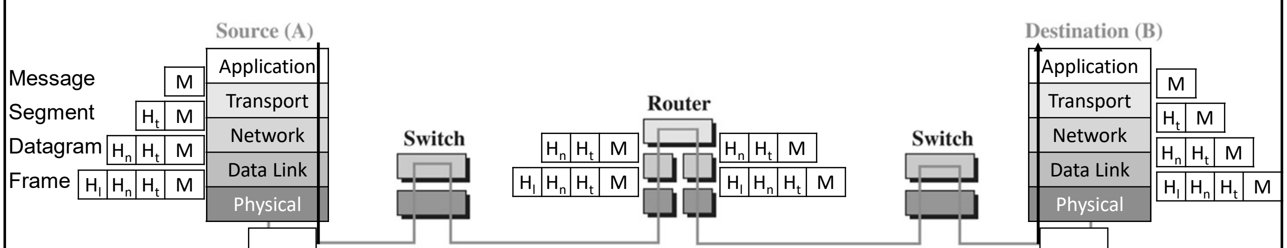
Welcome!

ELEC 8560 – Computer Networks

Physical Layer

1

Recall: End-to-End Communication via Internet



2

Outline

- Signals
- Signal impairments
- Performance
- Data transmission
- Bandwidth utilization: Multiplexing
- Transmission media

- Recommended reading: Forouzan – Chapter 2
- Extra reading: Kurose and Ross – Chapter 1

Outline

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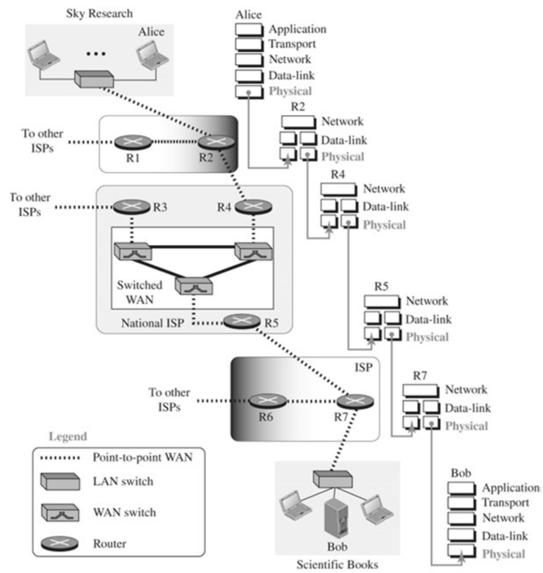
Communication at the Physical Layer

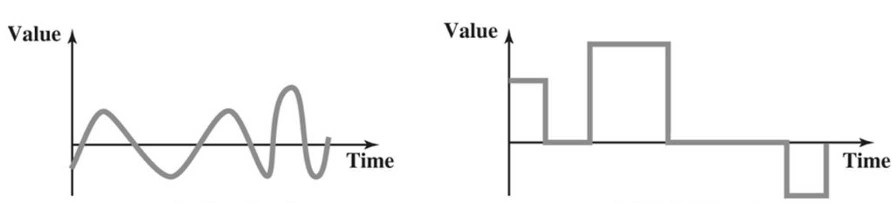
- Physical layer provides services to the data link layer
  - Put bits of the frames from data link layer “on the wire”
- Example:
  - Alice on Sky Research LAN →
  - LAN switch →
  - R2 in an ISP network →
  - Point-to-point WAN to R4 in a national ISP network →
  - R5 through a switched WAN network →
  - R7 in an ISP network →
  - LAN switch in Scientific Books LAN →
  - Mainframe represents Bob



Data Flow Diagram

Signals

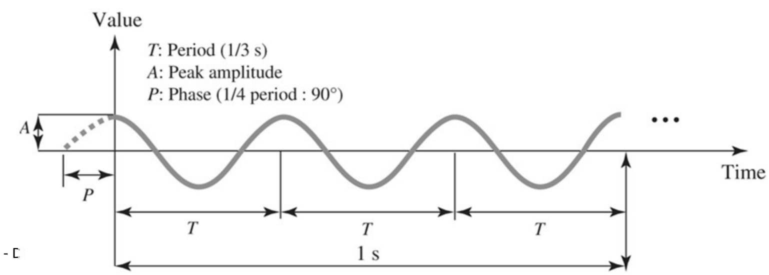
- What is exchanged between Alice and Bob is data, but what goes through the network at the physical layer is signals
- Signals can be analog or digital
  - Analog signals can have an infinite number of values in a range
  - Digital signals can have only a limited number of values



a. Analog signal b. Digital signal

Example: Analog Signals

- Sinusoidal signals are analog and periodic
- Peak amplitude (*A*): absolute value of its highest intensity
- Period (*T*): amount of time, in seconds, to complete one cycle
- Frequency (*f*): number of periods in one second), measured in Hz
- Phase (*P*): position of the waveform relative to time 0
- Wavelength (λ): distance, in meters, a signal travels in one period

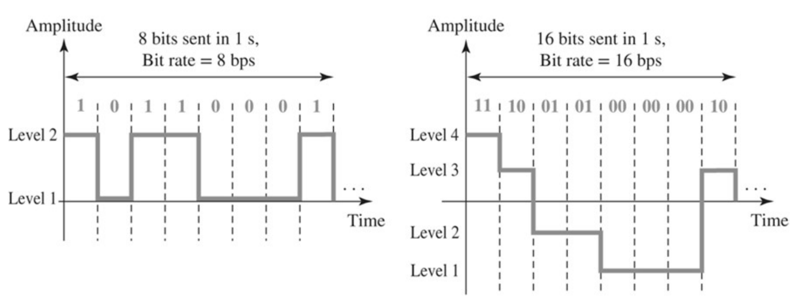


Example: Digital Signals

- Amplitude is limited to a finite set of values
- Number of levels (*L*) depends on the number of bits per symbol (*r*)

$$L = 2^r \quad \leftrightarrow \quad r = \log_2 L$$

- Bit Length (T_b): time duration of one bit, measured in seconds



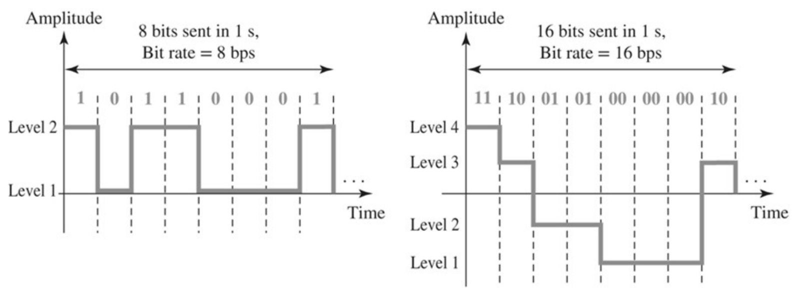
a. A digital signal with two levels

b. A digital signal with four levels

Example: Digital Signals (cont.)

