Chapter 3

Data Transmission

Terminology (1)

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

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

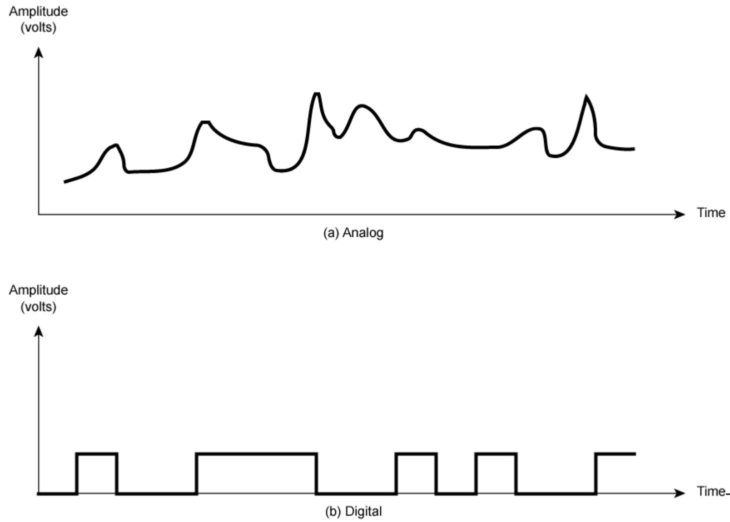
Terminology (3)

- 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

Frequency, Spectrum and Bandwidth

- Time domain concepts
  - Analog signal
    - Varies 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

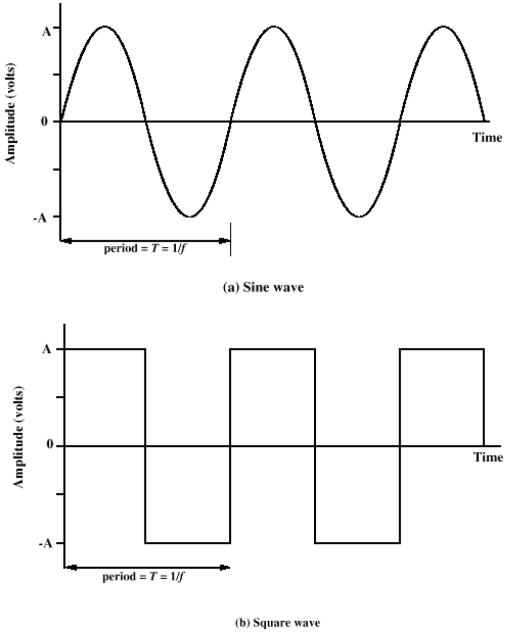
Analogue & Digital Signals



(a) Analog

(b) Digital

Periodic Signals



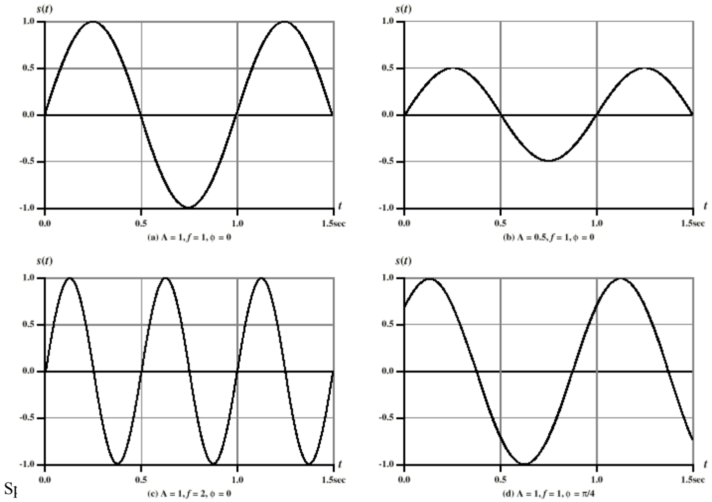
(a) Sine wave

(b) Square wave

Sine Wave

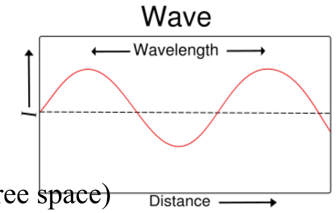
- Peak Amplitude (A)
  - Maximum strength of signal
  - Volts
- Frequency (f)
  - Rate of change of signal
  - Hertz (Hz) or cycles per second
  - Period = time for one repetition (T)
  - T = 1/f
- Phase (ϕ)
  - Relative position in time

Varying Sine Waves
s(t) = A sin(2πft +Φ)



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/s (speed of light in free space)



The wavelengths of frequencies audible to the human ear (20 Hz–20 kHz) are between approximately 17 m and 17 mm, respectively.

