Relationship between Data Rate and Bandwidth

Case I: Bandwidth = 4 MHz; data rate = 2 Mbps

Case II: Bandwidth = 8 MHz; data rate = 4 Mbps

Case III: Bandwidth = 4 MHz; data rate = 4 Mbps

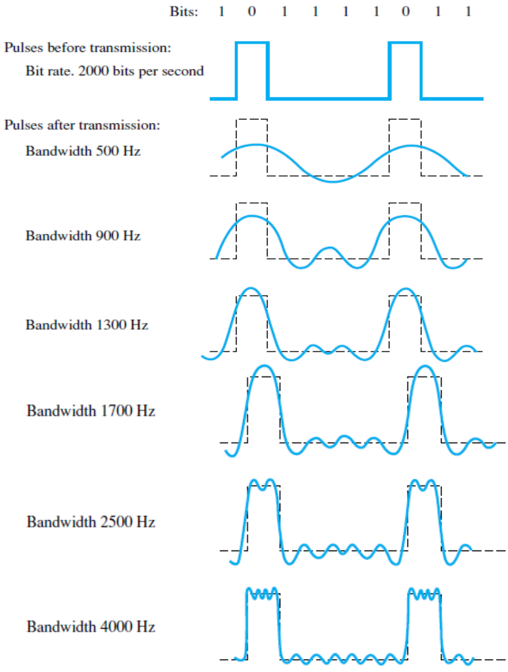


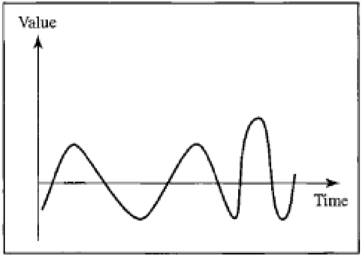
Figure 3.8 Effect of Bandwidth on a Digital Signal

Analog and Digital data transmission

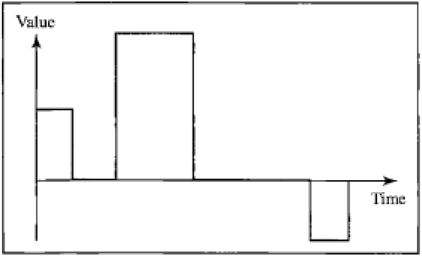
Analog and Digital ...

Data

- Entities that convey meaning or information
- Analog data take continuous values over time, e.g. voice, video, sensor data
- Digital data take discrete values, e.g. text, integers



a. Analog signal



b. Digital signal

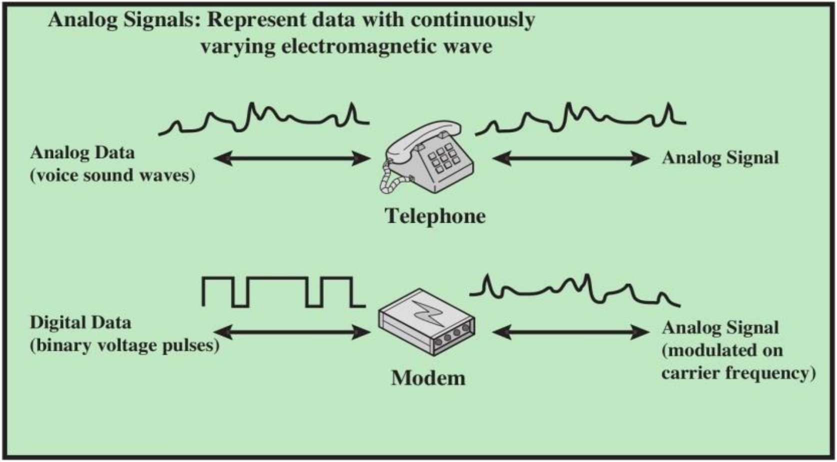
Analog and Digital …

- Signals
  - Electric or electromagnetic representations of data
- Transmission
  - Communication of data by propagating and processing signals

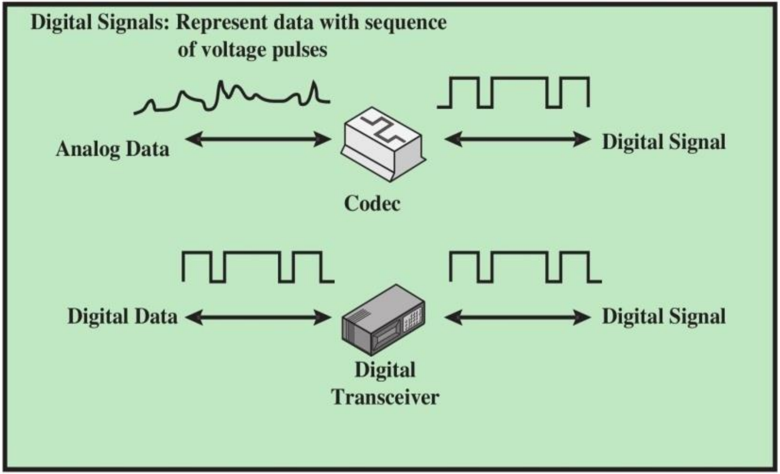
Analog vs Digital Signals

- Electric or electromagnetic representations of data
- Analog signal is continuously varying electromagnectic wave
- Digital signal is sequence of voltage pulses
- Digital signals generally cheaper and less susceptible to interference
- Digital signals suffer more from attenuation