- Bit rate (*N*): number of bits (data elements) sent in 1 second, measured in bps
- Baud (signal) rate (*S*): number of symbols (signal elements) sent in 1 second, measured in baud or sample per second

$N = 1/T_b$ $\qquad\qquad$ $S = N/r$



a. A digital signal with two levels

b. A digital signal with four levels

Example 1: Bit Rate

Assume we download a text document at the rate of 100 pages per second. A page is an average of 24 lines with 80 characters per line. If we assume that one character requires 8 bits, what is the bit rate?

Solution:

Bit rate = 100 × 24 × 80 × 8 = 1,536,000 bps = 1.536 Mbps

Example 2: Bit Rate

What is the bit rate for high-definition TV (HDTV)? Assume 1920 × 1080 frame resolution, 30 frames per sec, and 24 bits per pixel.

Solution:

$$\text{Bit rate} = 30 \times 1920 \times 1080 \times 24 = 1{,}492{,}992{,}000 \text{ bps} \approx 1.493 \text{ Gbps}$$

- TV stations reduce this rate to 20 to 40 Mbps through compression

Example 3: Bit Rate

A signal carries 4 bits per signal element. If 1000 signal elements are sent per second, find the bit rate.

Solution:

- In this case, $r = 4$, $S = 1000$, and N is unknown
- We can find the value of N from:

$$S = N \times (1/r) \rightarrow N = 1000 \times 4 = 4000 \text{ bps}$$

Example 4: Bit Rate

A signal has a bit rate of 8000 bps and a baud rate of 1000 baud. How many data elements are carried by each signal element? How many signal elements do we need?

Solution:

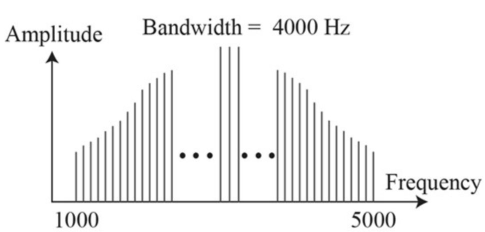
- In this example, S = 1000, N = 8000, and r and L are unknown
- We first find the value of r and then the value of L

$$S = N \times (1/r) \rightarrow r = 8000 / 1000 = 8 \text{ bits/baud}$$

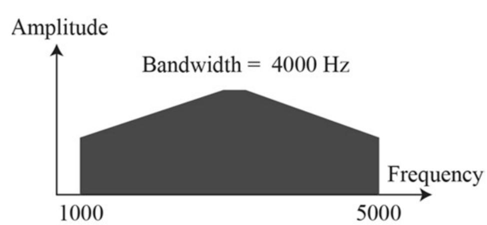
$$r = \log_2 L \rightarrow L = 2^r = 2^8 = 256$$

Bandwidth

- The bandwidth of a signal is the range of frequencies contained in a signal
- We usually use the frequency-domain to find the bandwidth



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

Example: Bandwidth

A periodic signal has a bandwidth of 20 Hz. The highest frequency is 60 Hz. What is the lowest frequency?

Solution:

$$B = f_{high} - f_{low} \rightarrow f_{low} = 40\ Hz$$

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Signal Impairments

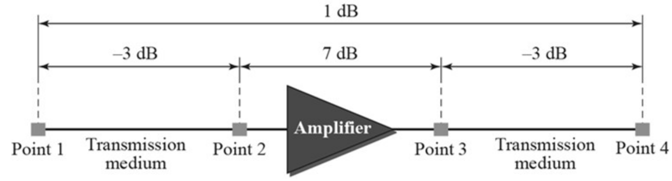
- Transmission media are not perfect → Impairment
- Signal at the beginning of the medium is not the same as the signal at the end of the medium due to:
  - Attenuation: Loss of energy over distance → amplification
  - Distortion: Changes in signal form or shape
  - Noise: Randomness introduced in the medium

Example: Attenuation

Suppose a signal travels through a transmission medium and its power is reduced to one half. Calculate the attenuation is dB.

Solution:

$$\text{Attenuation} = 10 \log_{10} P_2/P_1 = 10 \log_{10} 0.5 = -3 \text{ dB}$$

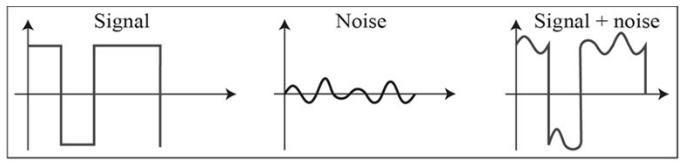


Example: Noise

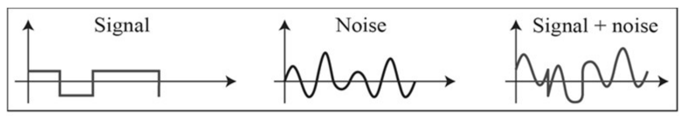
The power of a signal is 10 mW and the power of the noise is 1 μW, what are the values of SNR and SNR_{dB}?

Solution:

$$SNR = 10\ mW/1\ \mu W = 10{,}000 \rightarrow SNR_{dB} = 10 \log_{10} 10{,}000 = 40\ dB$$



a. High SNR



b. Low SNR

Data Rate Limits

Given a channel, how fast can we send data, in bits per second?

- It depends on:
  - The bandwidth available
  - The level of the signals we use
  - The quality of the channel (the level of noise)
- Nyquist bit rate for a noiseless channel:
  - theoretical max rate without noise

$$R = 2B \log_2 L$$

- Shannon capacity for a noisy channel:
  - theoretical max rate with noise

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

Example: Noiseless Channel

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

Solution:

$$R = 2B \log_2 L \rightarrow 265{,}000 = 2 \times 20{,}000 \times \log_2 L \rightarrow L = 2^{6.625} = 98.7 \text{ levels}$$

- 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

Example: Noisy Channel

Calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000 Hz (300 to 3300 Hz) assigned for data communications. The signal-to-noise ratio is usually 35 dB.

