CSE 3231
Computer Networks

Chapter 2
The Physical Layer

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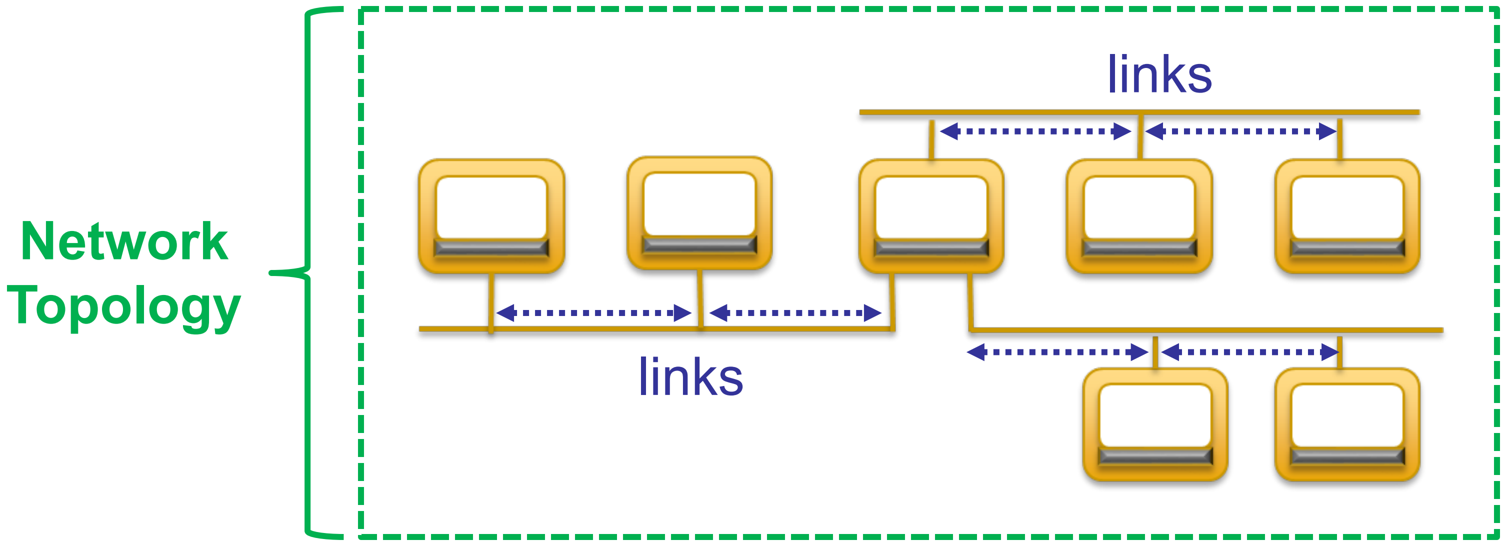
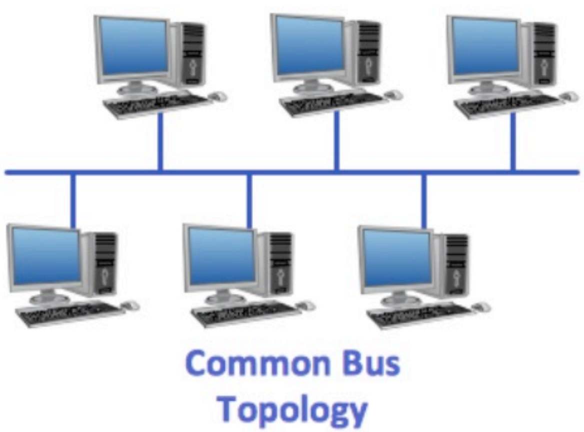
Network Terminology

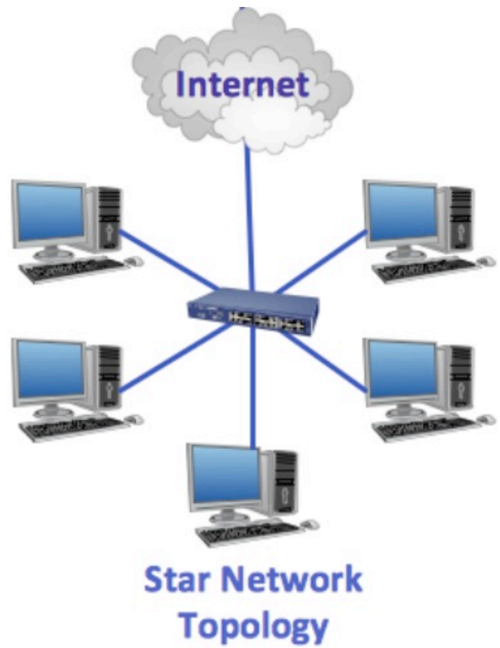
- Nodes in a local network are directly connected by *links*
- The configuration of the links and nodes is referred to as the *Network Topology*