Analog Signaling of Analog and Digital Data



Digital Signaling of Analog and Digital Data



Analog/Digital Signals and Data

	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 vs Digital transmission

- Analog transmission: analog signal is propagated through amplifiers.
- Digital transmission: analog or digital signals are propagated through repeaters.
- Digital transmission is preferred technology today:
    - digital equipment,
    - efficiently combine signals from different sources;
    - security;
    - repeaters can give more accurate data transmission

Transmission Impairments

Transmission Impairments

- Signal received may be different from signal transmitted causing:
  - Analog: degradation of signal quality
  - Digital: bit errors

- Most significant impairments:

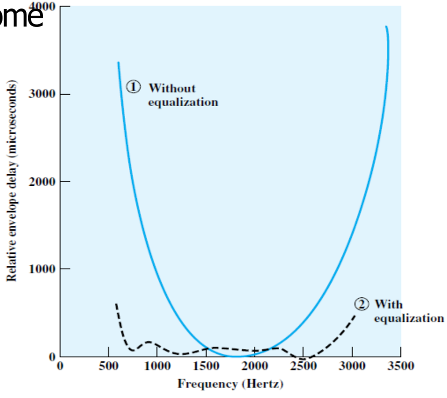
1. Attenuation and attenuation distortion
2. Delay distortion
3. Noise

Attenuation

- Signal strength reduces as a function of distance.
- Designing a transmission system:
  1. Received signal has sufficient strength to be interpreted by receiver electronics.
  2. Received signal is significantly higher than received noise to avoid errors.
  - Attenuation is different at different frequencies.
  - Apply equalization to overcome

Delay Distortion

- Component signals with different frequencies have different propagation delay through cable.
- Some signal components representing a bit interfere with neighbour bits: intersymbol interference
- Apply equalization to overcome



Noise

Thematic Noise

- Due to thermal agitation of electrons.
- Present in all transmission devices and media.
- Function of temperature:

$$N = kTB$$

where k = Boltzmann's constant = 1.38×10^{-23} J/K, B is bandwidth and T is temperature in kelvins.

Thermal noise is uniformly distributed across the bandwidths typically used in communications systems.

It is often referred to as **white noise**.

in decibel-watts,

$$\begin{aligned} N &= 10 \log k + 10 \log T + 10 \log B \\ &= -228.6 \text{ dBW} + 10 \log T + 10 \log B \end{aligned}$$

- The amount of thermal noise to be found in a bandwidth of 1 Hz in any device or conductor is

$$N_0 = kT(W/Hz)$$

where[9]

N_0 = noise power density in watts per 1 Hz of bandwidth
k = Boltzmann's constant = 1.38×10^{-23} J/K
T = temperature, in kelvins (absolute temperature), where the symbol K is used to represent 1 kelvin

Intermodulation Noise

- Caused when signals of different frequencies share the same medium.
- The effect of intermodulation noise is to produce signals at a frequency that is
  - the sum of the two original frequencies or multiples of those frequencies
  - difference of the two original frequencies or multiples of those frequencies.

- Intermodulation noise is produced by nonlinearities in the transmitter, receiver and/or intervening transmission medium.

Noise

Crosstalk

- Unwanted coupling of different signals.

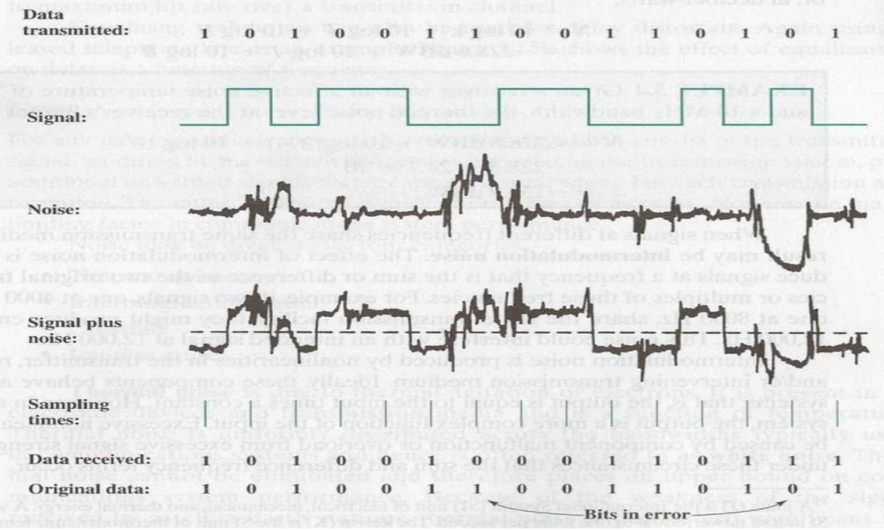
It can occur by electrical coupling between nearby twisted pairs or rarely coaxial cable lines carrying multiple signals