Solution:

$$C = B \log_2(1+\text{SNR}) = 3000 \log_2(1+10^{3.5}) = 34{,}881 \text{ bps}$$

- This means 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: Using Both Limits

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:

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

- 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:

$$R = 2B \log_2 L \rightarrow 4 \times 10^6 = 2 \times 10^6 \times \log_2 L \rightarrow L = 2^2 = 4 \text{ levels}$$

Shannon capacity gives us the upper limit; the Nyquist formula tells us how many signal levels we need

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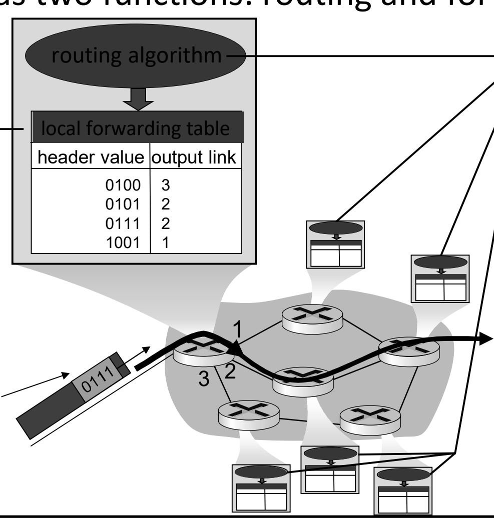
Performance

- One important issue in networking is the performance of the network, i.e., how good is it?
- Many metrics are used:
  - Bandwidth
  - Throughput
  - Latency (or Delay)
  - Bandwidth-delay product
  - Jitter
  - Packet loss
  - and more ..

Packet Switching

- Hosts break application-layer messages into packets
- Network core has two functions: routing and forwarding

Forwarding (or switching):
Local action: move arriving packets from router input link to appropriate router output link

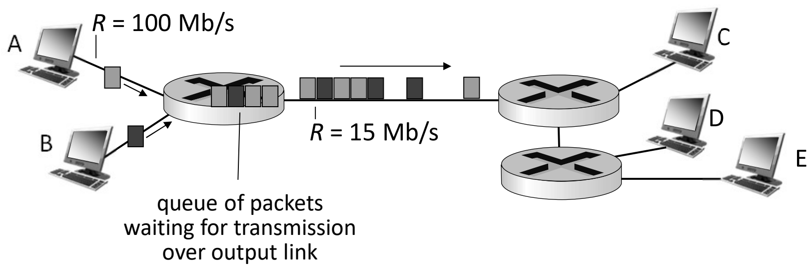


destination address in arriving packet's header

Routing:
Global action: determine source-destination paths taken by packets using routing algorithms

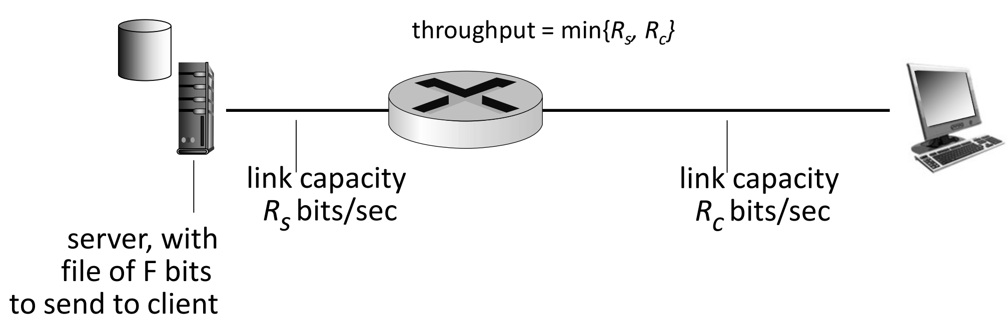
Packet Switching (cont.)

- Store and forward: entire packet must arrive at router before it can be transmitted on next link
- Queueing occurs when packets arrives faster than it can be serviced



Bandwidth vs. Throughput

- Bandwidth is how much data could theoretically be transferred from a source at any given time, measured in bps
- Throughput is how much data was actually transferred from a source at any given time, measured in bps



Example: Bandwidth vs. Throughput

A network with bandwidth of 10 Mbps can pass only an average of 12,000 frames per minute with each frame carrying an average of 10,000 bits. What is the throughput of this network?

Solution:

$$\text{Throughput} = 12{,}000 \times 10{,}000 / 60 = 2 \text{ Mbps}$$

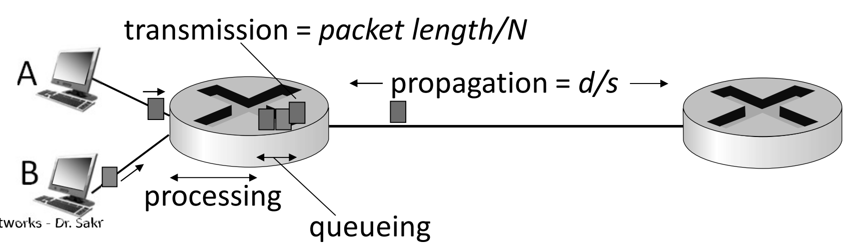
- Throughput is almost one-fifth of the bandwidth in this case

Latency (or Delay)

- How long it takes for an entire message to completely arrive at the destination from the time the first bit is sent out from the source
- Four types of delay:

Latency = propagation delay + transmission delay + queuing delay + processing delay

- Packet loss occurs when queue is full (arrival rate > transmission rate)



Example: Delay

What are the propagation time and the transmission time for a 5-MB (megabyte) message (an image) if the bandwidth of the network is 1 Mbps? Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4×10^8 m/s.

Solution:

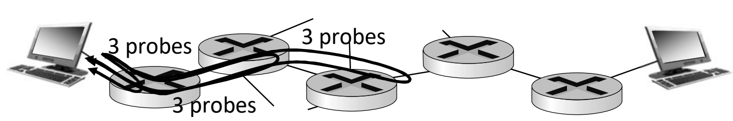
$$\text{Propagation time} = 12{,}000 \times 1000 / (2.4 \times 10^8) = 50 \text{ ms}$$

$$\text{Transmission time} = 5 \times 8 \times 10^6 / 10^6 = 40 \text{ s}$$

- A bit can go over the Atlantic Ocean in only 50 ms if there is a direct cable between the source and the destination
- Because the message is long and the bandwidth is low, the dominant factor is the transmission time, not the propagation time
- Repeat for a 2.5 KB message

Internet Delays

- traceroute program provides delay measurement from source to router along end-end Internet path towards destination
- For all R_i:
  - sends three packets that will reach router *i* on path towards destination (with time-to-live field value of R_i)
  - router R_i will return packets to sender
  - sender measures time interval between transmission and reply