Visible light ranges from deep red, roughly 700 nm to violet, roughly 400 nm (430–750 THz).

The speed of sound is 344 m/s (1238 km/h) in air at room temperature.

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 component sine waves
- Can plot frequency domain functions

Fourier Series

$$x(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty}[A_n \cos(2\pi n f_0 t) + B_n \sin(2\pi n f_0 t)]$$

where

$$A_0 = \frac{2}{T}\int_0^T x(t)\,dt$$

$$A_n = \frac{2}{T}\int_0^T x(t)\cos(2\pi n f_0 t)\,dt$$

$$B_n = \frac{2}{T}\int_0^T x(t)\sin(2\pi n f_0 t)\,dt$$

Fourier Series (II)

$$x(t) = \frac{C_0}{2} + \sum_{n=1}^{\infty} C_n \cos(2\pi n f_0 t + \theta_n)$$

where

$$C_0 = A_0$$

$$C_n = \sqrt{A_n^2 + B_n^2}$$

$$\theta_n = \tan^{-1}\left(\frac{-B_n}{A_n}\right)$$

Fourier Transform

- X(f) : Fourier transform
- x(t): Inverse Fourier transform

$$x(t) = \int_{-\infty}^{\infty} X(f) e^{j2\pi f t}\, df$$

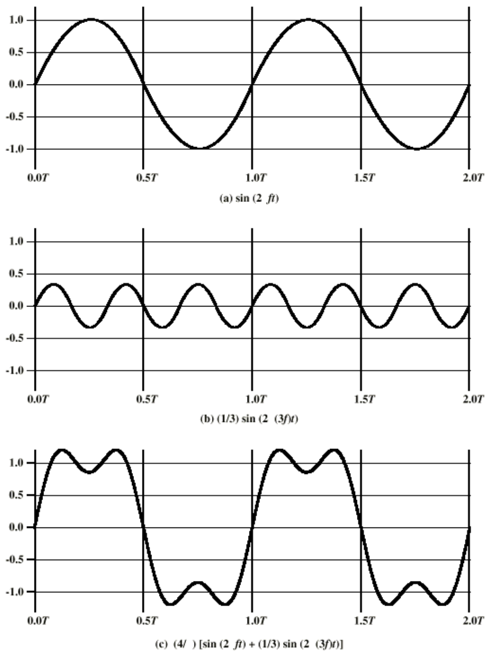
$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi f t}\, dt$$

Addition of Frequency Components (T=1/f)

$(a)\quad \sin(2\pi f t)$

$(b)\quad (1/3)\sin(2\pi(3f)t)$

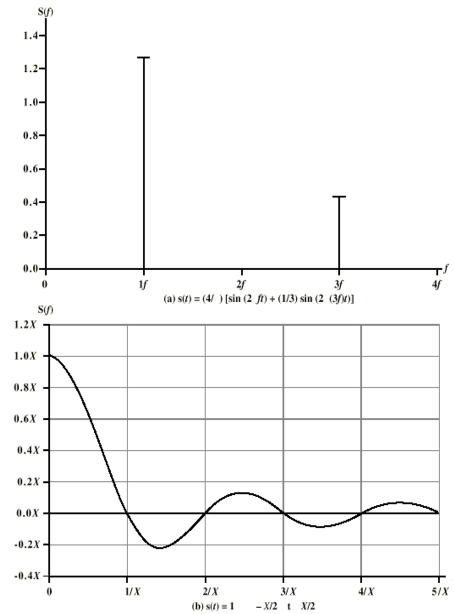
$(c)\quad (4/\pi)[\sin(2\pi f t) + (1/3)\sin(2\pi(3f)t)]$



Frequency Domain Representations

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

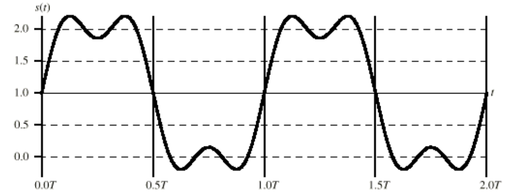
$(b)\quad s(t) = 1 \quad -X/2 \le t \le X/2$