Common Network Topologies

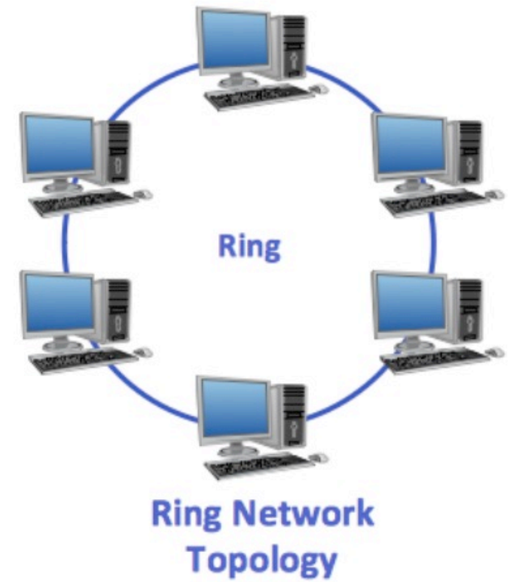
The bus topology uses a shared cable that connects all computers to each other





The star topology uses a central node that connects directly to each computer

The ring topology uses a shared cable that loops from one computer to another



Link Terminology

<u>Simplex</u> link

- Sends data only in one fixed direction at all times; useful for devices that only send data, like sensors

<u>Half-duplex</u> link

- Can transmit in both directions, but *not* at the same time, thus senders *must take turns*
- Could use a different cable or radio frequency for each direction to allow bi-directional transfer

