EXAMPLES OF ANALOG AND DIGITAL DATA

- Analog
  - Video
  - Audio
- Digital
  - Text
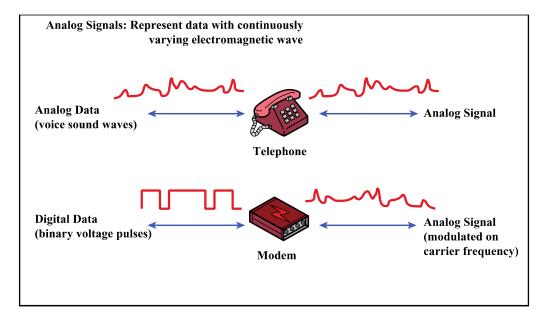 - Integers

ANALOG SIGNALS

- A continuously varying electromagnetic wave that may be propagated over a variety of media, depending on frequency

- Examples of media:
  - Copper wire media (twisted pair and coaxial cable)
  - Fiber optic cable
  - Atmosphere or space propagation

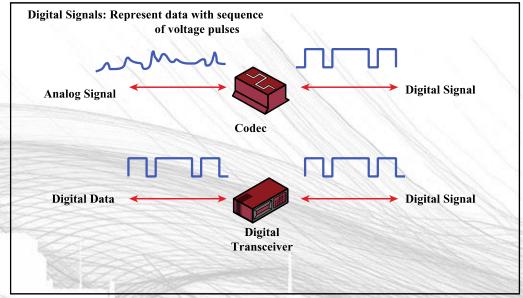- Analog signals can propagate analog and digital data

DIGITAL SIGNALS

- A sequence of voltage pulses that may be transmitted over a copper wire medium
- Generally cheaper than analog signaling
- Less susceptible to noise interference
- Suffer more from attenuation
- Digital signals can propagate analog and digital data

REASONS FOR CHOOSING DATA AND SIGNAL COMBINATIONS

- Digital data, digital signal
  - Equipment for encoding is less expensive than digital-to-analog equipment
- Analog data, digital signal
  - Conversion permits use of modern digital transmission and switching equipment
- Digital data, analog signal
  - Some transmission media will only propagate analog signals
  - Examples include optical fiber and satellite
- Analog data, analog signal
  - Analog data easily converted to analog signal

Analog Signals: Represent data with continuously varying electromagnetic wave

Analog Data (voice sound waves) ←→ Telephone ←→ Analog Signal

Digital Data (binary voltage pulses) ←→ Modem ←→ Analog Signal (modulated on carrier frequency)

Digital Signals: Represent data with sequence of voltage pulses

Analog Signal ←→ Codec ←→ Digital Signal

Digital Data ←→ Digital Transceiver ←→ Digital Signal

2.8 ANALOG AND DIGITAL SIGNALING OF ANALOG AND DIGITAL DATA
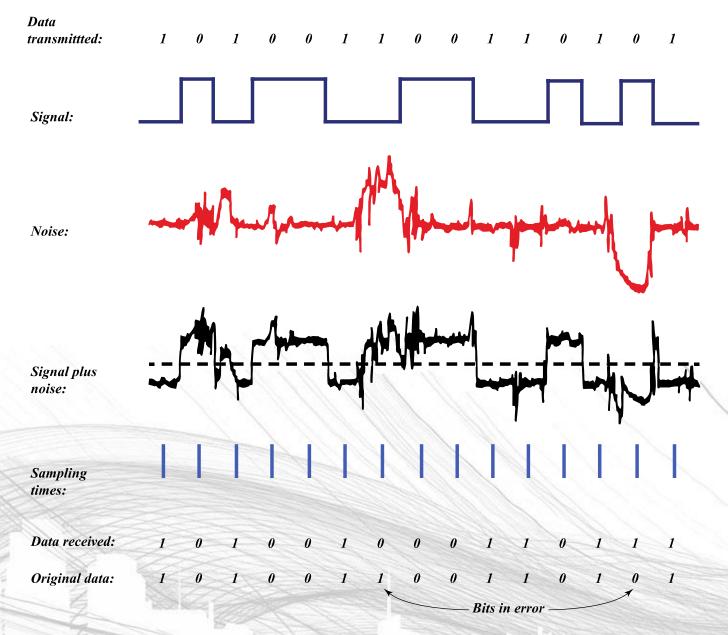
ANALOG TRANSMISSION

- Transmit analog signals without regard to content
- Attenuation limits length of transmission link
- Cascaded amplifiers boost signal's energy for longer distances but cause distortion
  - Analog data can tolerate distortion
  - Introduces errors in digital data