Spectrum & Bandwidth

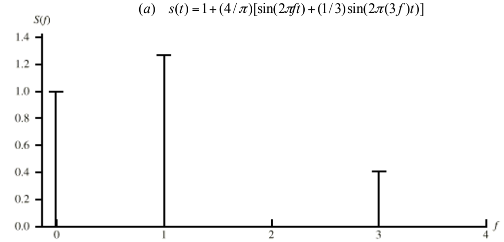
- Spectrum
  - Range of frequencies contained in signal
- Absolute bandwidth
  - Width of spectrum
- Effective bandwidth
  - Often just *bandwidth*
  - Narrow band of frequencies containing most of the energy
- DC Component
  - Component of zero frequency

Signal with DC Component



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

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



(b) S(f)

Data Rate and Bandwidth

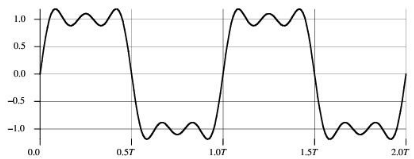
- Any transmission system has a limited band of frequencies
- This limits the data rate that can be carried
- A given bandwidth can support various data rates depending on the ability of the receiver to discern the difference between 0 and 1 in the presence of noise and other impairments

Square Wave

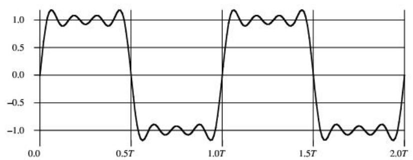
The frequency components of the square wave with amplitude A and –A can be expressed as:

$$s(t) = A \times \frac{4}{\pi} \times \sum_{k\ odd,\ k=1}^{\infty} \frac{sin(2\pi k f t)}{k}$$

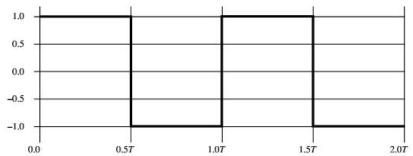
The relationship between data rate and bandwidth (p72-78)



(a) $(4/\pi)$ [sin $(2\pi ft)$ + (1/3) sin $(2\pi(3f)t)$ + (1/5) sin $(2\pi(5f)t)$]



(b) $(4/\pi)$ [sin $(2\pi ft)$ + (1/3) sin $(2\pi(3f)t)$ + (1/5) sin $(2\pi(5f)t)$ + (1/7) sin $(2\pi(7f)t)$]



(c) $(4/\pi) \sum (1/k) \sin(2\pi(kf)t)$, for k odd

Figure 3.7 Frequency Components of Square Wave ($T = 1/f$)

Effect of Bandwidth

- The higher the data rate of a signal, the greater is its required effective bandwidth.
- The greater the bandwidth of a transmission system, the higher is the date rate that can be transmitted over the system.
- The higher the center frequency, the higher the potential bandwidth and date rate.

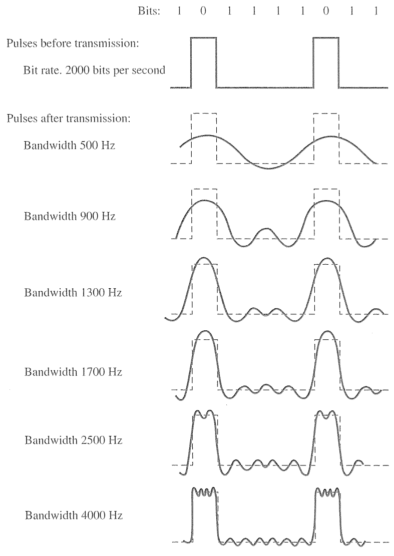


Figure 3.8 Effect of Bandwidth on a Digital Signal

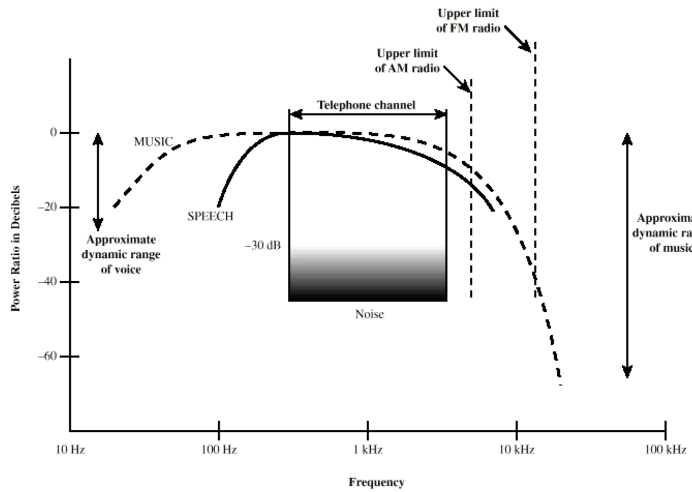
Analog and Digital Data Transmission

- Data
  - Entities that convey meaning
- Signals
  - Electric or electromagnetic representations of data
- 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

