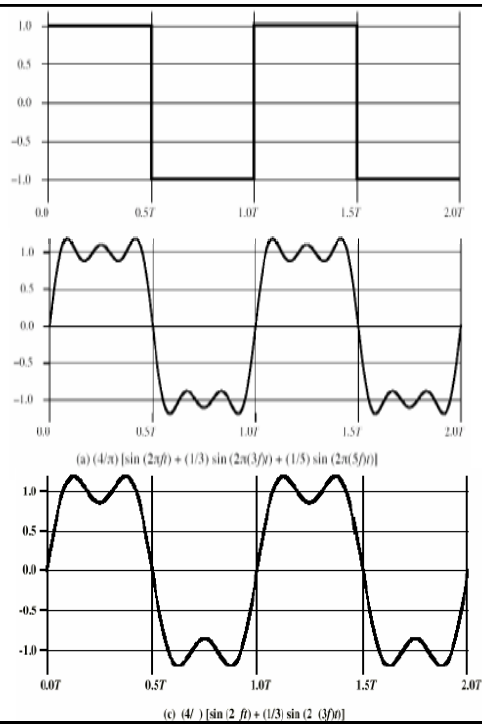
(a) s(t)=1+(4/π)[Sin(2πft)+(1/3)Sin(2π(3f)t)]



(b) S(f)

Data Rate and Bandwidth

- 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



Example

Case 1:	Case 2:
f = 1 MHz	f = ? MHz
R = ? Mbps	B = 8 MHz
B = ? MHz	R = ? Mbps

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

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Data Rate and Bandwidth (2)

Consider a square wave

- Data rate *R* = *2* x *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 (3)

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

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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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3.3

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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Delay Distortion

- Only in guided media
- Propagation velocity varies with frequency: highest velocity near the center frequency
- Particularly critical for digital data
- Solution: equalization

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Noise (1)

- Additional signals inserted between transmitter and receiver
- 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
- Intermodulation
  - Signals that are the sum and difference of original frequencies sharing a medium

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Noise (2)

- Crosstalk
  - A signal from one line is picked up by another
- Impulse
  - Irregular pulses or spikes
  - e.g. External electromagnetic interference (lightning, system flaws)
  - Short duration
  - High amplitude
  - Primary source of error in digital data communication

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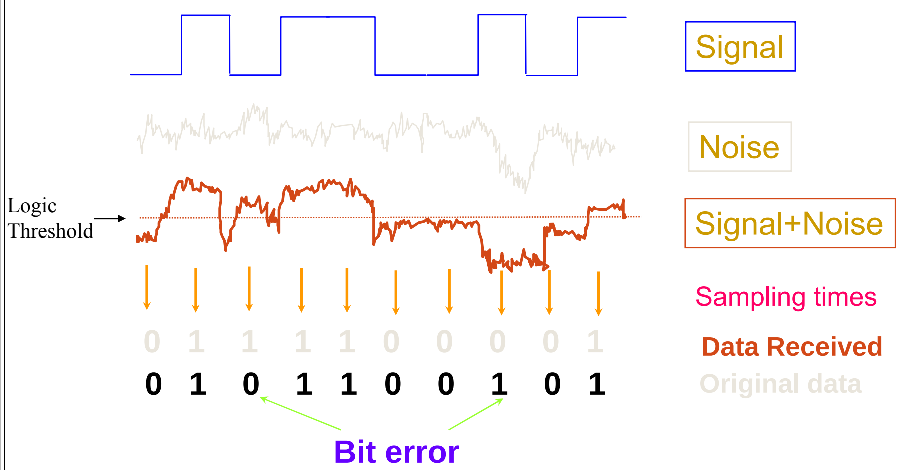
Effect of noise



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

Channel Capacity (3.4)

- 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)

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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
- 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
- $C = 2B \log_2 M$

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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 x 3100 x 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 $\log_2(1 + SNR)$
  - SNR = (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)
  $SNR_{dB} = 10 \log_{10}$ (signal/noise)
- Note: "SNR" in the Shannon capacity formula is a normal ratio, not dB.
  - See Example 3.3 in the textbook.

Required Reading

- Stallings chapter 3
- Reference: Appendix 3A (decibels)

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Exercises

- Calculate the thermal noise for an effective noise temperature of 27^{o}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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