Academic Year 2022/2023 2nd Semester

COMP123 – 121/122

Data Communications

Data Transmission Theory

Data Transmission

The successful transmission of data depends on two factors:

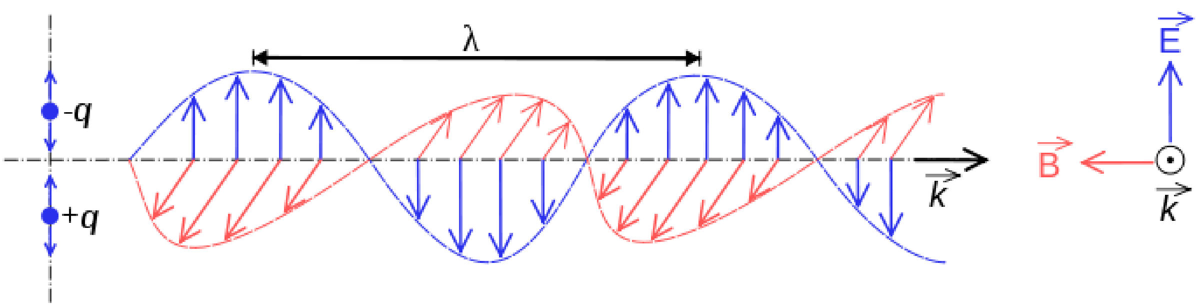
- quality of the signals being transmitted
- characteristics of the transmission medium

What are signals?

Signals are the electromagnetic waveforms used to encode and transmit data

Transmission Terminology (1/2)

- Data transmission occurs between transmitter and receiver over some transmission medium
- Communication is in the form of electromagnetic (EM) waves
- With guided media, the waves are guided along a physical path, e.g. twisted pair, coaxial cable, and optical fiber
- Unguided media, also called *wireless*, provides means for transmitting EM waves but do not guide them, e.g. air, vacuum, and sea water

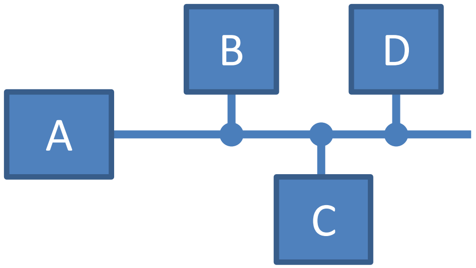


Transmission Terminology (2/2)

- Direct link refers to the transmission path between two devices in which signals propagate directly from transmitter to receiver with no intermediate devices

- A guided transmission medium is point to point if it provides a direct link between two devices and those are the only two devices sharing the medium

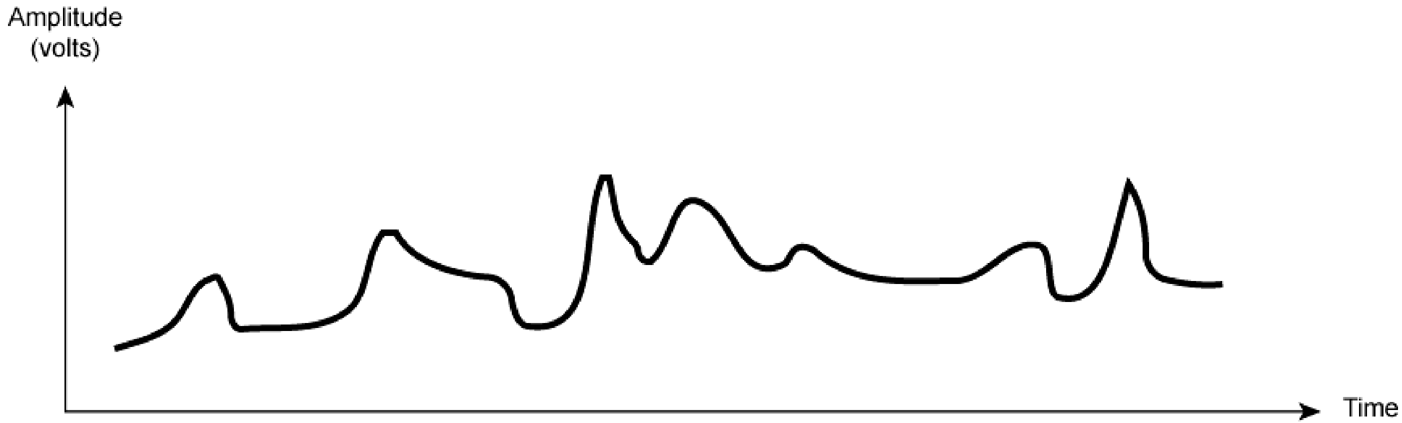
- In a multi-point guided configuration, more than two devices share the same medium



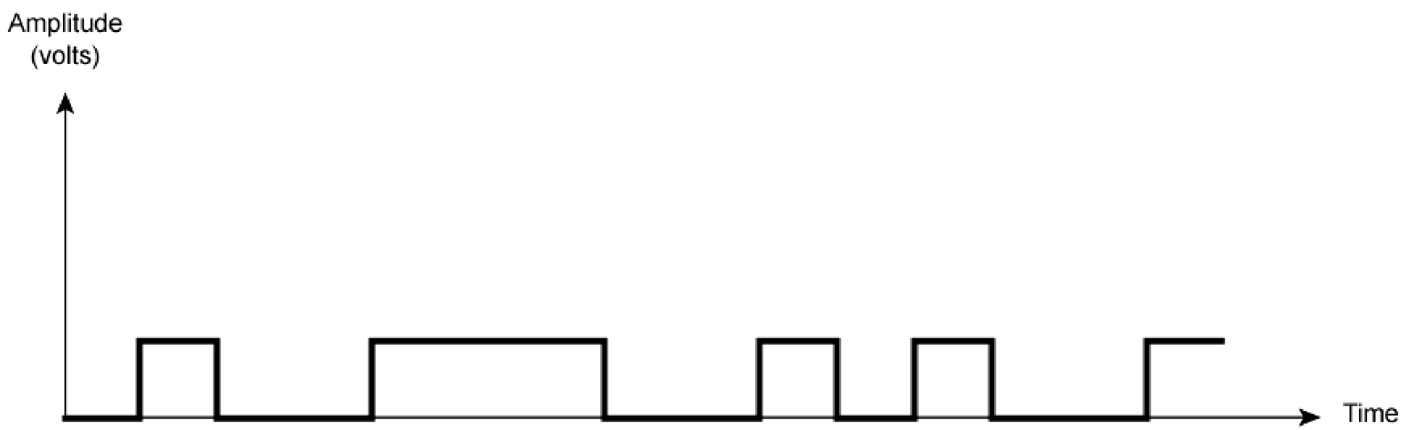
Analog and Digital Signals

- Signals can be viewed in either time or frequency domain
- Viewed as a function of time, an EM signal can be either analog or digital
- Analog signal intensity varies smoothly with no breaks
- Digital signal intensity maintains a constant level and then suddenly changes to another level

Analog and Digital Signals



(a) Analog

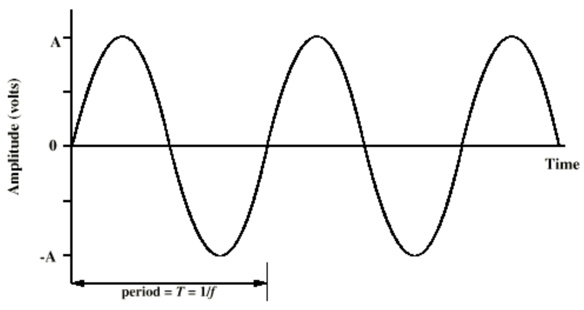


(b) Digital

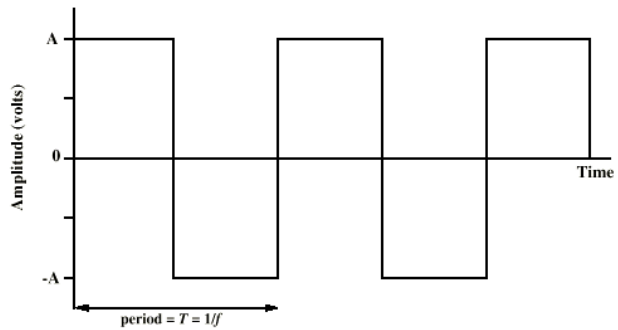
Periodic and Aperiodic Signals

- Periodic signal pattern repeats over time

$$s(t+T) = s(t) \quad -\infty < t < +\infty$$

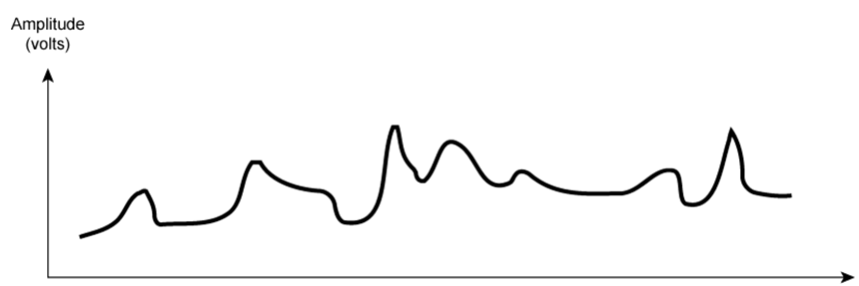


(a) Sine wave



(b) Square wave

- Aperiodic signal pattern do not repeats over time



What if the period is infinitive?