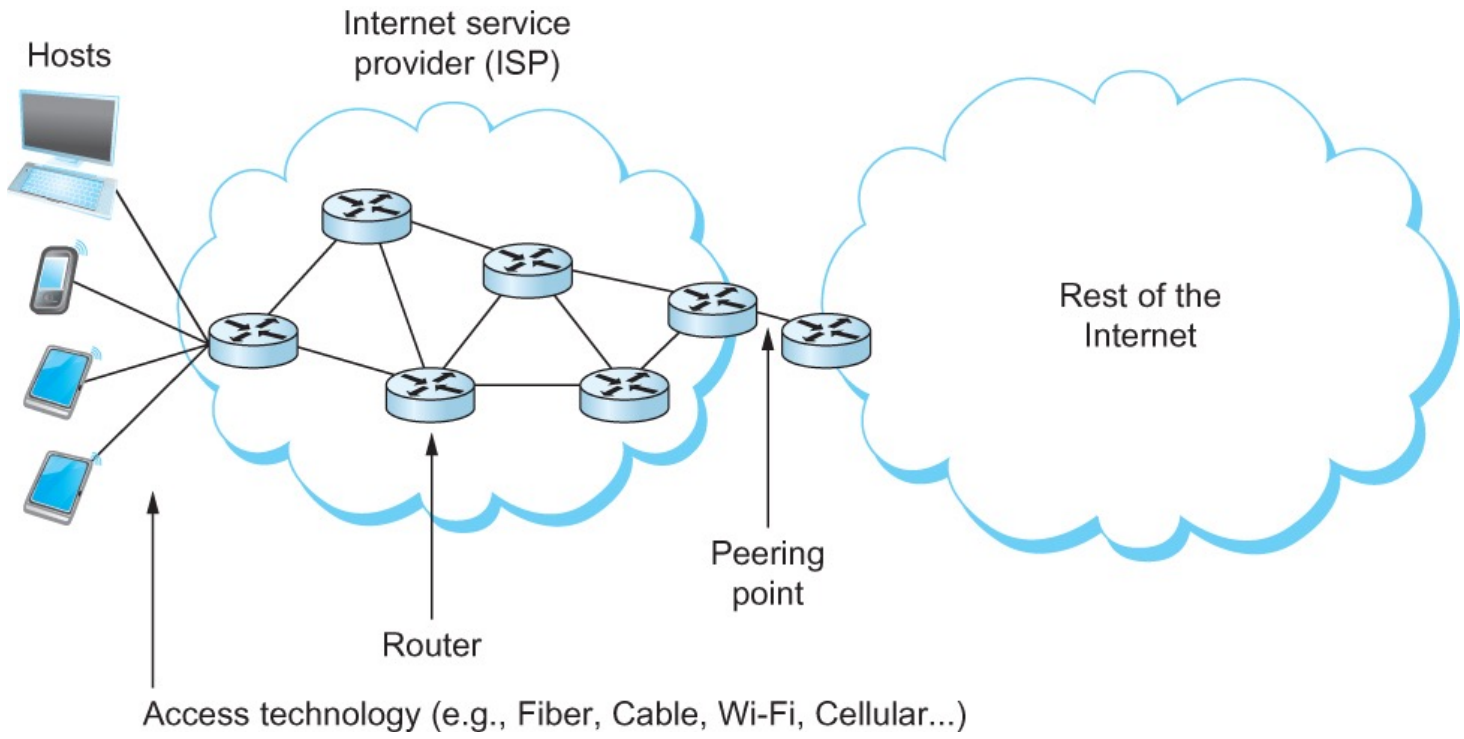
<u>Full-duplex</u> link

- Can transmit in both directions at once over the same cable or radio channel
- may use different frequencies for each direction

Transmission Media

- Network links use some type of electromagnetic radiation propagating either through a wired medium or by radio signals through free space
- One way to characterize links is by the medium they use
  - It may be copper wire as twisted pair or coaxial cable
  - Optical fiber for both commercial fiber-to-the home and long-distance links in the Internet's backbone
  - Air or free space for wireless links
  - Some systems use visible or IR light for short links

Networking Utilizes a Variety of Different Transmission Media



Network traffic crosses links over many different types of media

Signal Terminology

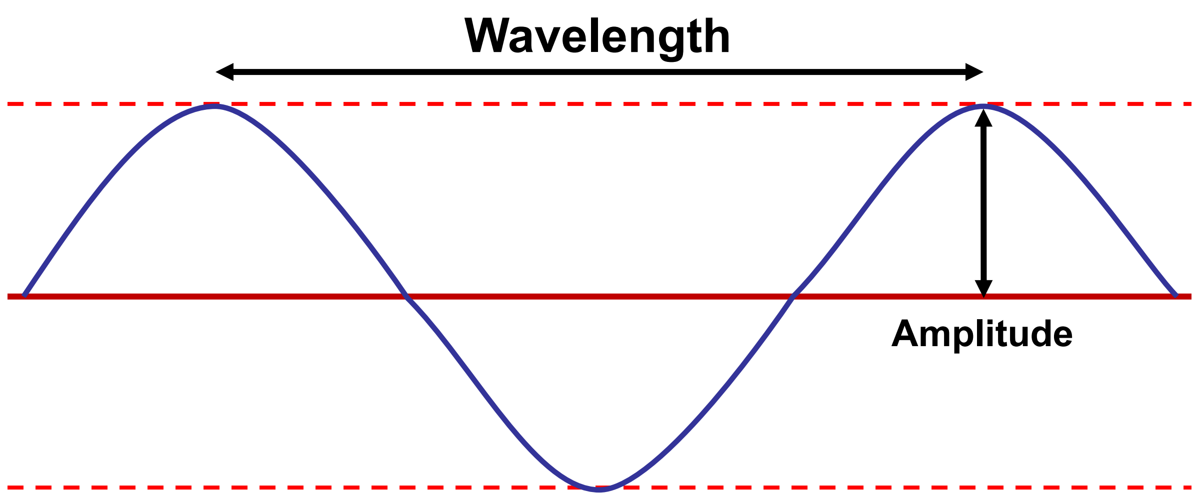
- The term *frequency* is a measure of how often electromagnetic waves oscillate
  - measured in *cycles / sec* (Hertz or Hz)
- The term *wavelength* refers to the distance between the *adjacent pair* of maxima or minima of a wave, measured in meters
  - calculated by (*speed of propagation* / *frequency*)
  - speed of propagation in copper wire: 2.3×10^8 m/sec
  - wavelength for 10 MHz signal through copper wire:

    propagation-speed-in-copper / frequency

    2.3×10^8 m/sec / 1.0×10^7 Hz = 23 meters / cycle

Wavelength and Amplitude

- Wavelength: length of one complete cycle
  - inversely proportional to frequency
    - as frequency increases, wavelength decreases
    - 10MHz = 23 meters, 100Mhz = 2.3 meters
- Amplitude: height (strength) of the signal