Impulse Noise

- is noncontinuous, consisting of irregular pulses ,short peak of noise,

e.g. lightning, electrical disturbances, flaws in communications system

Effect of Noise on a Digital Signal



Channel Capacity

Channel Capacity

- Channel capacity: maximum data rate at which data can be transmitted over a given communication channel, under given conditions.
- Relate:
  - Data rate, *C* [bits per second]
  - Bandwidth, *B* [Hertz]
  - Noise
  - Error rate
- Two theoretical models:

  Nyquist Capacity: assumes noise-free environment

  Shannon Capacity: considers noise

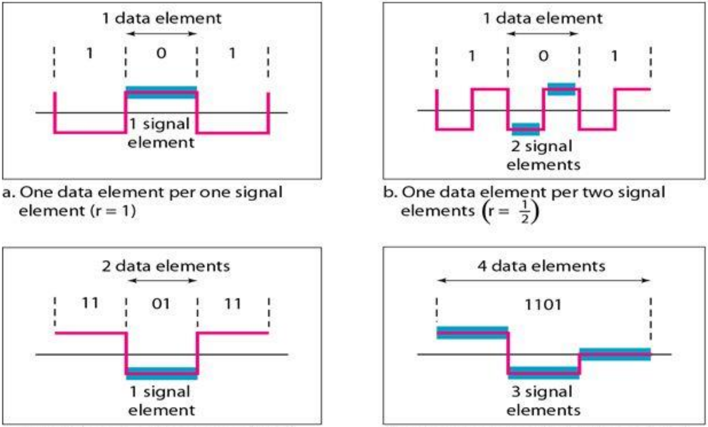
Nyquist Capacity

- Assumes channel that is noise free
- Given a bandwidth of B, the highest signal rate is $2B$
- Single signal element may carry more than 1 bit; signal with M levels may carry $\log_2 M$ bits

$$C = 2B \log_2 M$$

- Tradeoffs:
  - Increase the bandwidth, increases the data rate.
  - Increase the signal levels, increases the data rate.
  - Increase the signal levels, harder for receiver to interpret the bits (practical limit to M).

- Signal rate is the measure of the number of changes to the signal (per second) that propagate through a transmission medium.



a. One data element per one signal element ($r = 1$)

b. One data element per two signal elements $\left(r = \frac{1}{2}\right)$

c. Two data elements per one signal element ($r = 2$)

d. Four data elements per three signal elements $\left(r = \frac{4}{3}\right)$

Example of Nyquist Capacity

A telephone system with modem allows bandwidth of 3100 Hz. What is the maximum data rate? M=2 bits

Shannon Capacity

- With noise, some bits may be corrupted; higher data rate, more bits corrupted
- Increasing signal strength overcomes noise
- Signal-to-noise ratio:

$$SNR = \frac{signalpower}{noisepower}$$

- Shannon capacity:
  - $C = B \log_2(1 + SNR)$
- Tradeoffs:
  - Increase bandwidth or signal power, increases data rate
  - Increase of noise, reduces data rate
  - Increase bandwidth, allows more noise
  - Increase signal power, causes increased intermodulation noise

- We have a channel with a 1-MHz bandwidth. The SNR for this channel is 63. What are the appropriate/maximum bit rate and signal level?
- Solution
- First, we use the Shannon formula to find the upper limit.

$$C = B \log_2 (1 + \text{SNR}) = 10^6 \log_2 (1 + 63) = 10^6 \log_2 64 = 6 \text{ Mbps}$$

For better performance we choose something lower, 4 Mbps, for example.
Then we use the Nyquist formula to find the number of signal levels.

- $4\text{Mbps} = 2*1\text{Mbps}* \log_2 M$
- $M = 4\text{levels}$

- We need to send 265 kbps over a noiseless channel with a bandwidth of 20 kHz. How many signal levels do we need?

$$265{,}000 = 2 \times 20{,}000 \times \log_2 L$$

$$\log_2 L = 6.625 \qquad L = 2^{6.625} = 98.7 \text{ levels}$$

- Since this result is not a power of 2, we need to either increase the number of levels or reduce the bit rate.
- If we have 128 levels, the bit rate is 280 kbps.
- If we have 64 levels, the bit rate is 240 kbps.

- Consider an extremely noisy channel in which the value of the signal to noise ratio is almost zero. In other words, the noise is so strong that the signal is faint. Find the channel capacity C.

$$C = B \log_2 (1+SNR)$$
$$C = B \log_2 (1+0)$$
$$C = B \times 0 = 0$$

- This means that the capacity of this channel is zero regardless of the bandwidth. In other words, we cannot receive any data through this channel.

Example of Shannon and Nyquist Capacity

A channel uses spectrum of between 3MHz and 4MHz, with $SNR_{dB} = 24dB$. How many signal levels are required to achieve Shannon capacity?