Acoustic Spectrum (Analog)

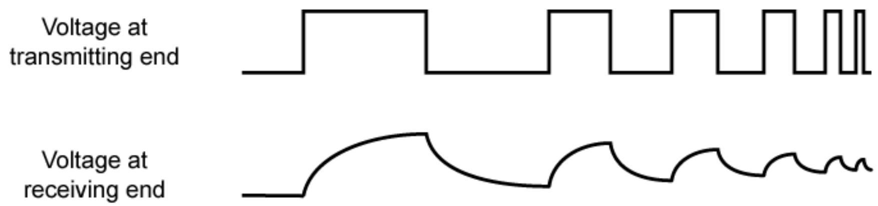


Analog and Digital Signals

- Data are propagated by electromagnetic signals
- Analog
  - – Continuously variable
  - – Various media
    - wire, fiber optic, space
  - – Speech bandwidth 100Hz to 7kHz
  - – Telephone bandwidth 300Hz to 3400Hz
  - – Video bandwidth 4MHz
- Digital
  - – Use two DC components

Advantages & Disadvantages of Digital

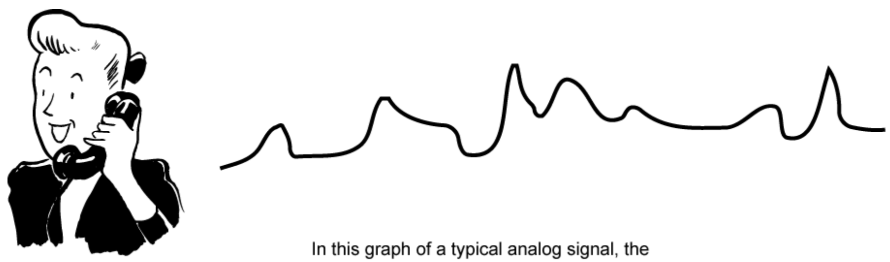
- Cheaper
- Less susceptible to noise
- Greater attenuation
  - – Pulses become rounded and smaller
  - – Leads to loss of information



Components of Speech (example)

- Frequency range (of hearing) 20Hz-20kHz
  - – Speech 100Hz-7kHz
- Easily converted into electromagnetic signal for transmission
- Sound frequencies with varying volume converted into electromagnetic frequencies with varying voltage
- Limit frequency range for voice channel
  - – 300−3400Hz

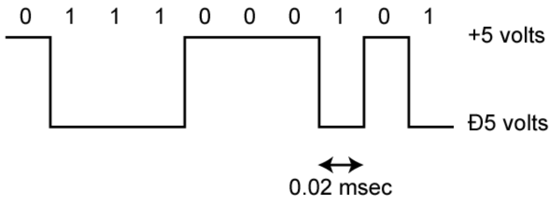
Conversion of Voice Input into Analog Signal



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.

Binary Digital Data (example)

- From computer terminals etc.
- Two DC components
- Bandwidth depends on data rate

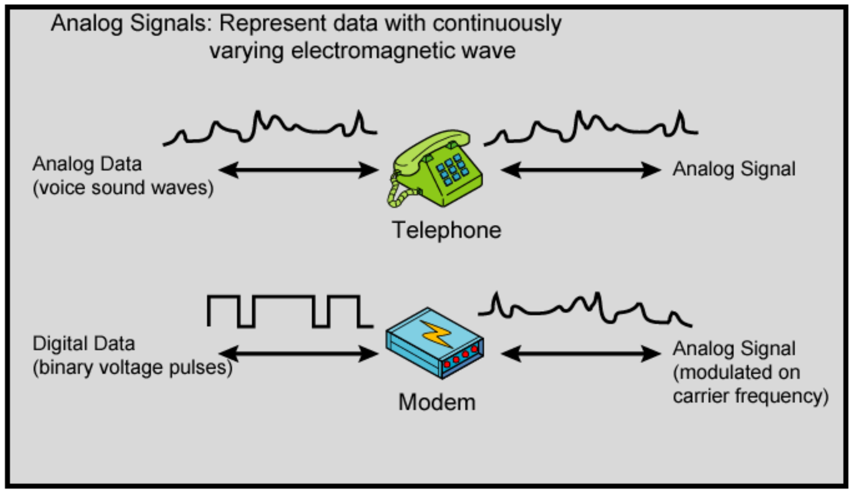


User input at a PC is converted into a stream of binary digits (1s and 0s). In this graph of a typical digital signal, binary one is represented by Ð5 volts and binary zero is represented by +5 volts. The signal for each bit has a duration of 0.02 msec, giving a data rate of 50,000 bits per second (50 kbps).