DIGITAL TRANSMISSION

- Concerned with the content of the signal
- Attenuation endangers integrity of data
- Digital Signal
  - Repeaters achieve greater distance
  - Repeaters recover the signal and retransmit
- Analog signal carrying digital data
  - Retransmission device recovers the digital data from analog signal
  - Generates new, clean analog signal

ABOUT CHANNEL CAPACITY

- Impairments, such as noise, limit data rate that can be achieved

- For digital data, to what extent do impairments limit data rate?

- **Channel Capacity – the maximum rate at which data can be transmitted over a given communication path, or channel, under given conditions**

Data transmittted: 1 0 1 0 0 1 1 0 0 1 1 0 1 0 1

Signal:

Noise:

Signal plus noise:

Sampling times:

Data received: 1 0 1 0 0 1 0 0 0 1 1 0 1 1 1

Original data: 1 0 1 0 0 1 1 0 0 1 1 0 1 0 1

Bits in error

2.9 EFFECT OF NOISE ON DIGITAL SIGNAL

CONCEPTS RELATED TO CHANNEL CAPACITY

- Data rate - rate at which data can be communicated (bps)
- Bandwidth - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise - average level of noise over the communications path
- Error rate - rate at which errors occur
  - Error = transmit 1 and receive 0; transmit 0 and receive 1

NYQUIST THEOREM

- Nyquist gives the upper bound for the bit rate of a transmission system by calculating the bit rate directly from the number of bits in a symbol (or signal levels) and the bandwidth of the system (assuming 2 symbols/per cycle and first harmonic).

- Nyquist theorem states that for a noiseless channel:

$$C = 2 \, B \, \log_2 M$$

C= capacity in bps

B = bandwidth in Hz

M = number of discrete signal or voltage levels

3.29

Example 1

Consider a noiseless channel with a bandwidth of 3000 Hz transmitting a signal with two signal levels. The maximum bit rate can be calculated as

$$\text{BitRate} = 2 \times 3000 \times \log_2 2 = 6000 \text{ bps}$$

Example 2

Consider the same noiseless channel transmitting a signal with four signal levels (for each level, we send 2 bits). The maximum bit rate can be calculated as

$$\text{BitRate} = 2 \times 3000 \times \log_2 4 = 12{,}000 \text{ bps}$$

Example 3

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

Solution

We can use the Nyquist formula as shown:

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

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

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.

SIGNAL-TO-NOISE RATIO

- Ratio of the power in a signal to the power contained in the noise that's present at a particular point in the transmission

- Typically measured at a receiver

- Signal-to-noise ratio (SNR, or S/N)

$$(SNR)_{dB} = 10\log_{10}\frac{\text{signal power}}{\text{noise power}}$$

- A high SNR means a high-quality signal, low number of required intermediate repeaters

- SNR sets upper bound on achievable data rate

SHANNON CAPACITY FORMULA

- Equation:

$$C = B \log_2 \left(1 + \mathrm{SNR} \right)$$

- Represents theoretical maximum that can be achieved

- In practice, only much lower rates achieved
  - Formula assumes white noise (thermal noise)
  - Impulse noise is not accounted for
  - Attenuation distortion or delay distortion not accounted for

EXAMPLE OF NYQUIST AND SHANNON FORMULATIONS

- Spectrum of a channel between 3 MHz and 4 MHz ; $SNR_{dB} = 24$ dB

$$B = 4\,\text{MHz} - 3\,\text{MHz} = 1\,\text{MHz}$$

$$SNR_{dB} = 24\,\text{dB} = 10\log_{10}(SNR)$$

$$SNR = 251$$

- Using Shannon's formula

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

EXAMPLE OF NYQUIST AND SHANNON FORMULATIONS

- How many signaling levels are required?

$$C = 2B \log_2 M$$

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

$$4 = \log_2 M$$

$$M = 16$$

Example 4

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. For this channel the capacity C is calculated as

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

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 5

We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000. The signal-to-noise ratio is usually 3162. For this channel the capacity is calculated as

$$C = B \log_2 (1 + \text{SNR}) = 3000 \log_2 (1 + 3162) = 3000 \log_2 3163$$
$$= 3000 \times 11.62 = 34{,}860 \text{ bps}$$

This means that the highest bit rate for a telephone line is 34.860 kbps. If we want to send data faster than this, we can either increase the bandwidth of the line or improve the signal-to-noise ratio.