Demo: Internet Delays

- In Windows, open the Command Prompt window and enter “tracert eurecom.fr”

```
C:\Users\admin>tracert eurecom.fr

Tracing route to eurecom.fr [193.55.113.222]
over a maximum of 30 hops:

  6    22 ms    22 ms    22 ms  tcore4-toronto12_39.net.bell.ca [64.230.52.178]
  7     *        *        *     Request timed out.
  8    27 ms    23 ms    22 ms  tcore4-chicagocp-bundle-ether15.net.bell.ca [142.124.127.174]
  9    20 ms    20 ms    21 ms  bx10-chicagodt_ae1.net.bell.ca [64.230.78.175]
 10    28 ms    24 ms    25 ms  bx10-chicagodt_et-8/1/2_ae8.net.bell.ca [184.150.181.36]
 11   116 ms   113 ms   115 ms  et-3-3-0.cr2-par7.ip4.gtt.net [213.200.119.214]
 12   113 ms   113 ms   114 ms  renater-gw-th2.gtt.net [77.67.123.210]
 13   119 ms   120 ms   119 ms  te-0-1-0-14-ren-nr-lyon2-rtr-091.noc.renater.fr [193.51.180.55]
 14   120 ms   120 ms   120 ms  xe-0-0-14-marseille2-rtr-131.noc.renater.fr [193.51.180.105]
 15   118 ms   117 ms   117 ms  xe-1-0-10-marseille1-rtr-131.noc.renater.fr [193.51.180.121]
 16   122 ms   124 ms   122 ms  te0-2-0-0-ren-nr-sophia-rtr-091.noc.renater.fr [193.51.177.21]
 17   122 ms   122 ms   122 ms  eurocom-valbonne-gi9-7-sophia-rtr-021.noc.renater.fr [193.51.187.17]
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ic link

Jitter

- Jitter occurs when different packets encounter different delays and the application using the data at the receiver site is time-sensitive (e.g., audio and video data)

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- Signals
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Data Transmission

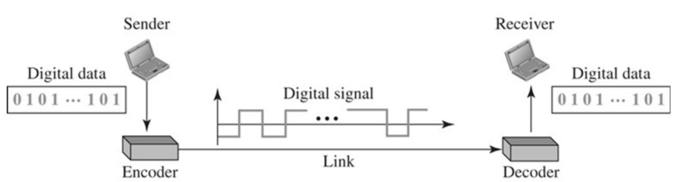
- Data can be either digital or analog
- A computer network is designed to send information from one point to another
- Digital transmission:
  - Analog or digital signals
  - Desirable and less susceptible to noise but requires a low-pass channel
- Analog transmission:
  - Analog or digital signals
  - Better for a bandpass channel

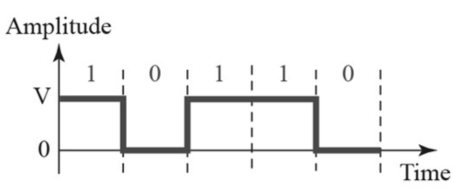
Digital Transmission of Digital Signals

- Digital-to-Digital Conversion is the process of representing digital data using digital signals:
  - Line coding
  - Block coding
  - Scrambling
- Digital data can be in the form of text, numbers, graphical images, audio, or video, are stored in computer memory as sequences of bits

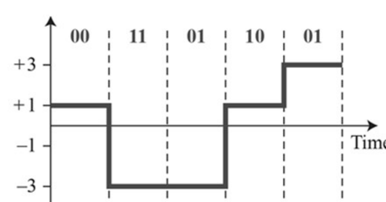
Line Coding

- Line coding: process of converting a sequence of bits to a digital signal
  - Examples: NRZ, NRZ-L, NRZ-I, 2B1Q, etc.





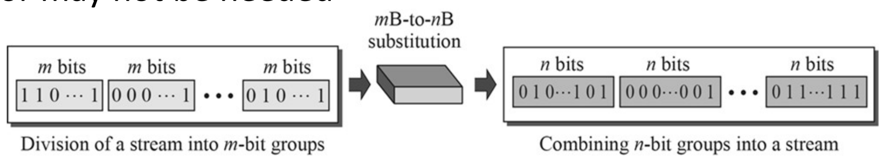
Unipolar NRZ scheme



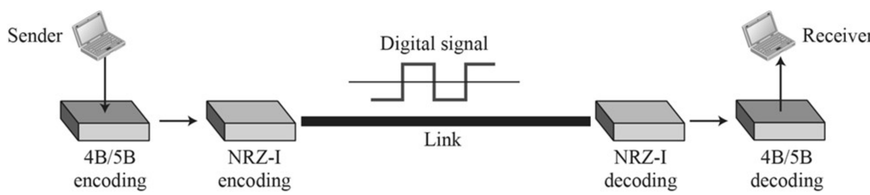
Multilevel scheme

Block Coding