Bandwidth and Throughput

- Bandwidth
  - The bandwidth of a communication link represents the *maximum bits-per-second* the link supports
    - (e.g. 100Base-T Ethernet $\leq$ 100 million-bits-per-sec)
- Throughput
  - Achievable performance for the data unit of interest (user data, packet, etc.)
  - Typical measures are bits/sec, packets/sec, etc.
  - Depends on input rate to the channel
  - Influenced by protocol and protocol overhead

Bandwidth and Throughput

- The terms Bandwidth and Throughput are often used to refer to the same thing, i.e.
  - the **amount of data** (usually in bits) that can be transmitted through the link, per unit of time.
- However, bandwidth represents the *capacity* of the communications link, it does not take delay into account
  - Under perfect conditions, the throughput will match the bandwidth of the link.
  - In practice, however, throughput is *generally lower* than the theoretical capacity of the link.
    - The *utilization* of the link is defined as the ratio between the throughput and the capacity (or bandwidth) of the link

Network Delays & Round Trip Time

- Latency is the time it takes for one bit to travel from source to destination
  - It may include any or all of the following:
    - Processing delay - occurs at nodes along the way
    - Queuing delay - delay while waiting to transmit
    - Propagation delay - time it takes for the signal to travel through the transmission medium
      - depends on the speed of light in that medium
  - Time for first bit to arrive:

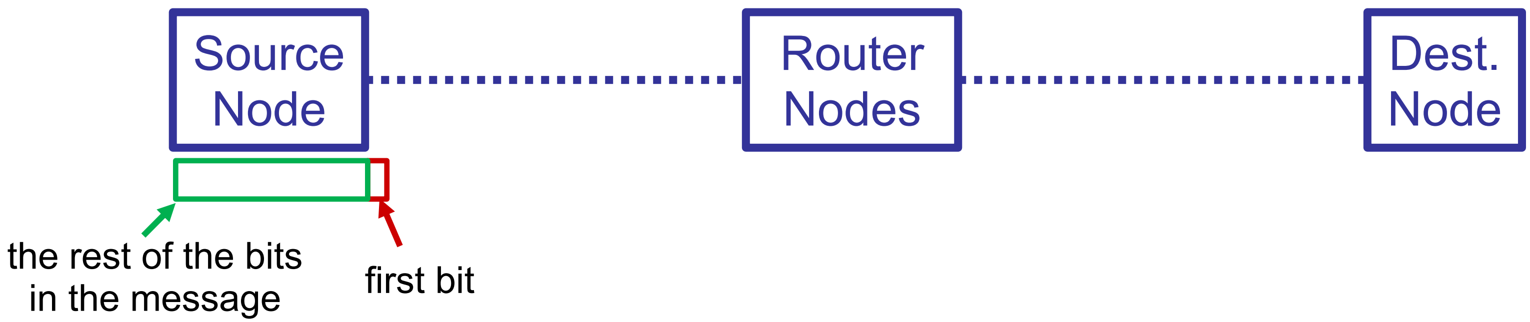
    Processing delay + *Queue delay* + *Propagation delay*

Network Delays & Round Trip Time

- Transmission delay measures the time it takes for the *rest of the bits* in the message to be delivered (after the first one arrives)
- *Total Network delay* = time for the first bit to arrive + time of the rest of the bits to arrive
  - *Total Network delay = Latency + Transmission delay*
  - example: a locomotive pulling 100 box cars (5000' long) leaves TownA and arrives at the station in TownB in exactly 1 hour - that is similar to *latency*
  - the rest of the train (a mile long) still has to enter the station - that is similar to the *transmission delay*