Example 6

For practical purposes, when the SNR is very high, we can assume that SNR + 1 is almost the same as SNR. In these cases, the theoretical channel capacity can be simplified to

$$C = B \times \frac{SNR_{dB}}{3}$$

For example, we can calculate the theoretical capacity of the previous example as

$$C = 2 \text{ MHz} \times \frac{36}{3} = 24 \text{ Mbps}$$

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Example 7

We have a channel with a 1-MHz bandwidth. The SNR for this channel is 63. What are the appropriate bit rate and signal level?
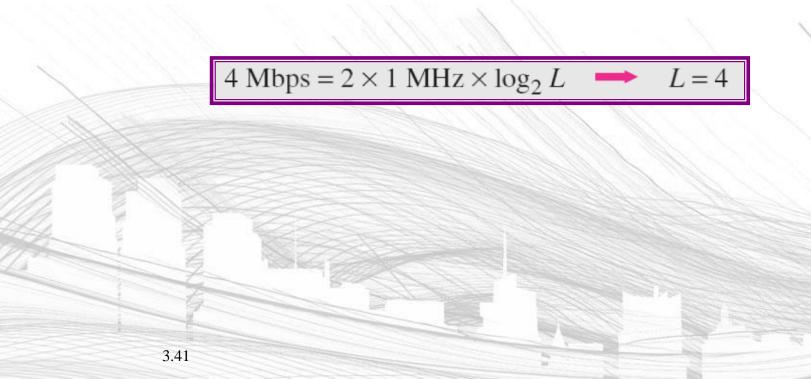
Solution

First, we use the Shannon formula to find the upper limit.

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

Example 7 cont.

The Shannon formula gives us 6 Mbps, the upper limit. For better performance we choose something lower, 4 Mbps, for example. Then we use the Nyquist formula to find the number of signal levels.

$$4 \text{ Mbps} = 2 \times 1 \text{ MHz} \times \log_2 L \quad \longrightarrow \quad L = 4$$

The Shannon capacity gives us the upper limit; the Nyquist formula tells us how many signal levels we need.
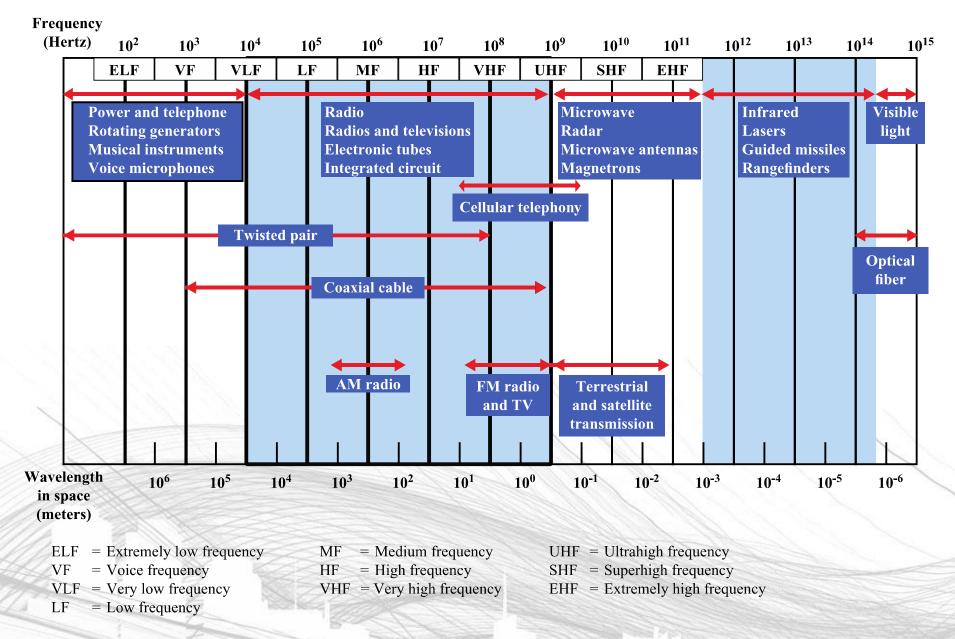
CLASSIFICATIONS OF TRANSMISSION MEDIA