Fundamental Periodic Signal - Sine Wave

- A general sine wave can be represented by three parameters: peak amplitude (*A*), frequency (*f*), and phase (ϕ)

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

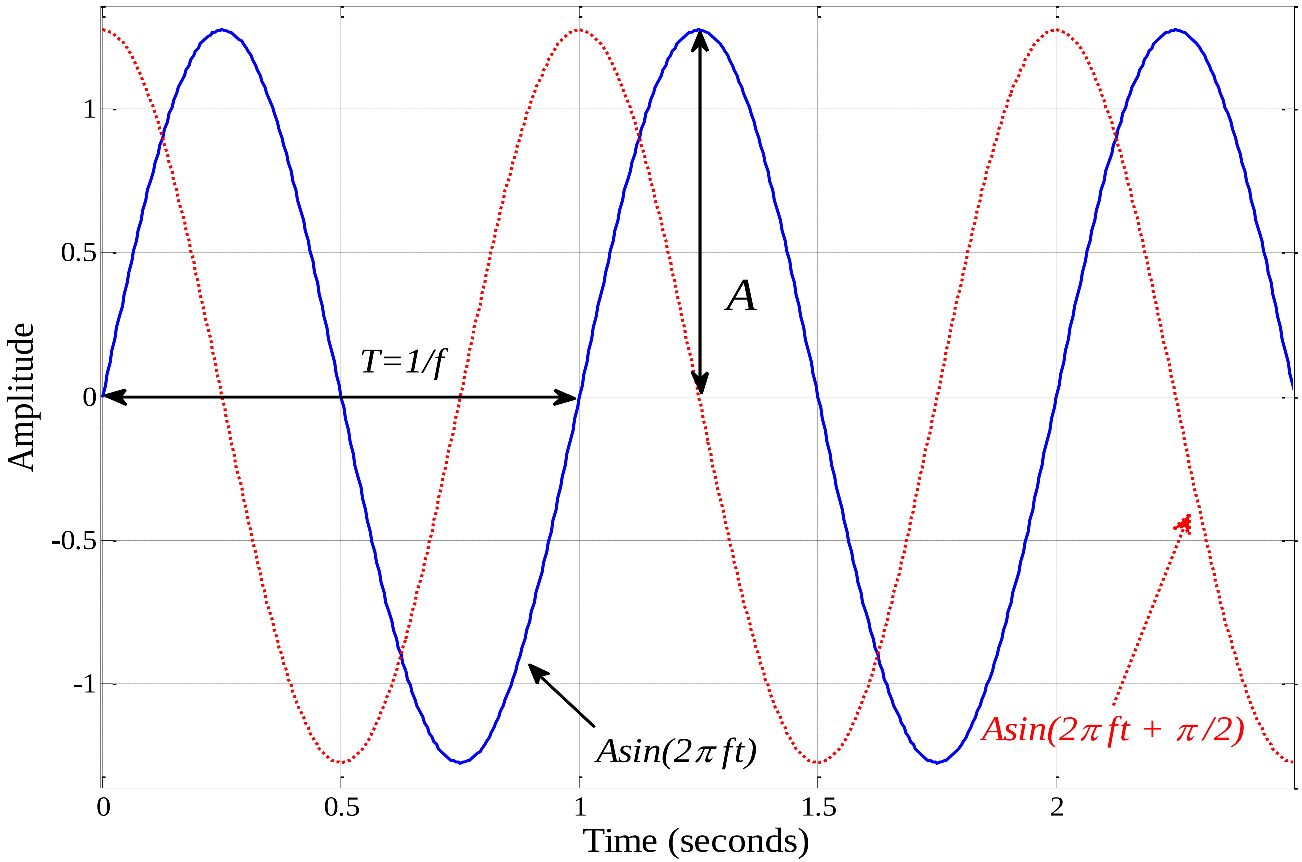
- A function with the form of the above equation is known as a sinusoid

What about $\cos(2\pi ft + \phi)$?

Fundamental Periodic Signal - Sine Wave

- peak amplitude (*A*)
  - maximum strength of signal
  - typically measured in volts
- frequency (*f*)
  - rate at which the signal repeats
  - Hertz (Hz) or cycles per second
  - period (T) is the amount of time for one repetition
  - T = 1/f
- phase (ϕ)
  - relative position in time within a single period of signal

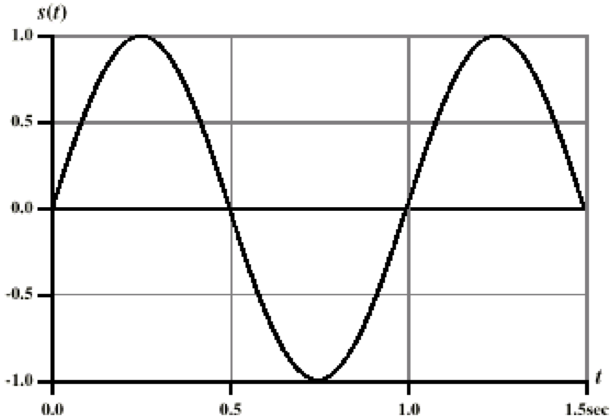
Fundamental Periodic Signal - Sine Wave



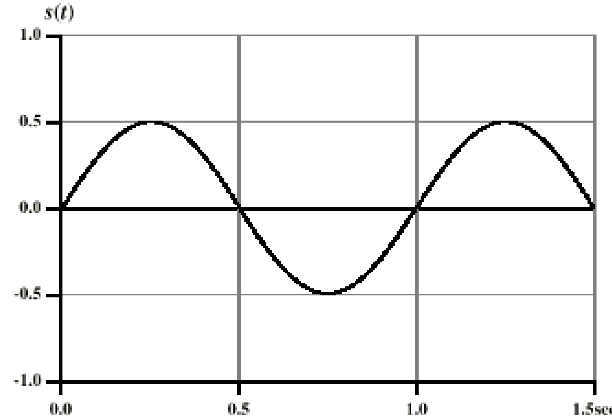
What is f ?

Note: 2π radians = 360° = 1 period

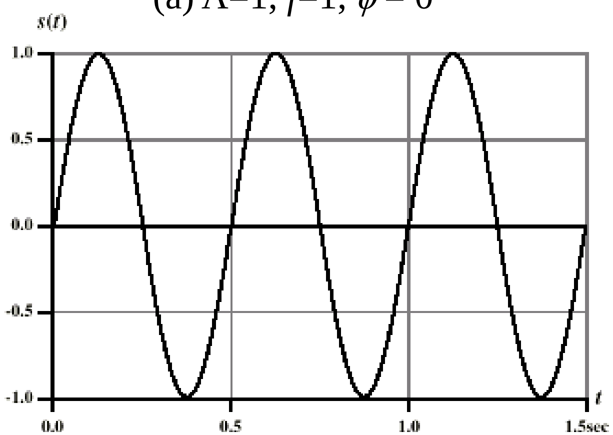
Varying Sine Waves



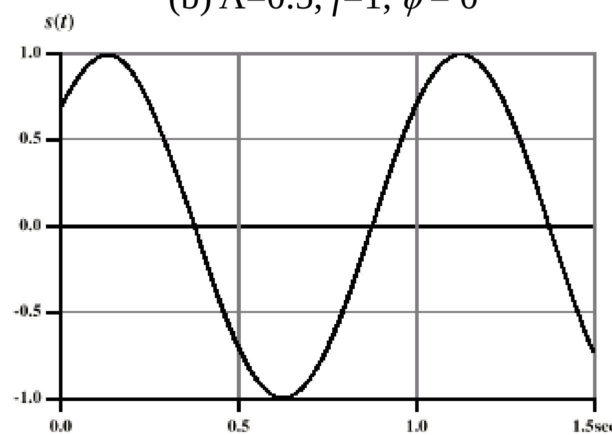
(a) A=1, f=1, $\phi = 0$



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



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



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

Exercise: write the equations for the above sine waves.

Some Useful Formulas for Trigonometric Functions

$$\tan A = \frac{\sin A}{\cos A}$$

$$\sin(A \pm B) = \sin A \cos B \pm \cos A \sin B$$

$$\cos(A \pm B) = \cos A \cos B \mp \sin A \sin B$$

$$\sin A \sin B = \frac{1}{2}\{\cos(A-B) - \cos(A+B)\}$$

$$\cos A \cos B = \frac{1}{2}\{\cos(A-B) + \cos(A+B)\}$$

$$\sin A \cos B = \frac{1}{2}\{\sin(A-B) + \sin(A+B)\}$$

$$\sin A + \sin B = 2\sin\frac{A+B}{2}\cos\frac{A-B}{2}$$

$$\sin A - \sin B = 2\cos\frac{A+B}{2}\sin\frac{A-B}{2}$$

$$\cos A + \cos B = 2\cos\frac{A+B}{2}\cos\frac{A-B}{2}$$

$$\cos A - \cos B = 2\sin\frac{A+B}{2}\sin\frac{A-B}{2}$$

$$\sin^2 A + \cos^2 A = 1$$

$$\sin 2A = 2\sin A\cos A$$

$$\cos 2A = \cos^2 A - \sin^2 A = 1 - 2\sin^2 A$$

$$\sin^2 A = \frac{1}{2} - \frac{1}{2}\cos 2A$$

$$\cos^2 A = \frac{1}{2} + \frac{1}{2}\cos 2A$$

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 T

$$\lambda = vT \quad \text{or} \quad \lambda f = v$$

, where $f=1/T$.

Example

In the US, ordinary household current is supplied at a frequency of 60Hz with a peak voltage of 170V. Thus, the power line voltage can be expressed as