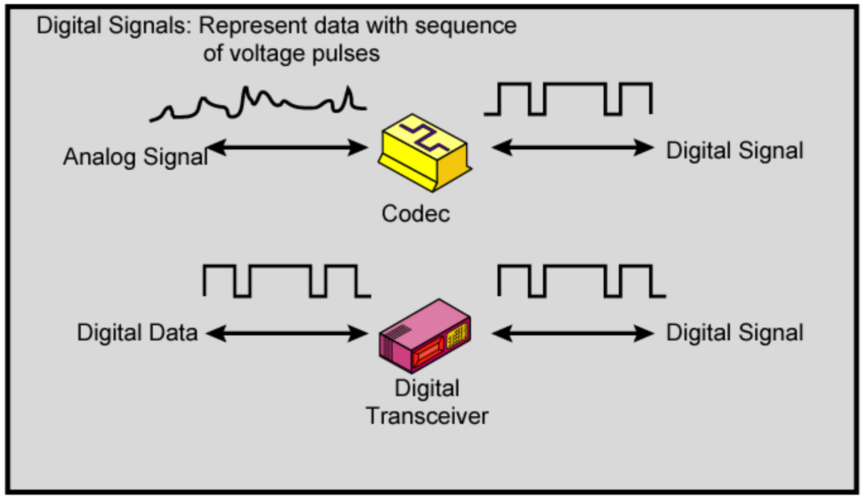
Data and Signals

- Usually use digital signals for digital data and analog signals for analog data
- Can use analog signal to carry digital data
  - Modem
- Can use digital signal to carry analog data
  - Compact Disc audio

Analog Signals Carrying Analog & Digital Data



Digital Signals Carrying Analog & Digital Data



Analog Transmission

- Analog signal transmitted without regard to content
- May be analog or digital data
- Attenuated over distance
- Use amplifiers to boost signal
- Also amplifies noise

Digital Transmission

- Concerned with content
- Integrity endangered by noise, attenuation etc.
- Repeaters can be used
  - receives signal
  - extracts bit pattern
  - retransmits
  - attenuation is overcome
  - noise is not amplified

Advantages of Digital Transmission

- Digital technology
  - Low cost LSI/VLSI technology
- Data integrity
  - Longer distances over lower quality lines
- Capacity utilization
  - High bandwidth links became economical
  - High degree of multiplexing easier with digital techniques
- Security & Privacy
  - Encryption
- Integration
  - Can treat analog and digital data similarly

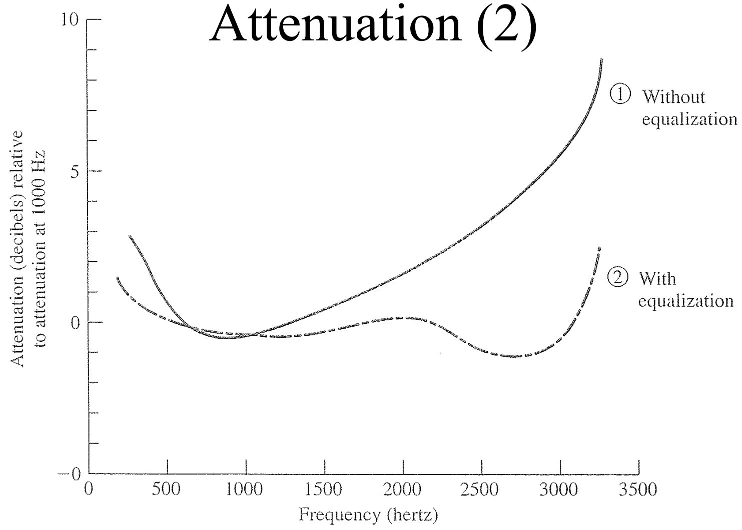
Transmission Impairments

- 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
- 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

Attenuation (2)