- Transmission Medium
  - Physical path between transmitter and receiver
- Guided Media
  - Waves are guided along a solid medium
  - E.g., copper twisted pair, copper coaxial cable, optical fiber
- Unguided Media
  - Provides means of transmission but does not guide electromagnetic signals
  - Usually referred to as wireless transmission
  - E.g., atmosphere, outer space

UNGUIDED MEDIA

- Transmission and reception are achieved by means of an antenna

- Configurations for wireless transmission
  - Directional
  - Omnidirectional

Frequency (Hertz)

10^2	10^3	10^4	10^5	10^6	10^7	10^8	10^9	10^{10}	10^{11}	10^{12}	10^{13}	10^{14}	10^{15}
ELF	VF	VLF	LF	MF	HF	VHF	UHF	SHF	EHF				

Power and telephone
Rotating generators
Musical instruments
Voice microphones

Radio
Radios and televisions
Electronic tubes
Integrated circuit

Microwave
Radar
Microwave antennas
Magnetrons

Infrared
Lasers
Guided missiles
Rangefinders

Visible light

Cellular telephony

Twisted pair

Optical fiber

Coaxial cable

AM radio

FM radio and TV

Terrestrial and satellite transmission

Wavelength in space (meters)

10^6	10^5	10^4	10^3	10^2	10^1	10^0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}

ELF = Extremely low frequency   MF = Medium frequency   UHF = Ultrahigh frequency
VF = Voice frequency   HF = High frequency   SHF = Superhigh frequency
VLF = Very low frequency   VHF = Very high frequency EHF = Extremely high frequency
LF = Low frequency

2.10 ELECTROMAGNETIC SPECTRUM OF TELECOMMUNICATIONS

TRANSMISSION FUNDAMENTALS 2-45

GENERAL FREQUENCY RANGES

- Microwave frequency range
  - 1 GHz to 40 GHz
  - Directional beams possible
  - Suitable for point-to-point transmission
  - Used for satellite communications
- Radio frequency range
  - 30 MHz to 1 GHz
  - Suitable for omnidirectional applications
- Infrared frequency range
  - Roughly, 3×10^{11} to 2×10^{14} Hz
  - Useful in local point-to-point multipoint applications within confined areas

TERRESTRIAL MICROWAVE

- Description of common microwave antenna
  - Parabolic "dish", 3 m in diameter
  - Fixed rigidly and focuses a narrow beam
  - Achieves line-of-sight transmission to receiving antenna
  - Located at substantial heights above ground level
- Applications
  - Long haul telecommunications service
  - Short point-to-point links between buildings
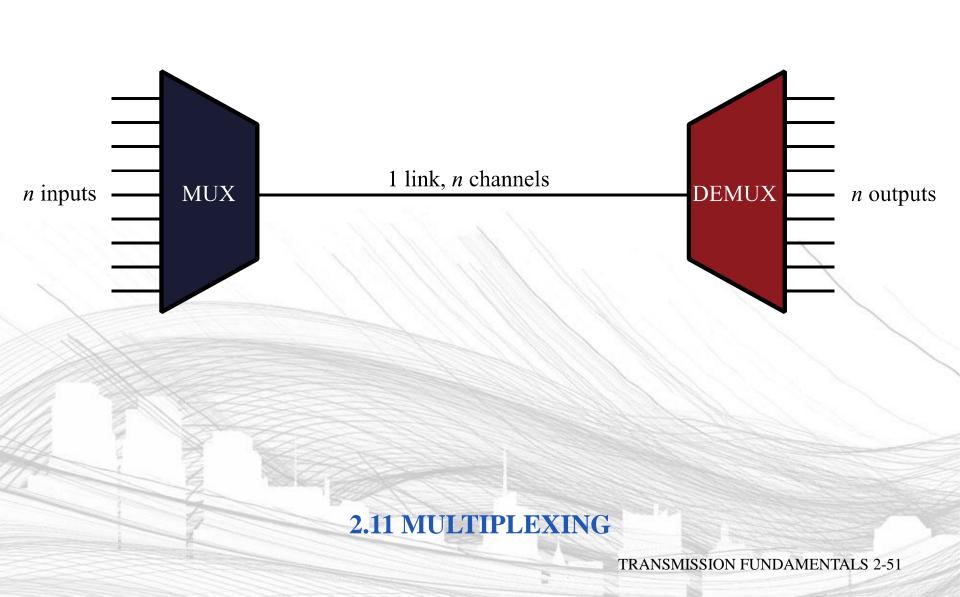
SATELLITE MICROWAVE