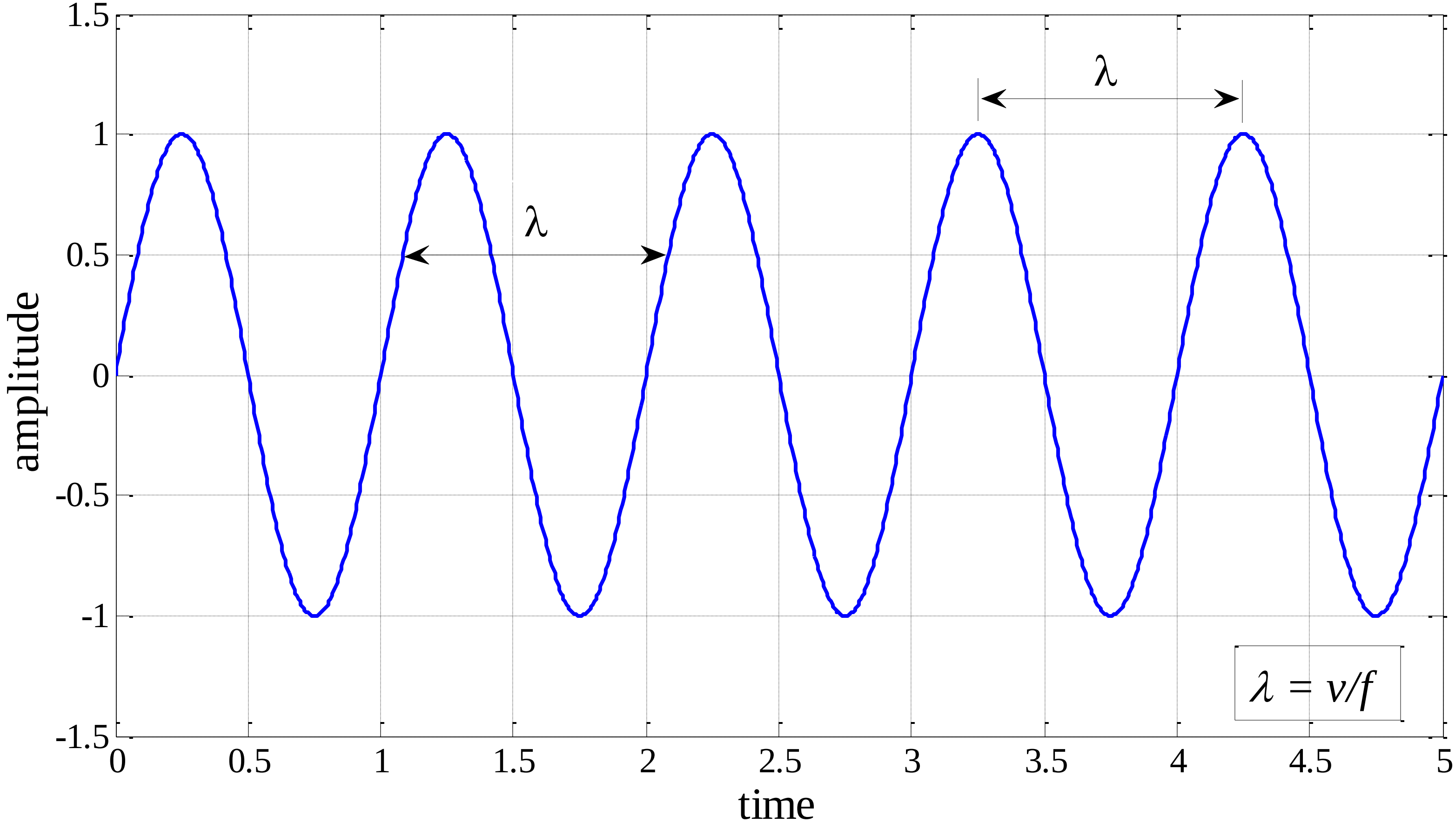
$$170\sin(2\pi \times 60 \times t)$$

$$T=1/60=0.0167s$$

Given the velocity of propagation is about 0.9c, c is speed of light in free space,

$$\lambda = vT = 0.9 \times 3 \times 10^8 \times 0.0167 = 4.5 \times 10^6 m$$
$$= 4500km$$

Wavelength (λ)



For EM wave, $v = c = 3.0 \times 10^8$ m/s

Units of Period and Frequency

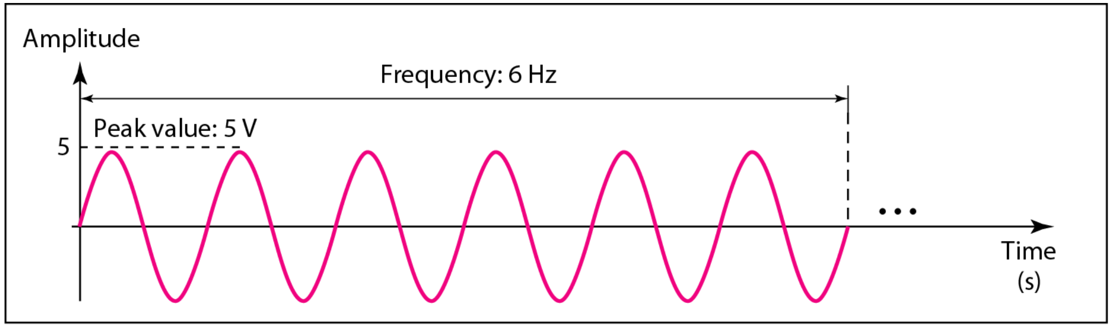
Unit	*Equivalent*	*Unit*	*Equivalent*
Seconds (s)	1 s	Hertz (Hz)	1 Hz
Milliseconds (ms)	10^{-3} s	Kilohertz (kHz)	10^{3} Hz
Microseconds (μs)	10^{-6} s	Megahertz (MHz)	10^{6} Hz
Nanoseconds (ns)	10^{-9} s	Gigahertz (GHz)	10^{9} Hz
Picoseconds (ps)	10^{-12} s	Terahertz (THz)	10^{12} Hz

Exercise: The period of a signal is 100 ms.
What is its frequency in kilohertz (kHz)?

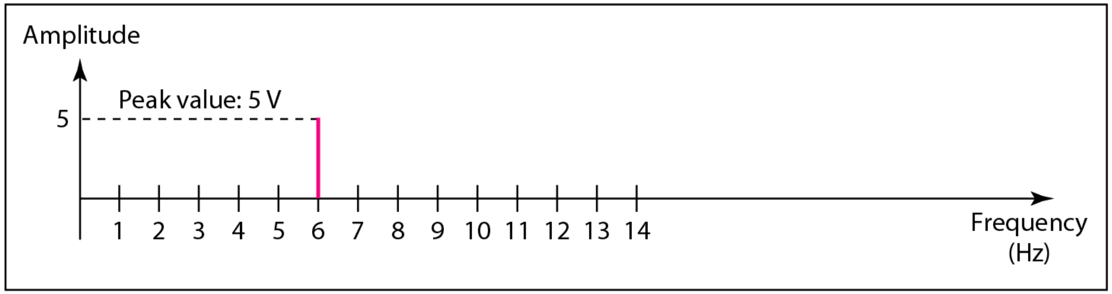
$$f = \frac{1}{T}$$

Frequency Domain Concepts

- A complete sine wave in the time domain can be represented by one single spike in the frequency domain



a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)



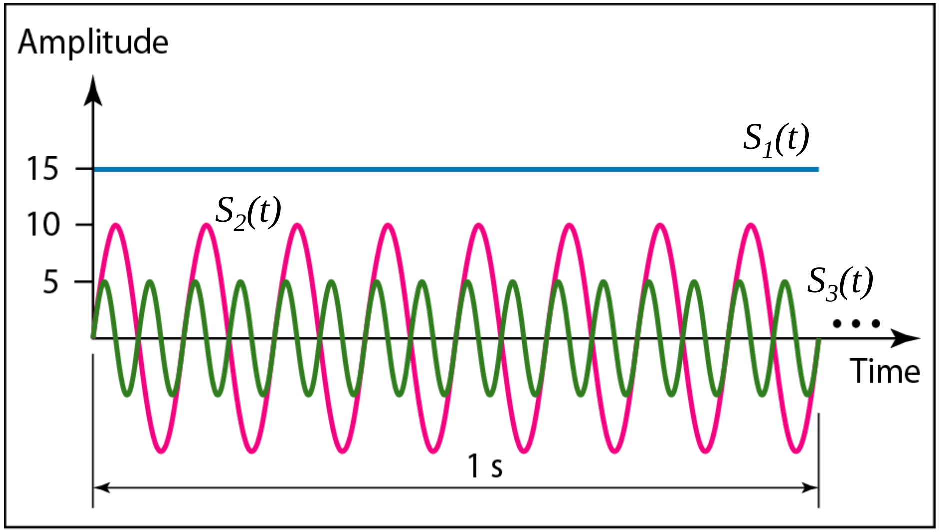
b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

Frequency Domain Concepts

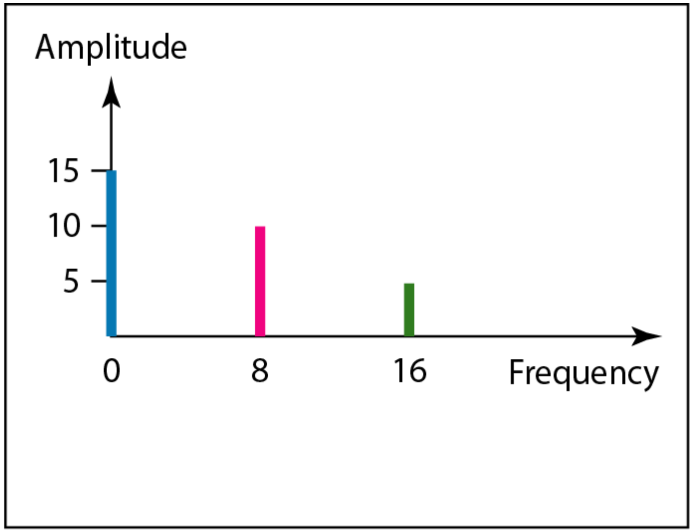
- Time domain and frequency domain of three sine waves
- The frequency of a signal with constant amplitude (DC) is zero
- The equation for the composite signal is

$$s(t) = s_1(t) + s_2(t) + s_3(t)$$
$$= 15 + 10\sin(16\pi t) + 5\sin(32\pi t)$$

Can you plot the composite signal in time domain?