(a) Attenuation

Decibels and Signal Strength

The decibel is a measure of the ratio between two signal levels. The decibel gain is given by

$$G_{dB} = 10 \log_{10} \frac{P_{out}}{P_{in}}$$

where

G_{dB}	=	gain, in decibels
P_{in}	=	input power level
P_{out}	=	output power level
$\log_{10}$	=	logarithm to the base 10

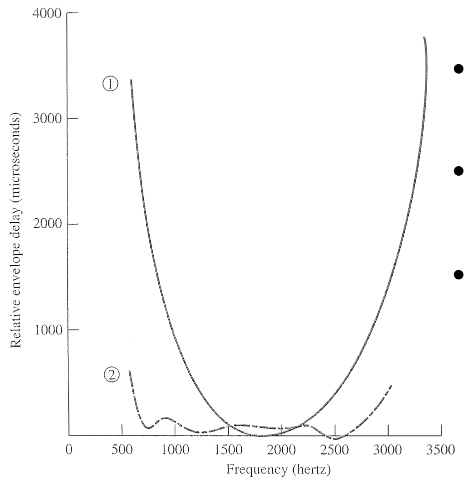
The decibel is also used to measure the difference in voltage, taking into account that power is proportional to the square of the voltage:

$$P = \frac{V^2}{R}$$

thus

$$L_{dB} = -G_{dB} = 20 \log_{10} \frac{V_{in}}{V_{out}}$$

Delay Distortion



(b) Delay distortion

- Propagation velocity varies with frequency
- Velocity is highest near the center frequency
- Fall off toward the two edges of the band

Noise (1)

- Additional signals inserted between transmitter and receiver
- Thermal $N_0 = kT(W/Hz)$
  - Due to thermal agitation of electrons
  - Uniformly distributed
  - White noise
- Intermodulation
  - Signals that are the sum and difference of original frequencies sharing a medium

Noise (2)

- Crosstalk
  - A signal from one line is picked up by another
- Impulse
  - Irregular pulses or spikes
  - e.g. external electromagnetic interference
  - Short duration
  - High amplitude

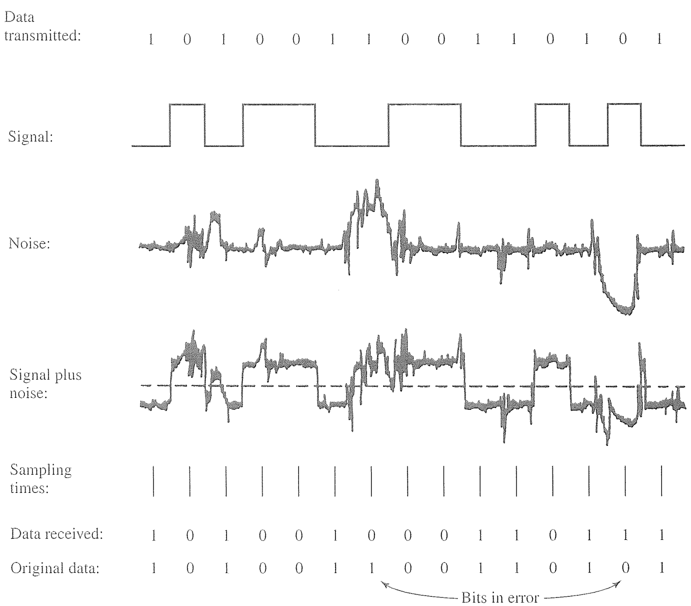


Figure 3.16 Effect of Noise on a Digital Signal

Channel Capacity

- The maximum rate at which data can be transmitted over a given communication path, or channel, under given conditions, is referred to as the channel capacity.
- Data rate
  - Bits per second
  - Rate at which data can be communicated
- Bandwidth
  - In cycles per second or Hertz
  - Constrained by transmitter and medium

Nyquist Bandwidth

- If rate of signal transmission is 2B then signal with frequencies no greater than B is sufficient to carry signal rate
- Given bandwidth B, highest signal rate is 2B
- Given binary signal, data rate supported by B Hz is 2B bps
- Can be increased by using M signal levels
- $C= 2B \log_2 M$ data rate, bandwidth, receiver's discernments, examples

Shannon Capacity Formula

- Consider data rate, noise and error rate
- Faster data rate shortens each bit so burst of noise affects more bits
  - At given noise level, high data rate means higher error rate
- Signal to noise ratio (in decibels)
- $SNR_{db}=10 \log_{10}$ (signal/noise)
- Capacity $C=B \log_2(1+SNR)$
- This is error free capacity