- Block coding adds redundancy to improve the performance of line coding (e.g., synchronization, error detection, etc.)
- May or may not be needed



mB/nB Encoding: Block of m bits → Block of n bits



Scrambling

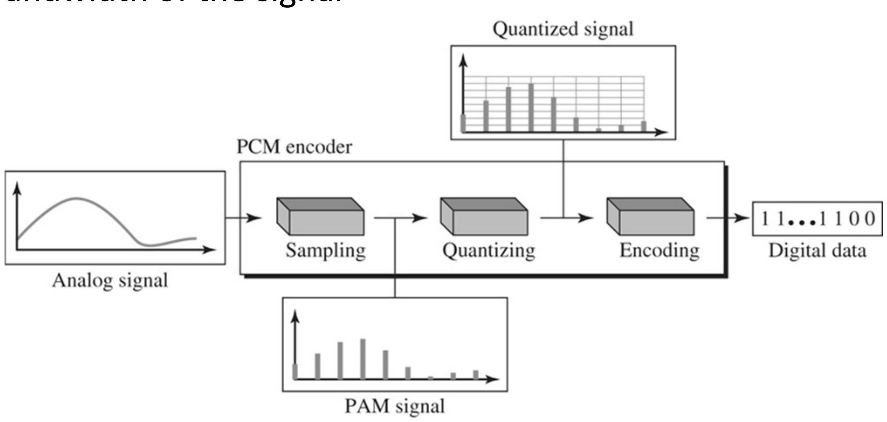
- Provides synchronization by avoiding long sequences of 0s
  - Substitutes long zero-level pulses with a combination of other levels
- Does not increase number of bits (or bit rate)

Digital Transmission of Analog Signals

- Analog-to-Digital Conversion is the process of representing analog signals using digital signals:
  - Pulse Code Modulation (PCM)
  - Delta Modulation (DM)
- Analog signals can be created by a microphone or camera

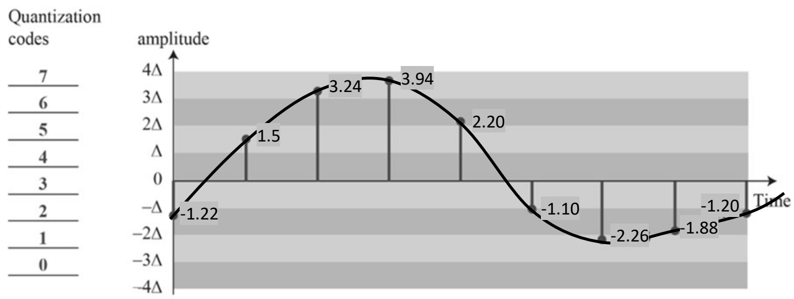
Pulse Code Modulation (PCM)

- PCM: Sampling at $f_s=1/T_s$ → Quantization to L levels → Encoding
- Nyquist Theorem: Sampling frequency f_s needs to be at least twice the bandwidth of the signal



Example 1: PCM

- PCM with $r=3$ and $L=8$ → $\Delta=(V_{max}-V_{min})/L$



PAM values	−1.22	1.50	3.24	3.94	2.20	−1.10	−2.26	−1.88	−1.20
quantized values	−1.50	1.50	3.50	3.50	2.50	−1.50	−2.50	−1.50	−1.50
error	−0.28	0	+0.26	−0.44	+0.30	−0.40	−0.24	+0.38	−0.30
Quantization code	**2**	**5**	**7**	**7**	**6**	**2**	**1**	**2**	**2**
Encoded words	**010**	**101**	**111**	**111**	**110**	**010**	**001**	**010**	**010**

Example 2: PCM

We want to digitize the human voice. What is the bit rate, assuming 8 bits per sample and human voice has a bandwidth of 4 kHz?

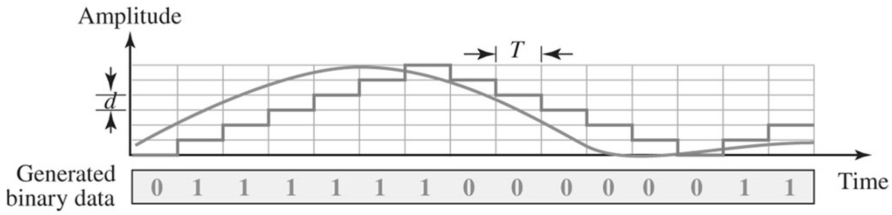
Solution:

Sampling rate = 2 × 4000 = 8000 samples per sec

Bit rate = 8000 × 8 = 64 kbps

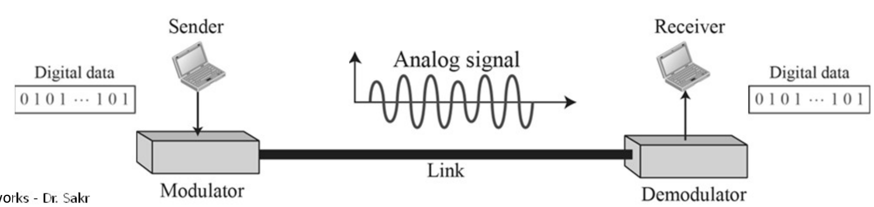
Delta Modulation (DM)

- DM is a less complex variant of PCM
- DM encodes the change from the previous sample (0 or 1)



Analog Transmission of Digital Data

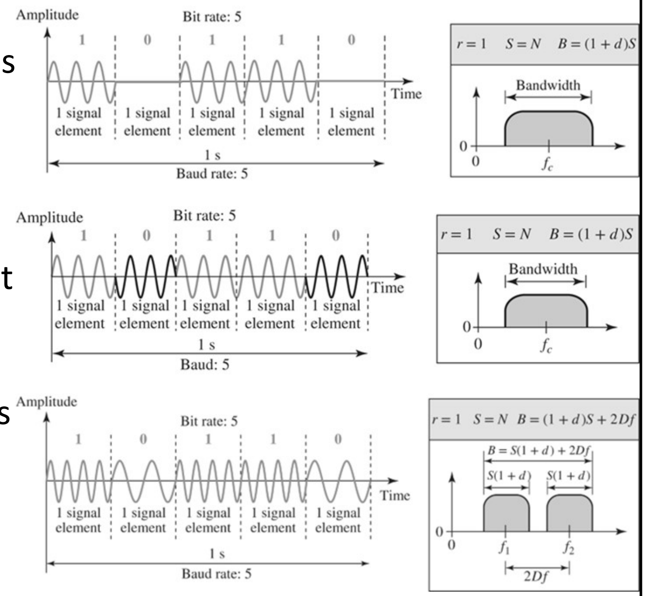
- Digital-to-Analog Conversion is the process of converting digital data to a bandpass analog signal
- This is done by changing one of the characteristics of an analog signal based on the information in digital data:
  - Amplitude Shift Keying (ASK)
  - Phase Shift Keying (PSK)
  - Frequency Shift Keying (FSK)
  - Quadrature Amplitude Modulation (QAM)



d: constant [0,1]
f_c: carrier frequency

Digital Modulation

- Amplitude Shift Keying (ASK) varies amplitude of carrier signal to represent digital data
  - 4-ASK, 8-ASK, ..
- Phase Shift Keying (PSK) varies phase of carrier signal to represent digital data
  - QPSK, 8-PSK, ..
- Frequency Shift Keying (FSK) varies frequency of carrier signal to represent digital data
  - 4-FSK, 8-FSK, ..



Example: ASK

We have an available bandwidth of 100 kHz which spans from 200 to 300 kHz. What are the carrier frequency and the bit rate if we modulated our data by using ASK with d = 1?