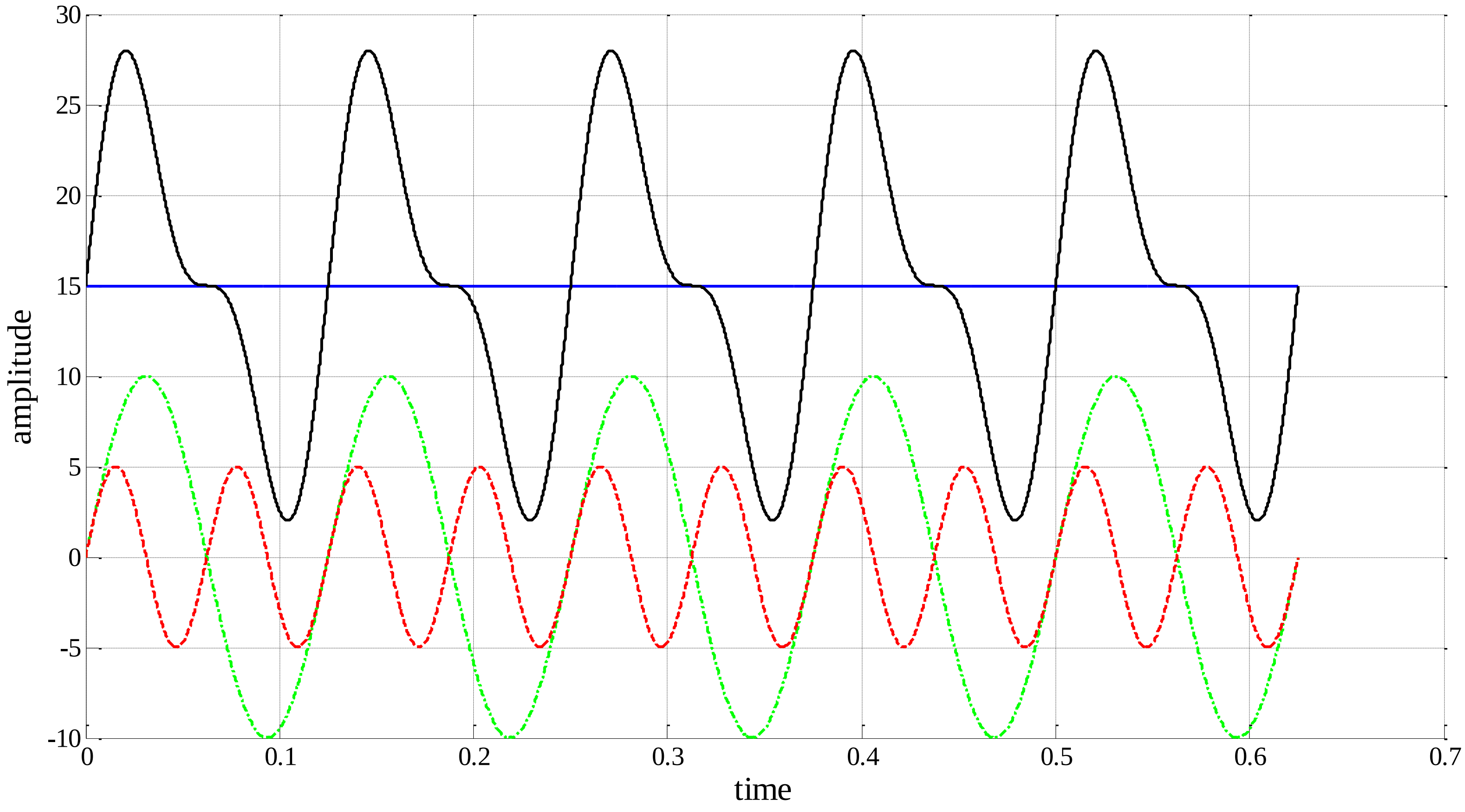


a. Time-domain representation of three sine waves with frequencies 0, 8, and 16



b. Frequency-domain representation of the same three signals

Frequency Domain Concepts



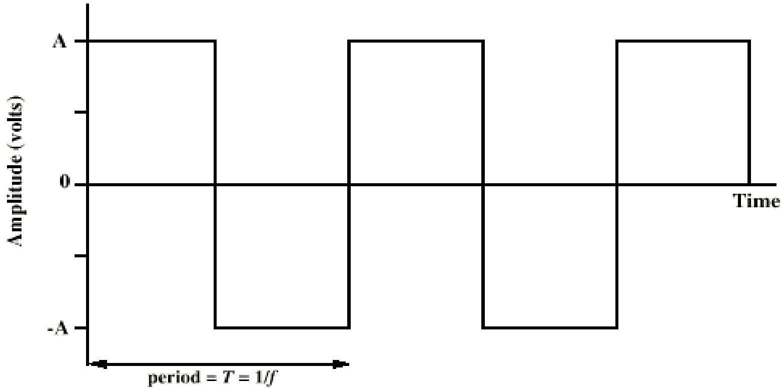
Fourier Analysis

- Signals are made up of many frequencies
- Components are sine waves
- Fourier analysis can show that any signal is made up of components at various frequencies, in which each component is a sinusoid
- Fourier series decompose periodic signals into the sum of a set of sinusoidal (sine or cosine) signals
- In general, Fourier Transform can be used to transform the signals (both periodic and aperiodic) from the time domain to the frequency domain
- Signals can be represented in the frequency domain

Fourier Series for Square Wave

- For a square wave with A=1, the Fourier Series can be calculated as

$$s_{square}(t) = \frac{4}{\pi}\sum_{k\text{ odd},k=1}^{\infty}\frac{\sin(2\pi kft)}{k} = \frac{4}{\pi}\times\left\{\frac{\sin(2\pi ft)}{1}+\frac{\sin(6\pi ft)}{3}+\frac{\sin(10\pi ft)}{5}+\cdots\right\}$$

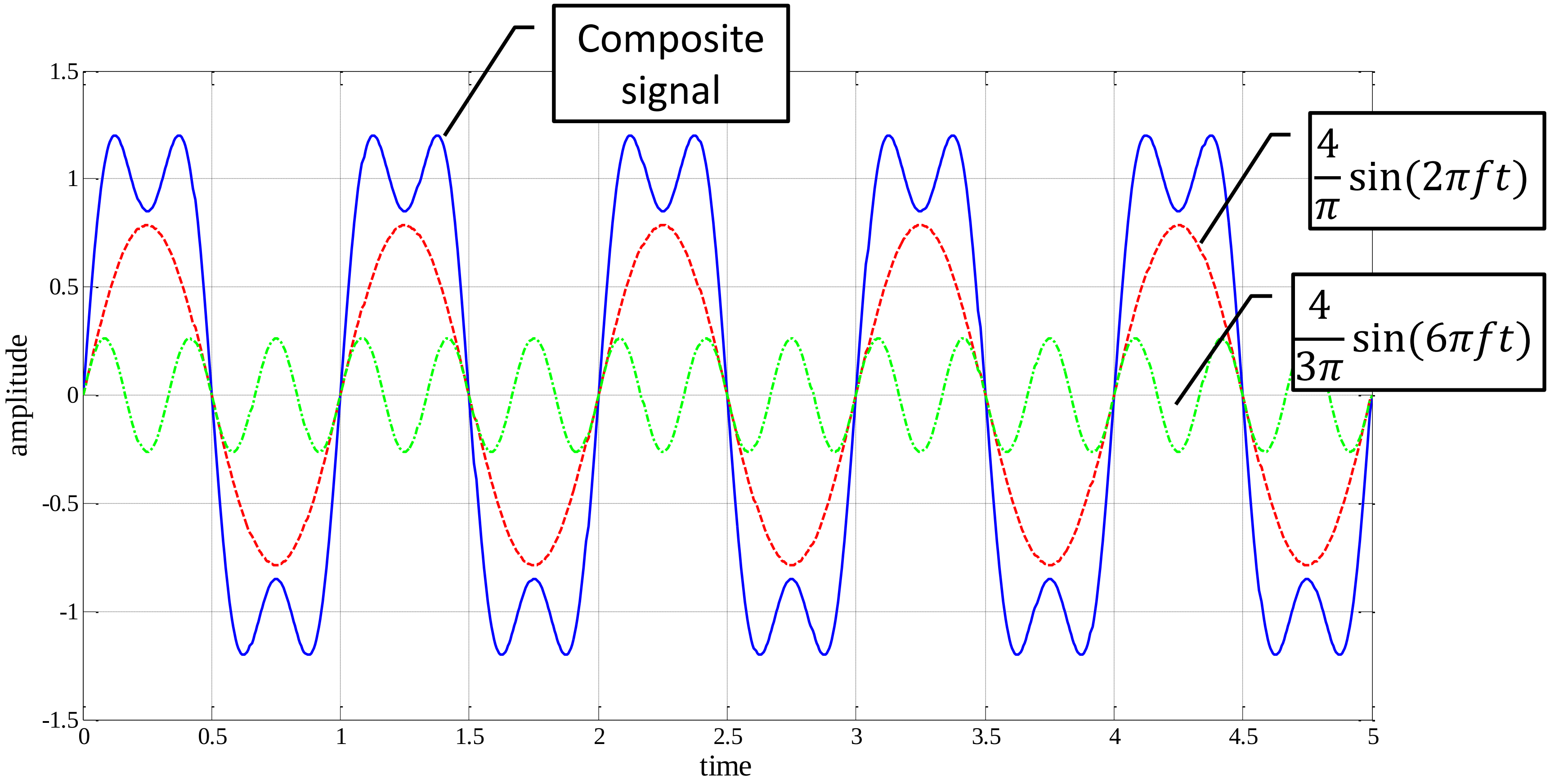


- *Each* sine wave differs from the others in amplitude and frequency
- *f* is called the fundamental frequency

https://www.youtube.com/watch?v=k8FXF1KjzY0

Addition of Frequency Components

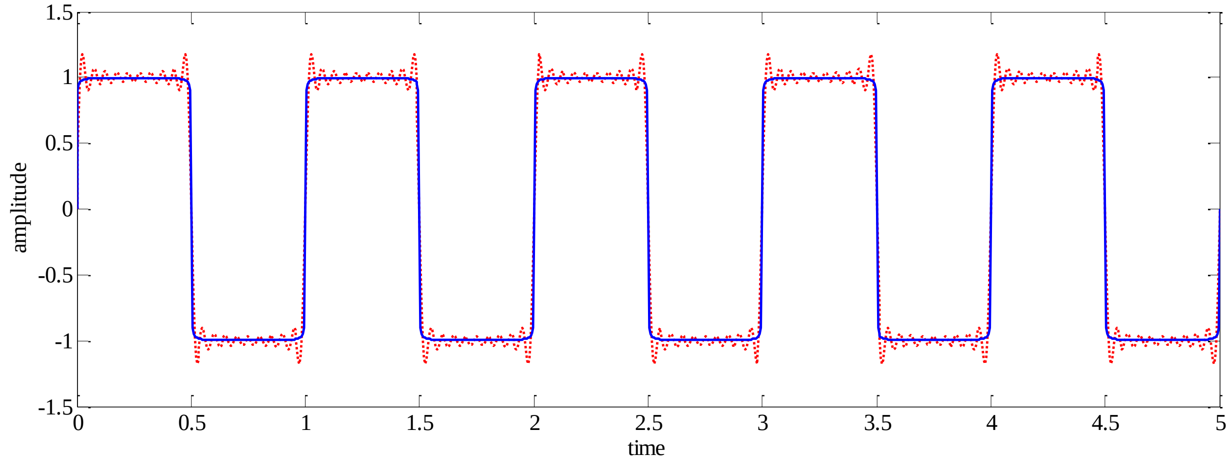
- Adding the first two terms, we have



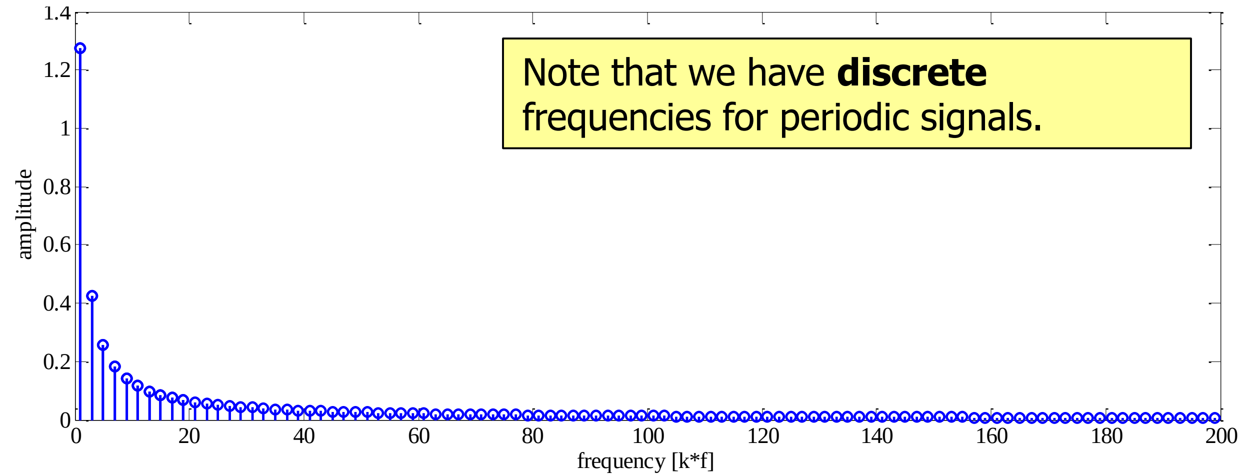
Addition of Frequency Components

- More frequency added, e.g. 10 terms (dashed) and 100 terms (solid), gets closer to a square wave