- Description of communication satellite
  - Microwave relay station
  - Used to link two or more ground-based microwave transmitter/receivers
  - Receives transmissions on one frequency band (uplink), amplifies or repeats the signal, and transmits it on another frequency (downlink)
- Applications
  - Television distribution
  - Long-distance telephone transmission
  - Private business networks

BROADCAST RADIO

- Description of broadcast radio antennas
  - Omnidirectional
  - Antennas not required to be dish-shaped
  - Antennas need not be rigidly mounted to a precise alignment
- Applications
  - Broadcast radio
    - VHF and part of the UHF band; 30 MHZ to 1GHz
    - Covers FM radio and UHF and VHF television

MULTIPLEXING

- Capacity of transmission medium usually exceeds capacity required for transmission of a single signal

- Multiplexing - carrying multiple signals on a single medium
  - More efficient use of transmission medium

n inputs

MUX

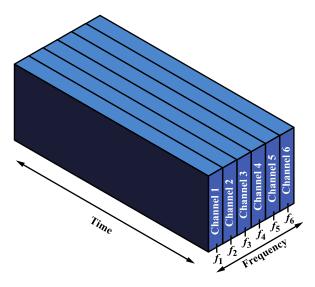1 link, n channels

DEMUX

n outputs

2.11 MULTIPLEXING

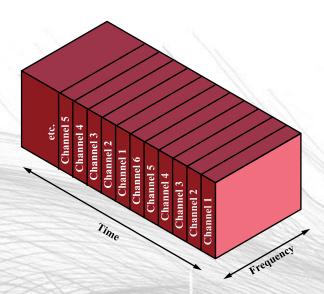# REASONS FOR WIDESPREAD USE OF MULTIPLEXING

- Cost per kbps of transmission facility declines with an increase in the data rate

- Cost of transmission and receiving equipment declines with increased data rate

- Most individual data communicating devices require relatively modest data rate support

MULTIPLEXING TECHNIQUES

- Frequency-division multiplexing (FDM)
  - Takes advantage of the fact that the useful bandwidth of the medium exceeds the required bandwidth of a given signal

- Time-division multiplexing (TDM)
  - Takes advantage of the fact that the achievable bit rate of the medium exceeds the required data rate of a digital signal
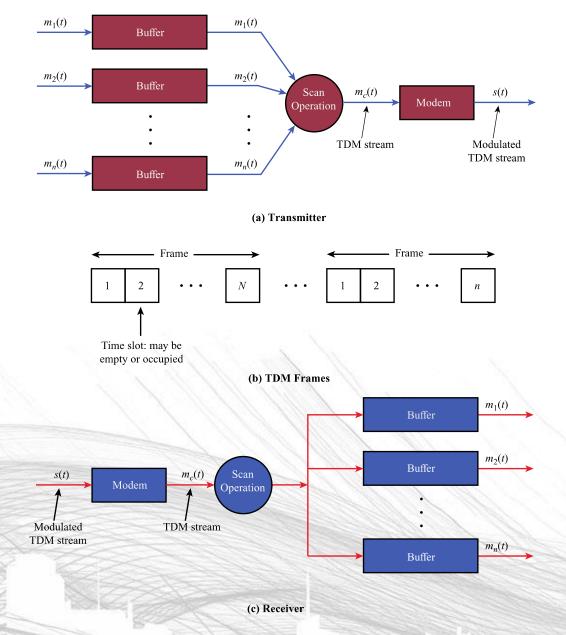
(a) Frequency division multiplexing

(b) Time division multiplexing

2.12 FDM AND TDM

(a) Transmitter

(b) TDM Frames

(c) Receiver

2.13 SYNCHRONOUS TDM SYSTEM