Solution:

- The middle of the bandwidth is located at 250 kHz → f_c = 250 kHz
- We can use the formula for bandwidth to find the bit rate (with d = 1 and r = 1)

$$B = (1 + d) \times S = 2 \times N \times (1/r) = 100 \text{ kHz} \rightarrow N = 50 \text{ kbps}$$

Bit rate N is the number of bits per second

Baud rate S is the number of signal elements per second

Example: PSK

Find the bandwidth for a signal transmitting at 12 Mbps for QPSK. The value of d = 0.

Solution:

- For QPSK, 2 bits are carried by one signal element → $r = 2$
- So, the signal rate (baud rate) is $S = N \times (1/r)$ = 6 Mbaud
- With a value of $d = 0$, we have $B = S$ = 6 MHz

Example: FSK

We have an available bandwidth of 100 kHz which spans from 200 to 300 kHz. What should be the carrier frequency and the bit rate if we modulated our data by using FSK with d = 1? Assume 2Df = 50 kHz.

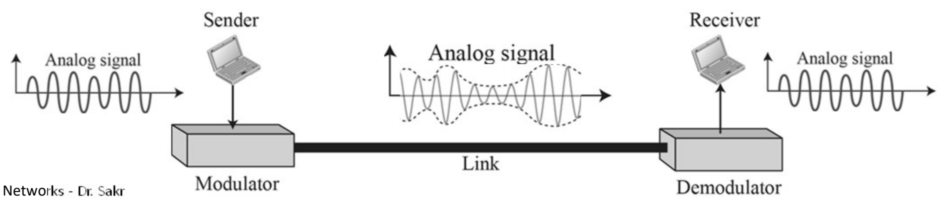
Solution:

- The midpoint of the band is at 250 kHz

$$B = (1 + d) \times S + 2Df = 100 \rightarrow S = 25 \text{ kbaud} \rightarrow N = 25 \text{ kbps}$$

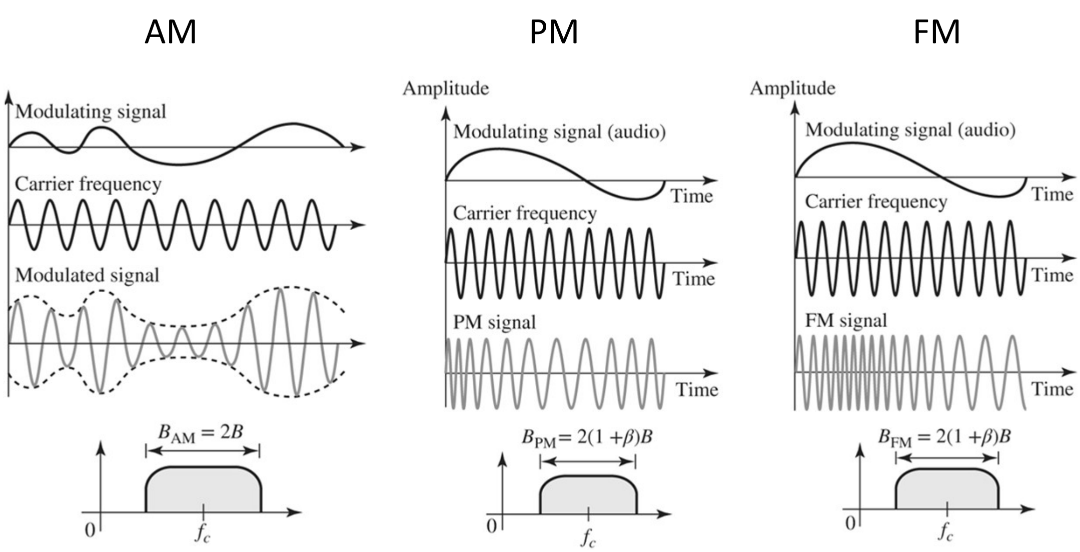
Analog Transmission of Analog Signals

- Analog-to-Analog Conversion is the process of converting analog data to a bandpass analog signal
- This is done by changing one of the characteristics of an analog signal based on the information in analog data:
    - Amplitude Modulation (AM)
    - Phase Modulation (PM)
    - Frequency Modulation (FM)



β: deviation ratio
f_c: carrier frequency

Analog Modulation



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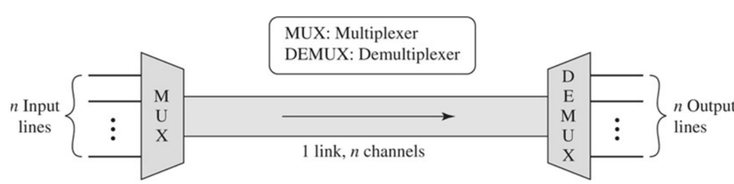
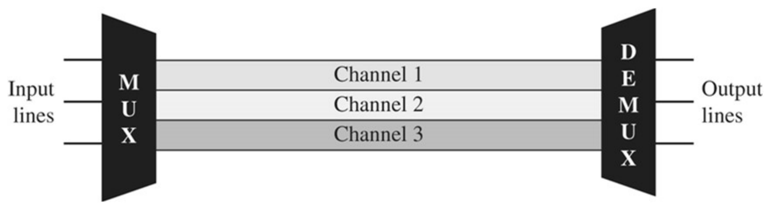
Bandwidth Utilization: Multiplexing

- In practice, communication links have limited bandwidths
  - Bandwidth is one of the most scarce resource in data communication
  - If the bandwidth of a link is greater than needed of devices, it is wasted
- Multiplexing is a set of techniques that allows the simultaneous transmission of multiple signals across a single data link:
  - Frequency-Division Multiplexing (FDM)
  - Time-Division Multiplexing (TDM)
  - Wavelength-Division Multiplexing (WDM)



Frequency-Division Multiplexing (FDM)

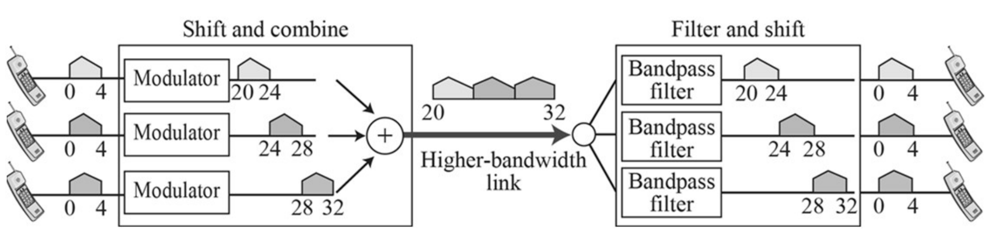
- FDM is an analog technique that can be applied when the bandwidth of a link is greater than the combined bandwidth of the signals to be transmitted together
- Signals generated by each user modulate different carrier signal, then combined into a single composite signal



Example 1: FDM

Assume a voice channel occupies a bandwidth of 4 kHz. We need to combine three voice channels into a link with a bandwidth of 12 kHz, from 20 to 32 kHz. Show the configuration, using the frequency domain. Assume there are no guard bands.