Time domain:



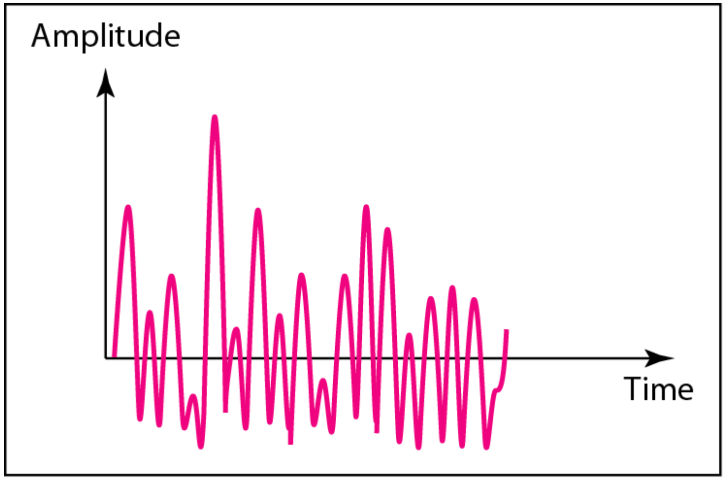
Frequency domain:



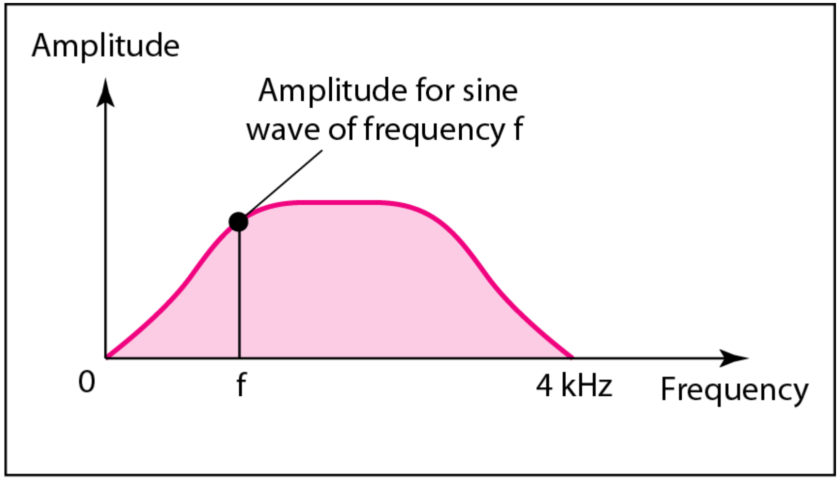
Note that we have **discrete** frequencies for periodic signals.

Frequency Domain Representation of Aperiodic Signals

- For aperiodic signals, we have a **continuous** frequency domain representation



a. Time domain



b. Frequency domain

Spectrum and Bandwidth

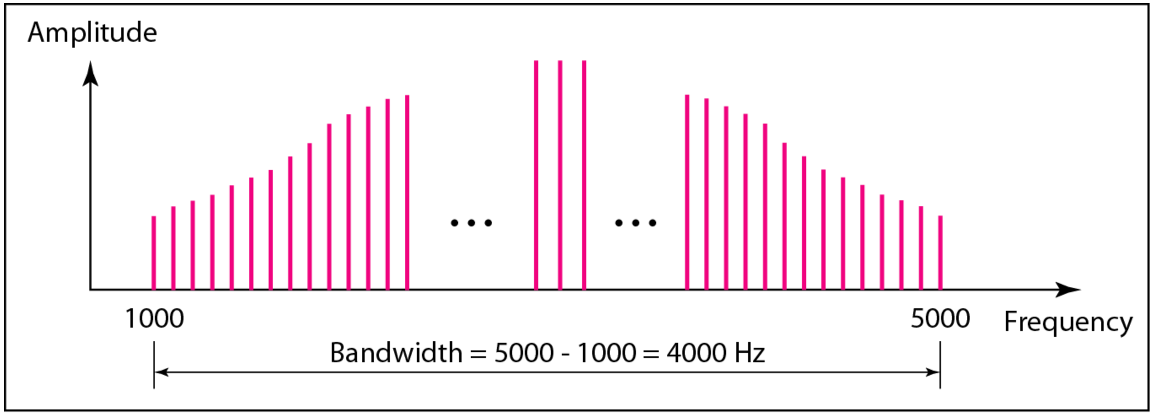
- Spectrum – range of frequencies that a signal spans from minimum to maximum
- Bandwidth – the absolute value of the difference between the highest frequencies and lowest frequencies

$$BW = f_{highest} - f_{lowest}$$

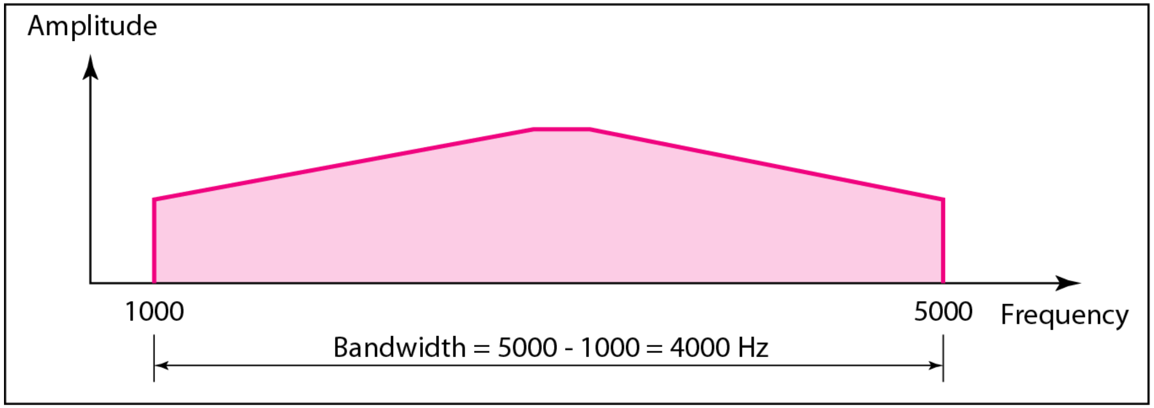
- Effective bandwidth – narrow band of frequencies containing major energy

What is the bandwidth of a square wave?

Bandwidth of a Periodic and Aperiodic Signal



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

For $s(t) = 15 + 10\sin(16\pi t) + 5\sin(32\pi t)$, $\mathrm{BW}_{S(t)} = ?$

Analog and Digital Data Transmission

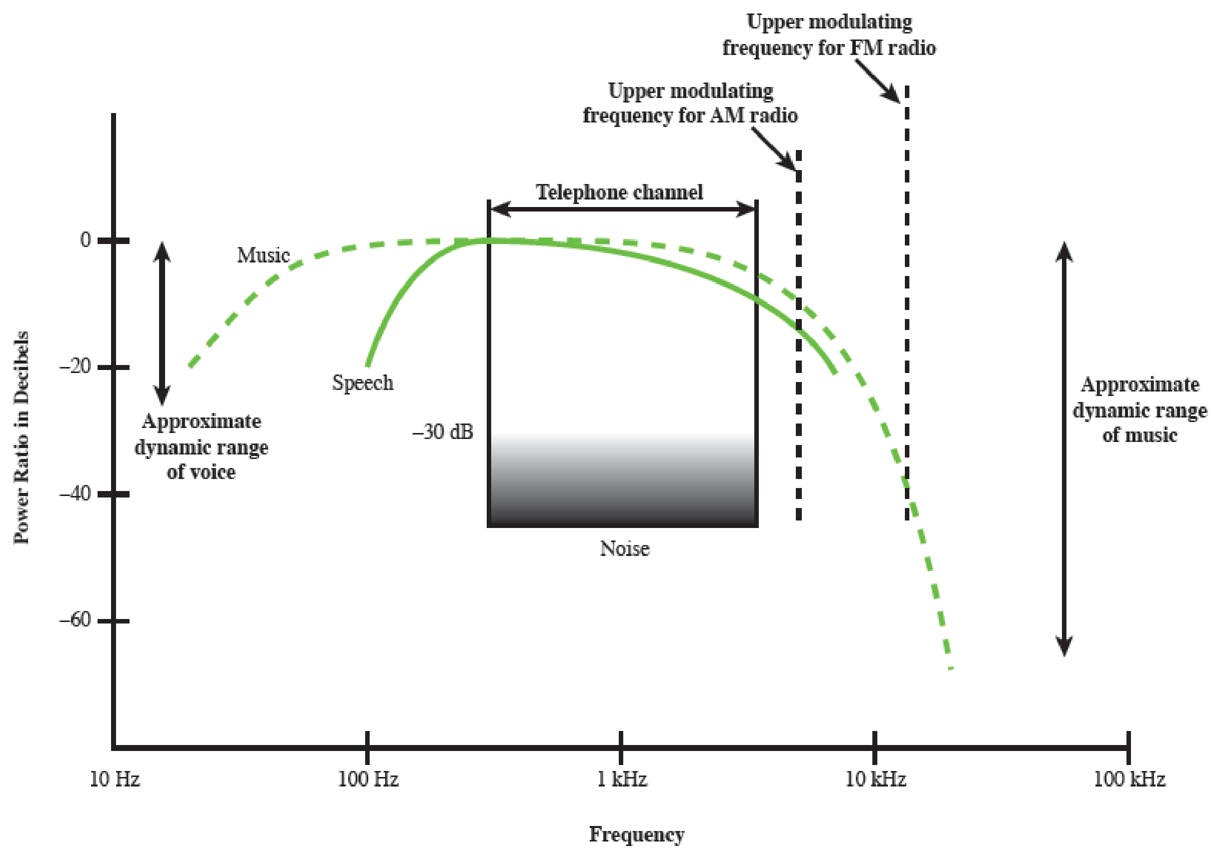
- data (analog and digital)
  - entities that convey information
- signals (analog and digital)
  - electric or electromagnetic representations of data
- signaling
  - physically propagates along a medium
- transmission
  - communication of data by propagation and processing of signals

Analog and Digital Data

- Analog data take on continuous values in some interval
- Most familiar example of analog data is audio, which is in the form of acoustic sound wave
- Another common example of analog data is video
- Digital data are discrete, discontinuous representation of information, e.g. text

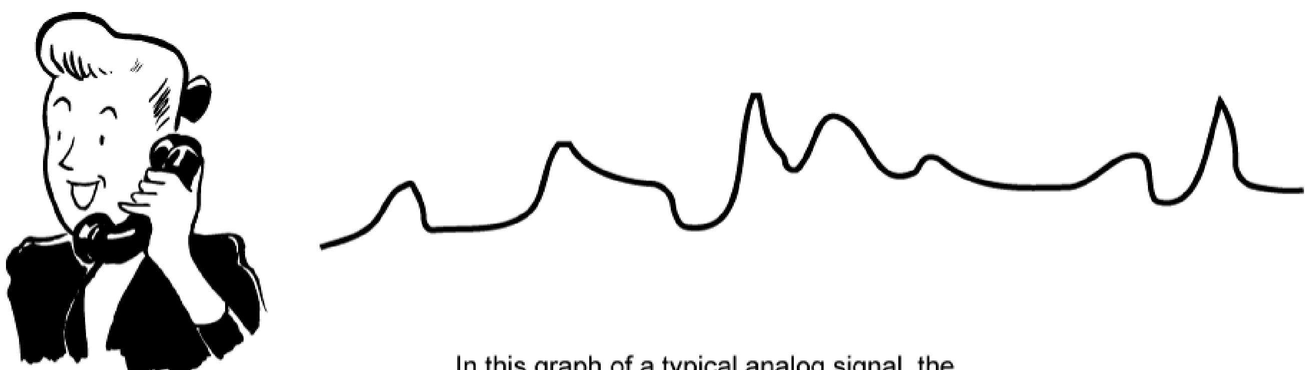
Acoustic Spectrum (Analog)

- Frequency components of typical speech around 100 Hz and 7 kHz



Audio (Analog) Signals

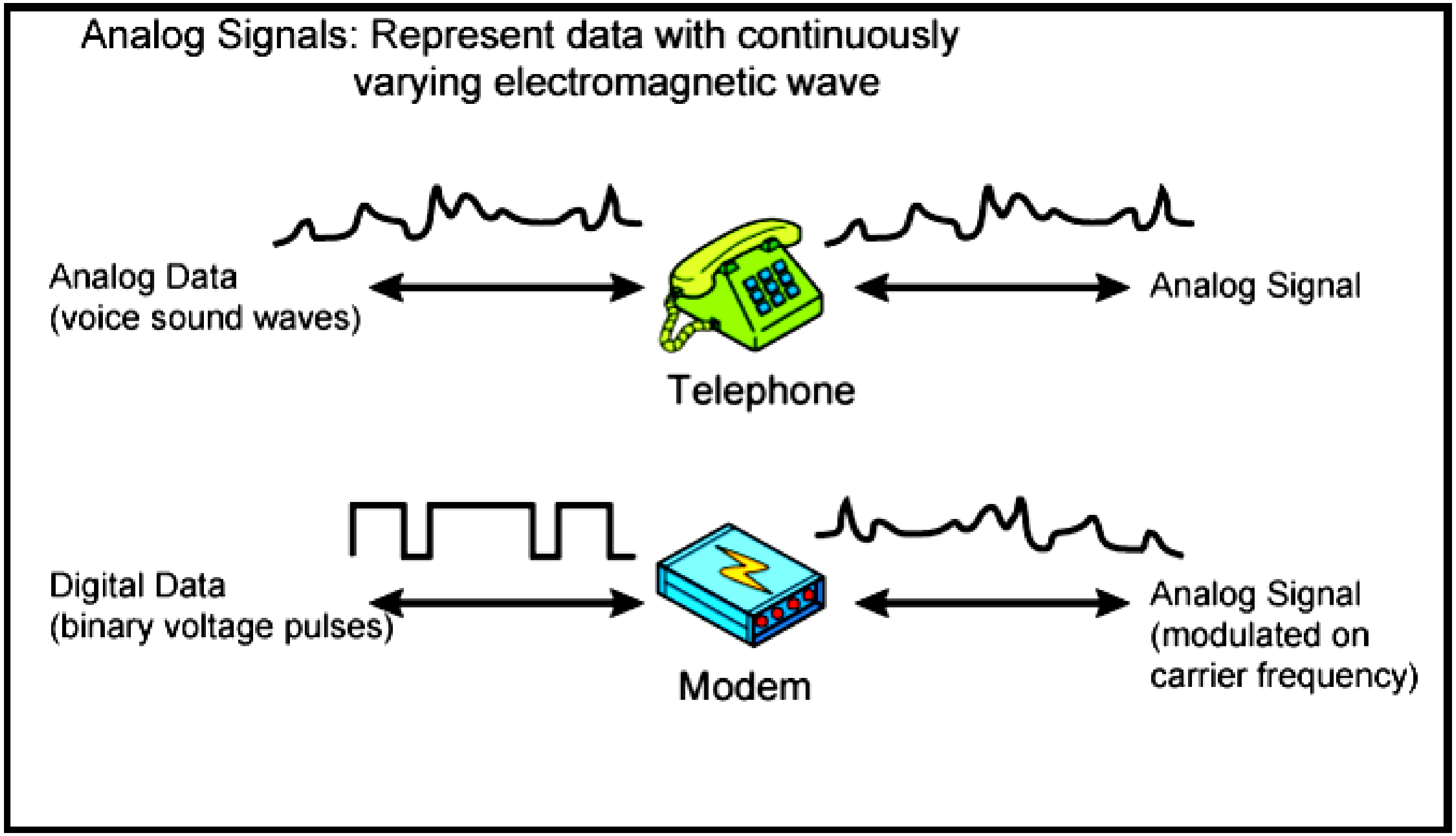
- frequency range of typical speech is 100Hz-7kHz
- easily converted into electromagnetic signals
- varying volume converted to varying voltage
- can limit frequency range for voice channel to 300-3400Hz



In this graph of a typical analog signal, the variations in amplitude and frequency convey the gradations of loudness and pitch in speech or music. Similar signals are used to transmit television pictures, but at much higher frequencies.

Analog Signaling

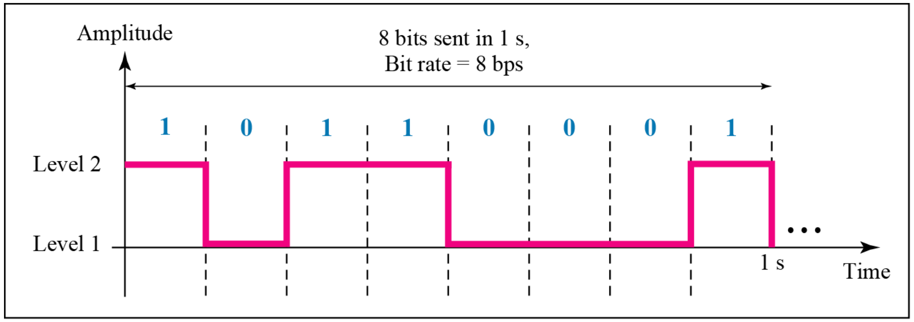
- Both analog and digital data can be transmitted using analog signal



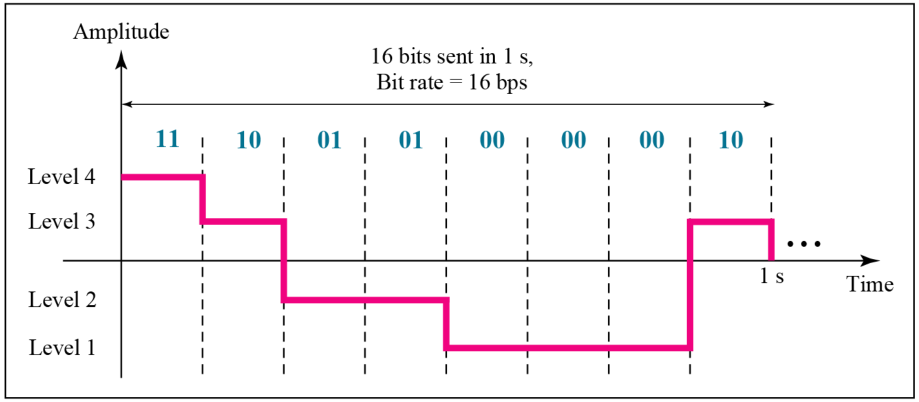
Digital Signals

- Data can be represented by digital signals, e.g. an 1 can be encoded as a positive voltage level and a 0 as a negative (or zero) voltage level

Bit rate is the number of bits sent in 1 second, expressed as bits per second (bps).