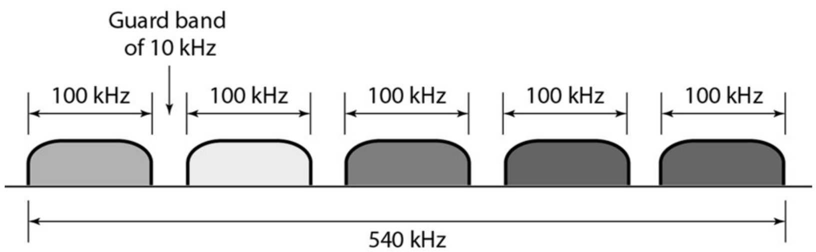
Solution:



Example 2: FDM

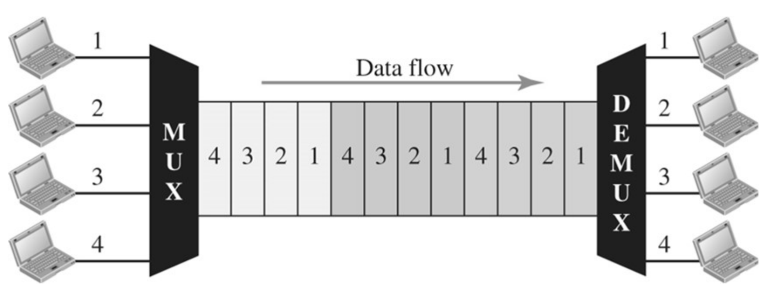
Five channels, each with a 100-kHz bandwidth, are to be multiplexed together. What is the minimum bandwidth of the link if there is a need for a guard band of 10 kHz between the channels to prevent interference?

Solution:



Time-Division Multiplexing (TDM)

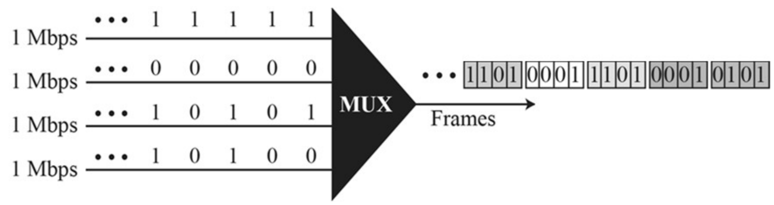
- TDM is a digital technique that allows several connections to share the high bandwidth of a link
  - In other words, combines several low-rate channels into one high-rate one
- Each connection occupies a portion of time in the link



Example: TDM

For the TDM system below, Find (a) the input bit duration, (b) the output bit duration, (c) the output bit rate, and (d) the output frame rate.

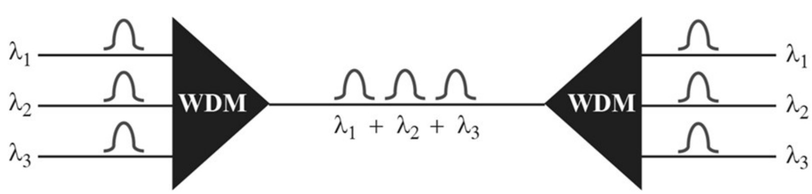
Solution:



- Input bit duration = 1/1 Mbps = 1μs
- Output bit duration = 0.25 μs
- Output bit rate = 1/0.25 μs = 4 Mbps
- Output frame rate = 4 Mbps/4 bits per frame = 1,000,000 frames per sec

Wavelength-Division Multiplexing (WDM)

- WDM is an analog technique used for fiber-optic cable to combine several signals into one line
- Each connection has different wavelength
  - The combining and splitting of light sources are easily done by a prism
  - Multiple light sources are combined into one single light source at the multiplexer, and do the reverse at the demultiplexer

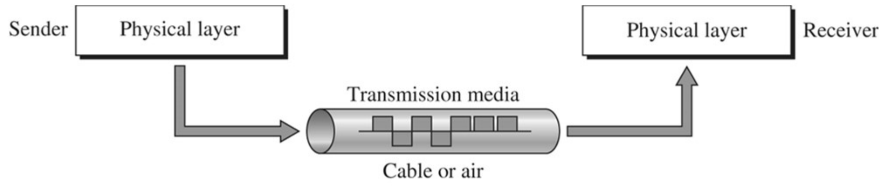


Outline

- Signals
- Signal impairments
- Performance
- Data transmission
- Bandwidth utilization: Multiplexing
- Transmission media

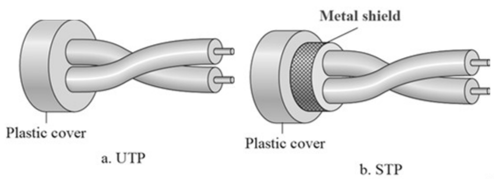
Transmission Media

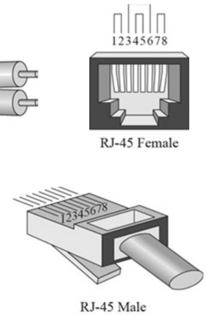
- Transmission media are located below the physical layer and are directly controlled by the physical layer (Layer 0?)
  - Guided Media: provide a wired conduit from one device to another, include twisted-pair, coaxial, and fiber-optic cables
  - Unguided Media: transport electromagnetic wireless waves without using a physical conductor

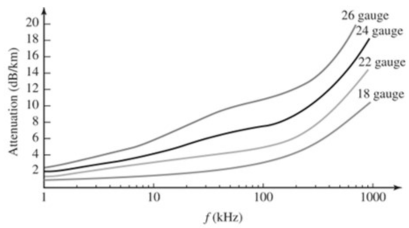


Twisted-Pair Cable

- Two conductors, each with its own plastic insulation, twisted together







Category	Maximum Bandwidth	Maximum Data Rate	Maximum Distance Supported
Cat1	0.4 MHz	1 Mbps	--
Cat2	4 MHz	4 Mbps	--
Cat3	16 MHz	10 Mbps	100 meters
Cat4	20 MHz	16 Mbps	100 meters
Cat5	100 MHz	100 Mbps	100 meters
Cat5e	100 MHz	1 Gbps	100 meters
Cat6	250 MHz	1 Gbps	100 meters 37 meters for 10 Gb data rates
Cat6a	500 MHz	10 Gbps	100 meters
Cat7	600 MHz	10 Gbps	100 meters