- A digital signal can also have more than two levels



Digital Signaling

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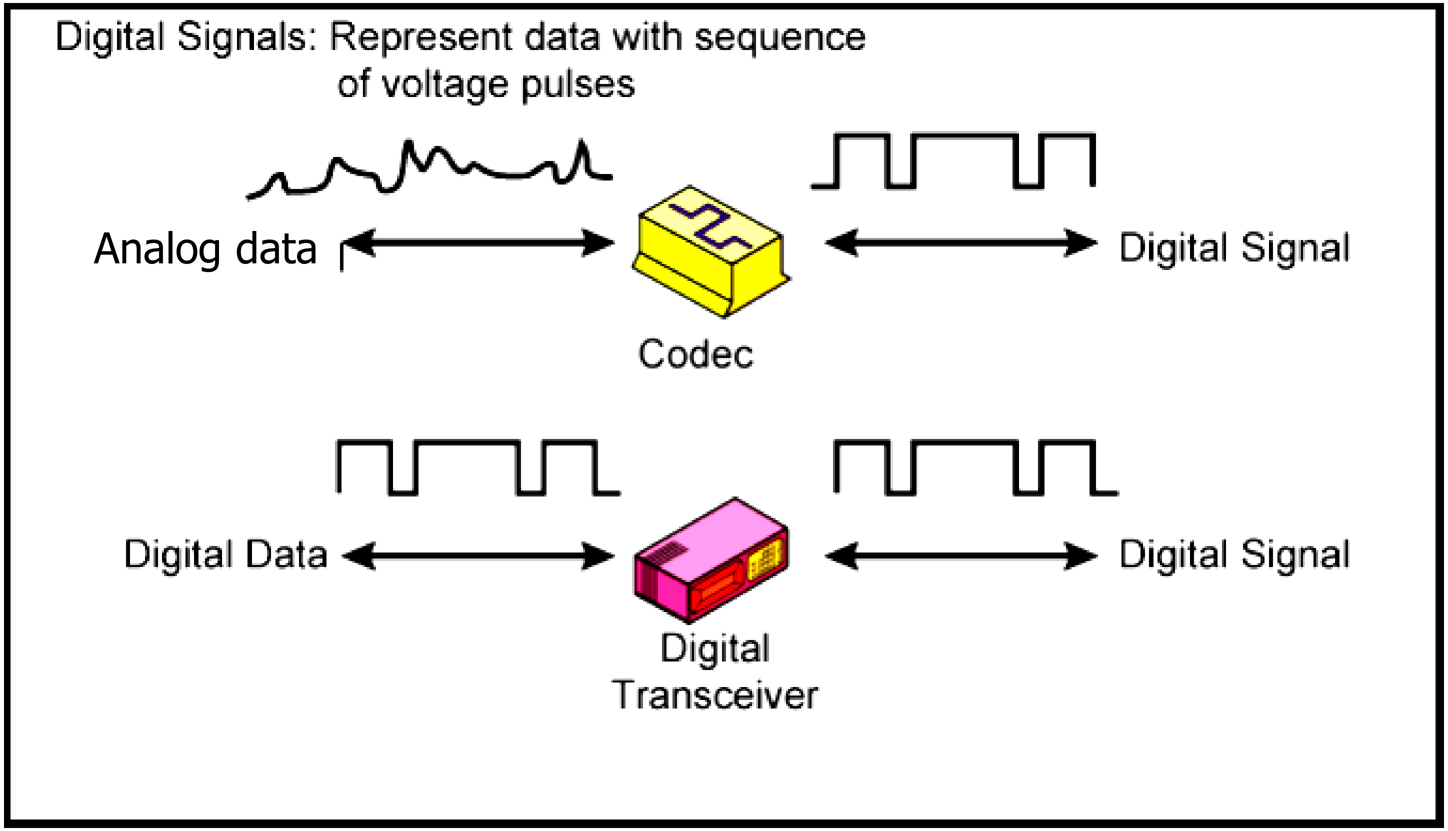


Data and Signals

(a) Data and Signals

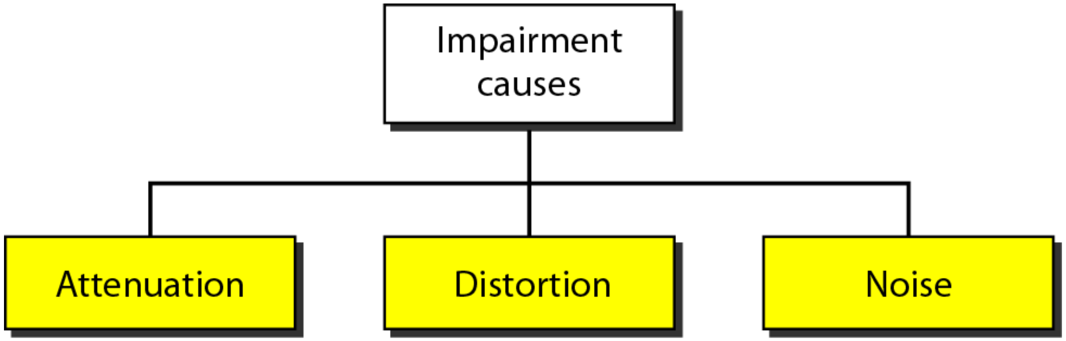
	Analog Signal	Digital Signal
Analog Data	Two alternatives: (1) signal occupies the same spectrum as the analog data; (2) analog data are encoded to occupy a different portion of spectrum.	Analog data are encoded using a codec to produce a digital bit stream.
Digital Data	Digital data are encoded using a modem to produce analog signal.	Two alternatives: (1) signal consists of two voltage levels to represent the two binary values; (2) digital data are encoded to produce a digital signal with desired properties.

Analog and Digital Transmission

- Analog data are encoded using a codec to produce a digital bit stream
- Digital data are encoded using a modem to produce an analog signal
- Amplifiers are used for analog transmission
- Repeaters are used for digital transmission

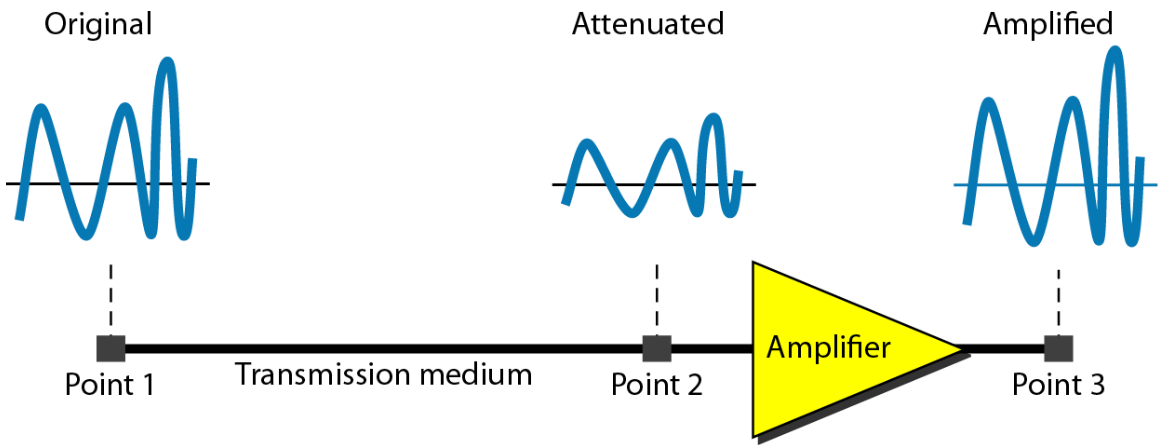
Transmission Impairments

- signal received may differ from signal transmitted causing:
  - analog - degradation of signal quality
  - digital - bit errors
- most significant impairments are
  - attenuation
  - distortion
  - noise



Attenuation

- Attenuation means a loss of energy
- Signal strength falls off with distance over any transmission medium
- Amplifier is often used to compensate for this loss

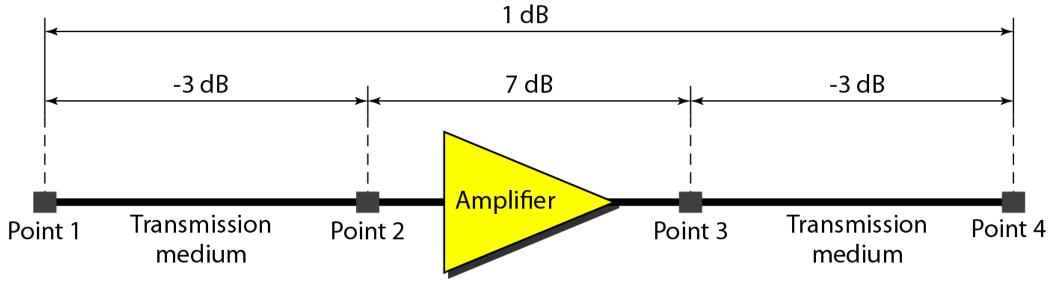


Decibel (dB)

- The decibel (dB) measures the relative strengths of two signals or one signal at two different points
- The decibel is negative if a signal is attenuated and positive if a signal is amplified

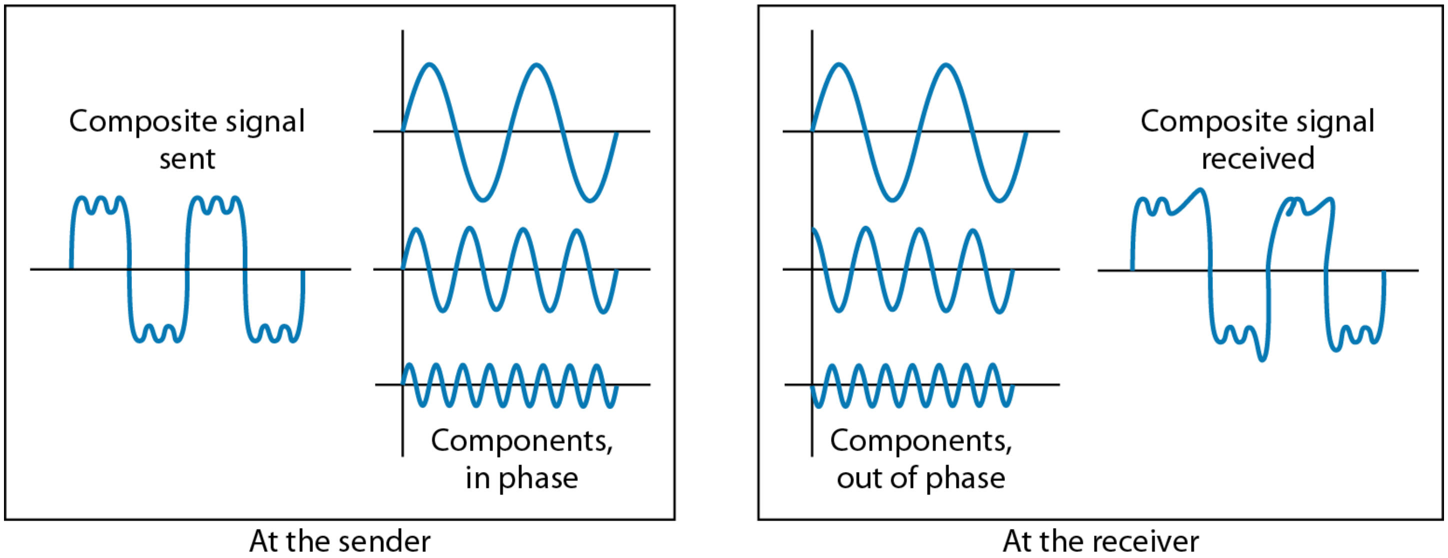
$$\text{dB} = 10\log_{10}\frac{P_2}{P_1}$$

- For example, the decibel for the following can be calculated as dB=-3+7-3=+1



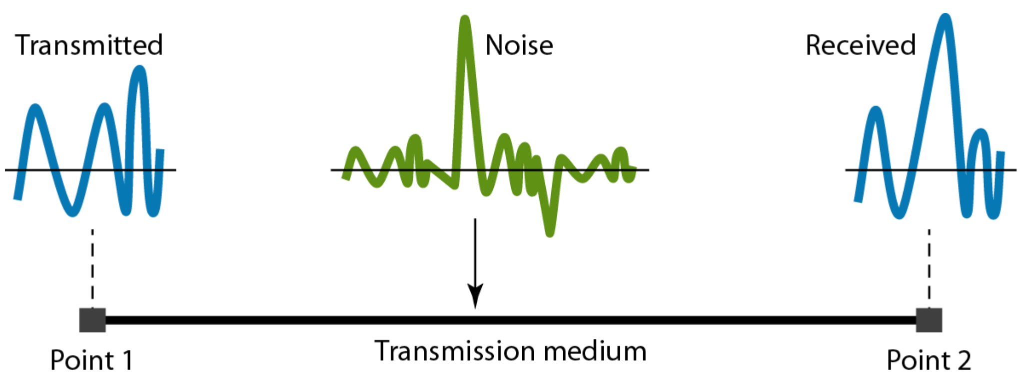
Distortion

- Distortion means that the signal changes its form or shape
- Can occur in a composite signal made of different frequencies
- Each signal component has its own propagating speed and its own delay in arriving the destination
- Differences in delay may create a difference in phase



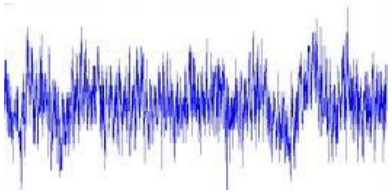
Noise

- Noise is the unwanted signals added between transmitter and receiver
- Noise is the major limiting factor in communications system performance
- There are four main categories of noise
  - Thermal noise
  - Intermodulation noise
  - Crosstalk
  - Impulse noise

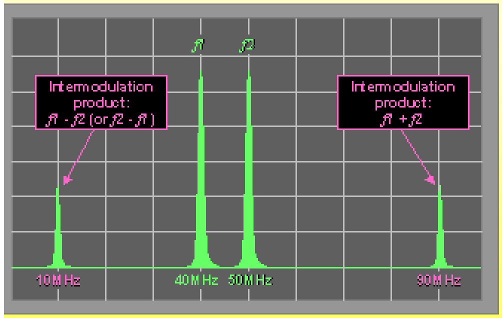


Thermal and Intermodulation Noise

- 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

Crosstalk and Impulse Noise

- Cross Talk
  - 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

- 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

Signal-to-Noise Ratio (SNR)

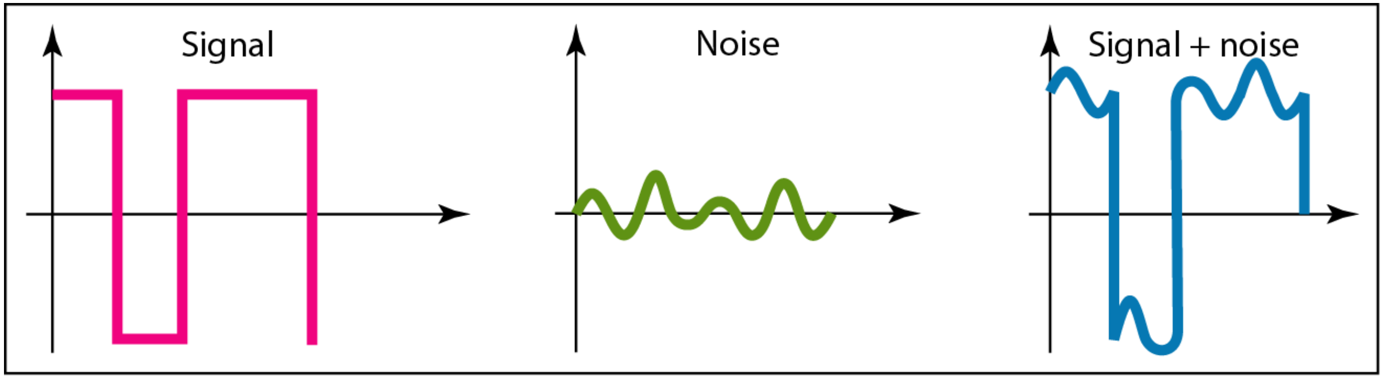
- The signal-to-noise ratio(SNR) is defined as

$$\text{SNR} = \frac{\text{average signal power}}{\text{average noise power}}$$

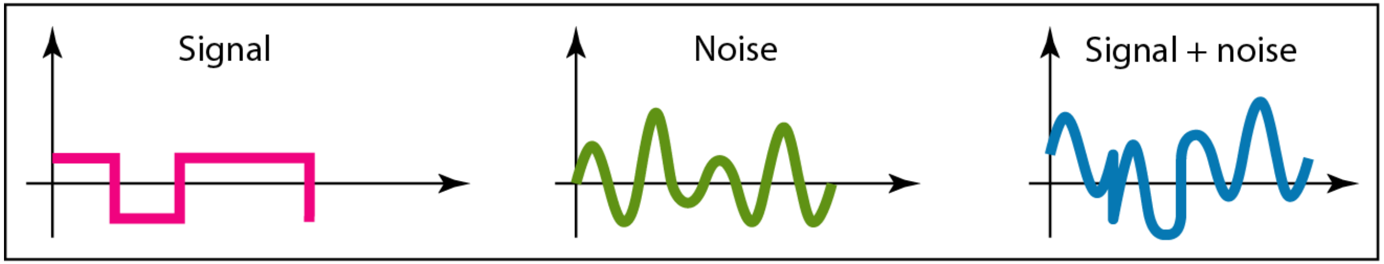
$$\text{SNR}_{\text{dB}} = 10\log_{10}\text{SNR}$$

- Average signal and noise power is considered since they may change with time
- A high SNR means the signal is less corrupted by noise, while a low SNR means the signal is more corrupted by noise

Signal-to-Noise Ratio (SNR)



a. Large SNR



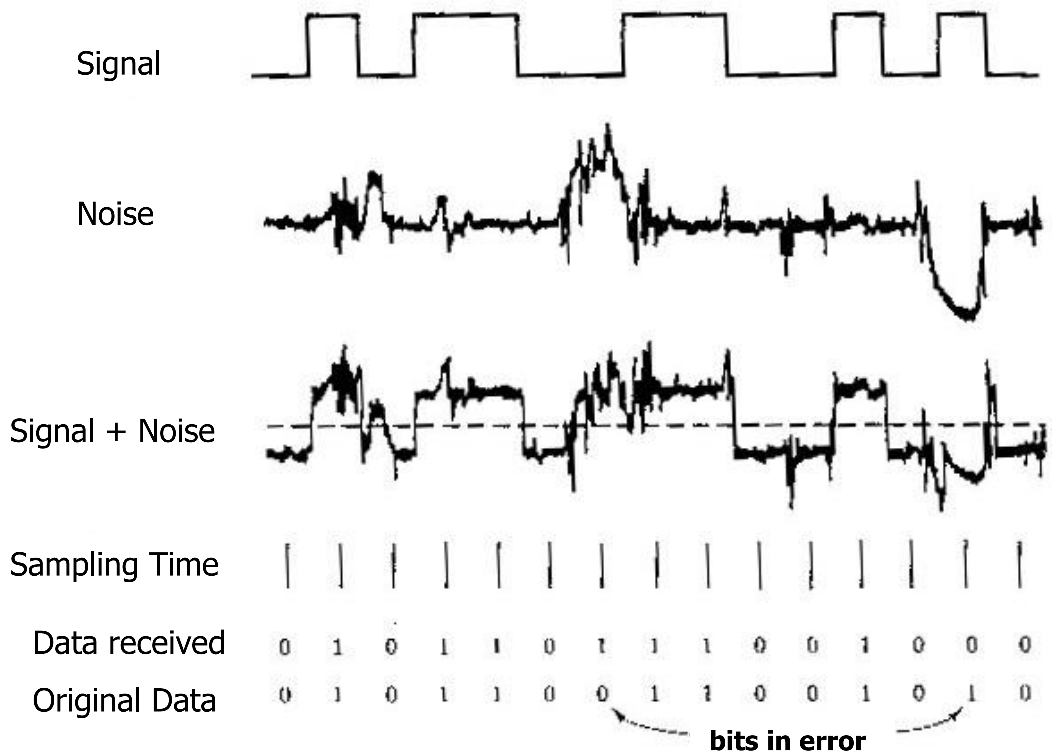
b. Small SNR

Which *signal + noise* looks more like the original signal?

Effect of Noise on a Digital Signal

- The effect of noise on a digital signal is bit errors
- Error rate is defined as the rate of bits in error

$$\text{Error Rate} = \frac{\text{number of bit errors}}{\text{total number of bits sent}}$$



What is the Error Rate?

Channel Capacity

- Data rate depends on three factors:
  - bandwidth available
  - level of the signals
  - quality of the channel (level of noise)
- Channel capacity is the maximum data rate at which data can be transmitted over a given communications channel under given conditions
- Two theoretical formulas were developed to calculate the channel capacity: one by Nyquist for a noiseless channel, another by Shannon for a noisy channel

Noiseless Channel: Nyquist Bit Rate

- For a noise less channel, the Nyquist bit rate formula defines the capacity as

$$\text{BitRate} = 2B\log_2 M$$

  where B is the bandwidth of the channel in Hz, M is the signal levels used to represent data and BitRate is in bits per second (bps)
- Bit rate can be increased by increasing signal levels
  - however this increases burden on receiver
  - noise and other impairments limit the value of M

Noisy Channel: Shannon Capacity

- The relation of data rate, noise and error rate are
  - faster data rate corrupts more bits   Why?
  - given noise level, higher data rate means higher error rate
- Shannon developed formula relating these to signal to noise ratio ~~(in decibels)~~

$$C = B\log_2(1+SNR)$$

  where B the channel bandwidth and SNR is the signal-to-noise ratio
- Only theoretical maximum capacity
- Get much lower rates in practice

Example: Shannon Capacity and Nyquist Bit Rate

- Suppose that the spectrum of a channel is between 3 MHz and 4 MHz and SNR_{dB} = 24 dB. Then

  B = 4 MHz – 3 MHz = 1 MHz

  SNR_{dB} = 24 dB = 10 log10(SNR)

  SNR = 251

- Using Shannon's formula,

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

- Assume we can achieve this channel capacity.
- Based on Nyquist's formula, how many signaling levels are required? We have

  $C = 2B \log_2 M$

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

  $4 = \log_2 M$

  $M = 2^4 = 16$ (levels)

Summary

- Transmission concepts and terminology
  - guided/unguided media
- Frequency, spectrum and bandwidth
- Analog vs. digital data and signals
- Transmission impairments
  - attenuation/delay distortion/noise
- Channel capacity
  - Nyquist (noiseless channel)
  - Shannon (noisy channel)