Cat7a	1,000 MHz (1 GHz)	10 Gbps	100 meters 50 meters for 40 Gb data rates
Cat8	200 MHz (2 GHz)	Cat8.1: 25 Gbps Cat8.2: 40 Gbps	30 meters

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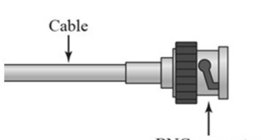
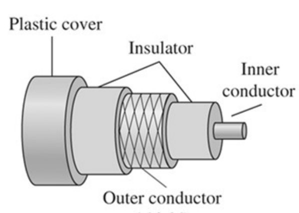
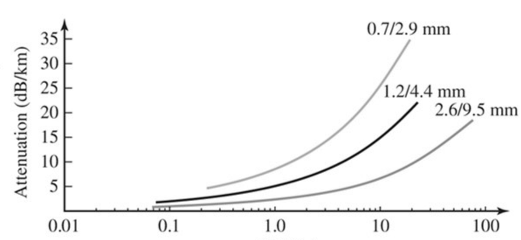
Coaxial Cable

- A central core conductor of solid or stranded wire enclosed in an insulating sheath, which is encased in an outer conductor of metal foil, braid, or a combination of the two
- Outer metallic wrapping serves both as a shield against noise and as the second conductor
- Carries broadband signals of higher frequency ranges vs. twisted-pair

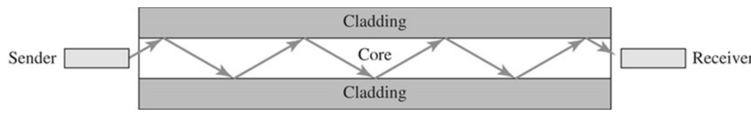


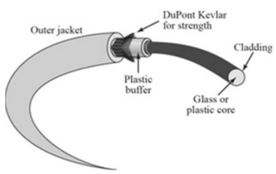


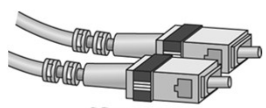


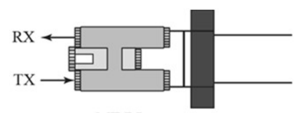
Fiber-Optic Cable

- Glass or plastic fiber, transmits signal in the form of light, high-speed
- Uses the nature of light:
  - Light travels in a straight line as long as it is moving through a single uniform substance
  - If a light traveling in a substance enters another substance (of a different density), the ray changes direction



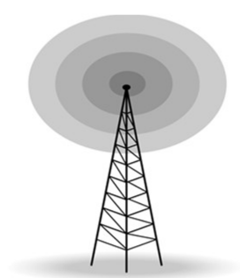


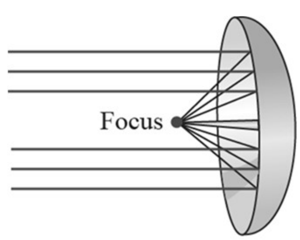




Unguided Media: Wireless Communication

- Signals are broadcast through free space and are available to anyone who has a device capable of receiving them
- Radio waves: omnidirectional, ranging between 3 kHz and 1 GHz
- Microwaves: unidirectional, ranging between 1 and 300 GHz
- Infrared: short-range, cannot penetrate walls, ranging between 300 GHz and 400 THz

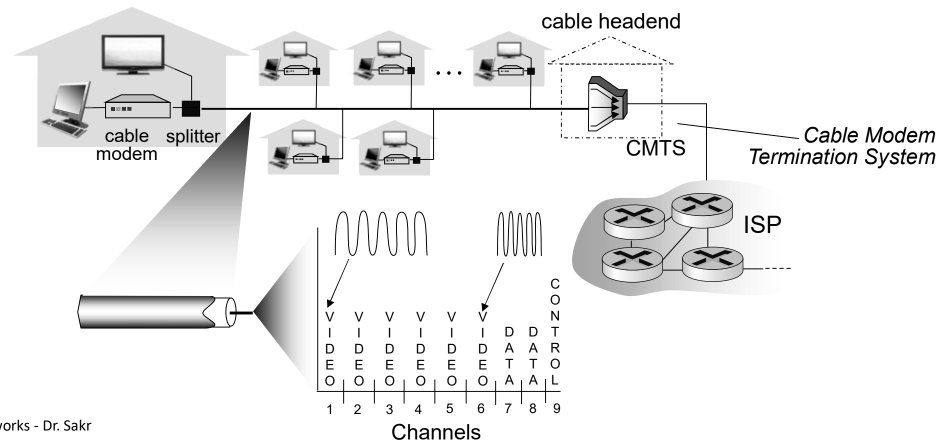




Parabolic dish antenna

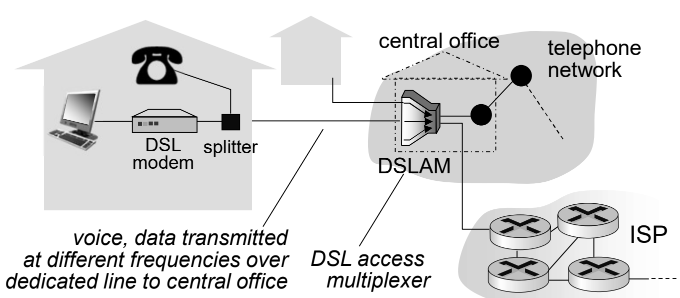
Example 1: Cable-Based Access Network

- FDM is used to transmit different channels simultaneously
- Fiber/coaxial attaches homes to ISP router, homes share access network to cable headend



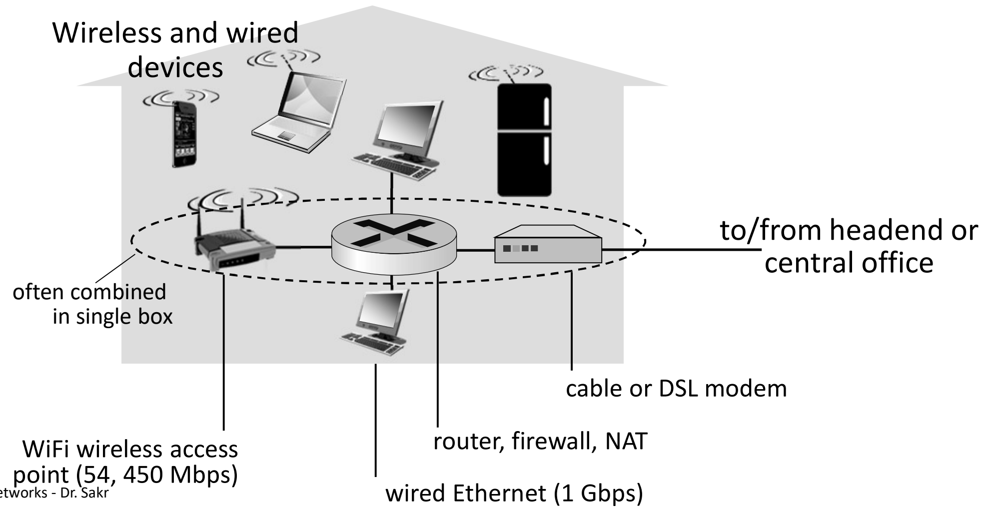
Example 2: Digital Subscriber Line (DSL) Access Network

- Use Existing telephone line to central office DSLAM
- Data over DSL phone line goes to internet and voice to telephone network



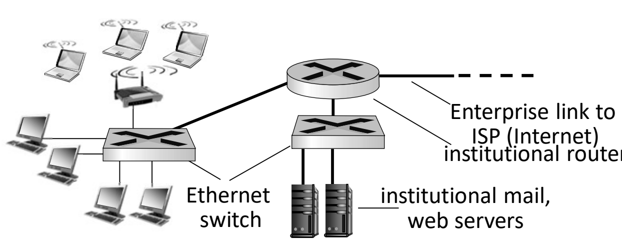
Example 3: Home Networks

- Mix of wired and wireless link technologies



Example 4: Enterprise Networks

- Companies, universities, etc.
- Mix of wired and wireless link technologies connecting a mix of switches and routers
  - Ethernet: wired access at 100 Mbps, 1 Gbps, 10 Gbps
  - Wi-Fi: wireless access points at 11, 54, 450 Mbps



Summary

- We covered:
  - Signals and impairments
  - Performance metrics
  - Data transmission: Analog vs. Digital
  - Bandwidth Utilization: Multiplexing
  - Transmission Media: Guided vs. Unguided