Network Delays & Round Trip Time

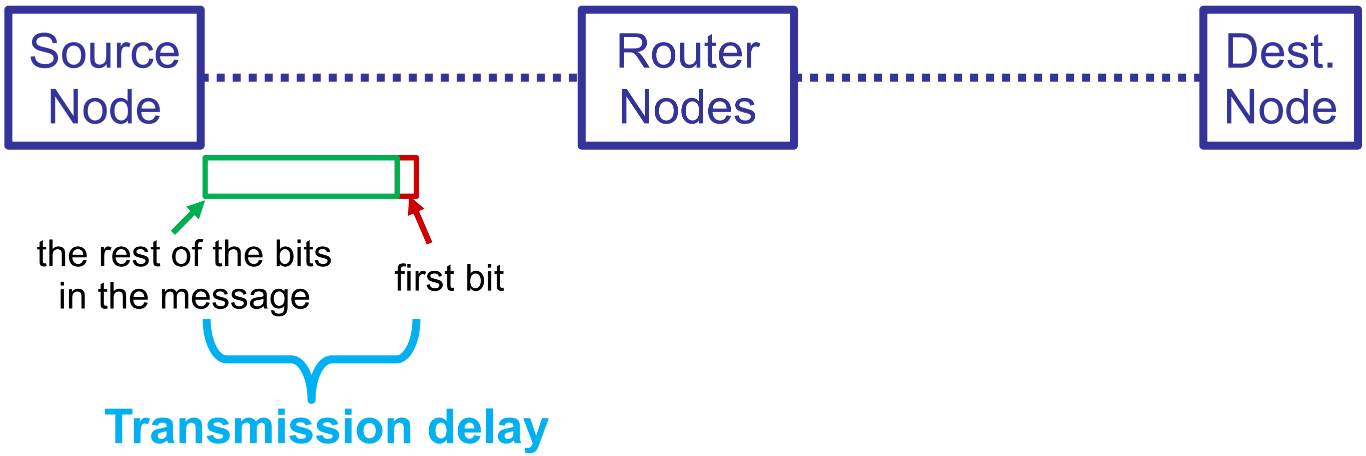
- Network delay:



1. Beginning of communication - first bit is transmitted

Network Delays & Round Trip Time

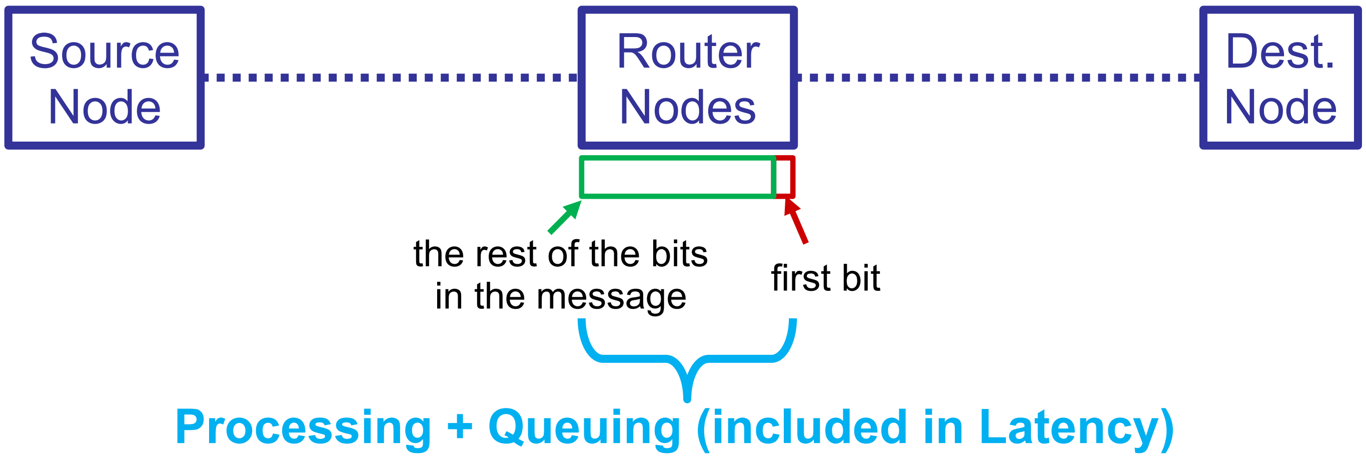
- Network delay:



1. Beginning of communication - first bit is transmitted
2. Entire message has been transmitted

Network Delays & Round Trip Time

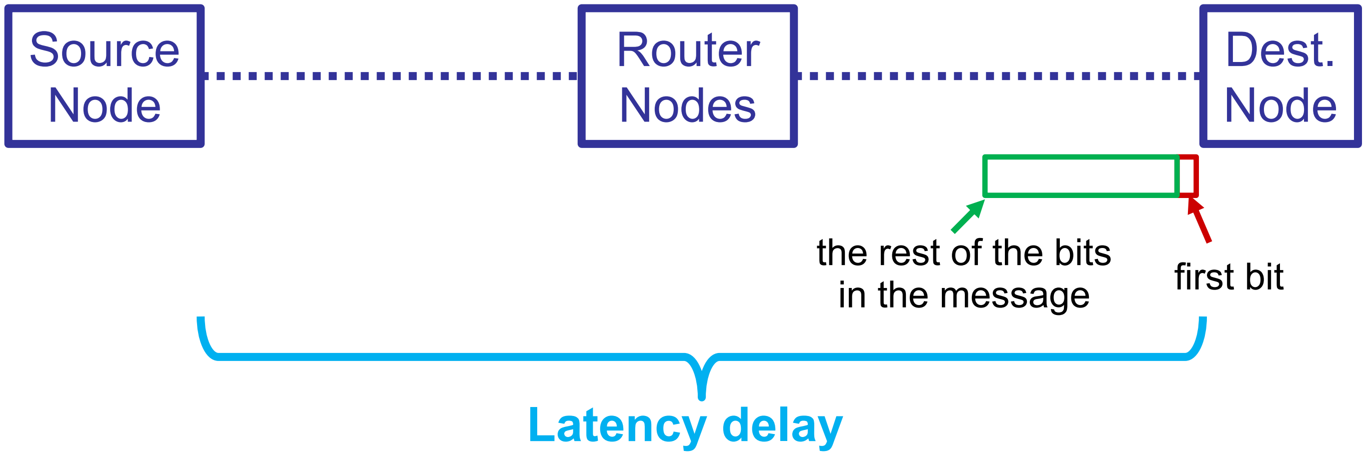
- Network delay:



1. Beginning of communication - first bit is transmitted
2. Entire message has been transmitted
3. Router processes message to determine destination

Network Delays & Round Trip Time

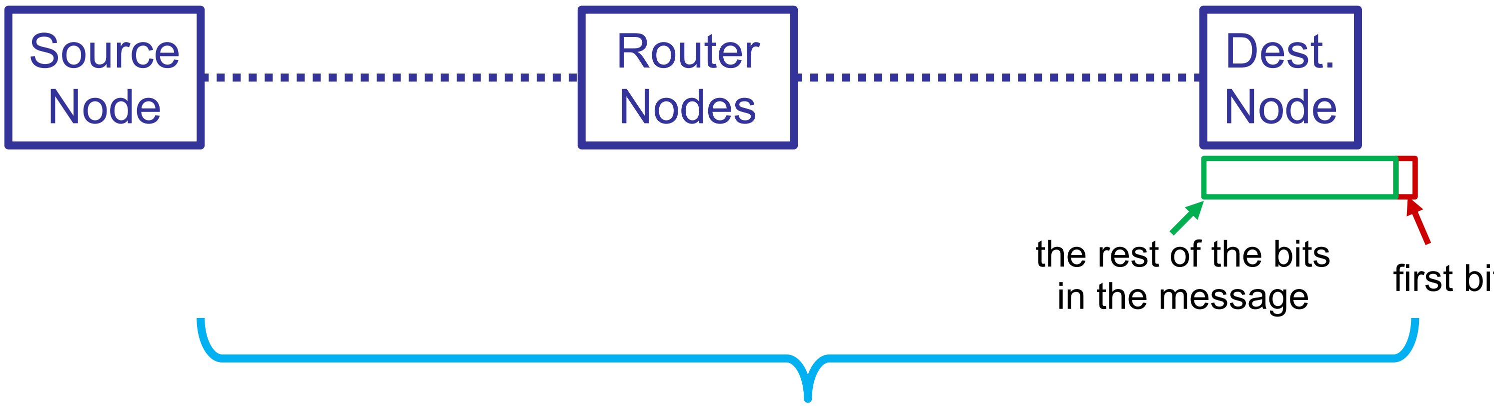
- Network delay:



1. Beginning of communication - first bit is transmitted
2. Entire message has been transmitted
3. Router processes message to determine destination
4. Destination received the first bit

Network Delays & Round Trip Time

- Network delay:



Network delay = Latency + Transmission delay

1. Beginning of communication - first bit is transmitted
2. Entire message has been transmitted
3. Router processes message to determine destination
4. Destination received the first bit
5. Destination received the rest of the bits

Network Delays & Round Trip Time

- Round Trip Time (RTT) measures the total time it takes for a *message* to be delivered to the destination and the reply to arrive
  - this includes all of the other delay times, including transmission delay
  - *Network delay* = (*Processing delay* + *Queuing delay* + *Propagation delay* + *Transmission delay*)
  - *Round Trip Time* = 2 x (*Network delay*)

Bandwidth-Delay Product

- We can think of the channel between a pair of nodes as a hollow pipe
  - Bandwidth is like the width of the pipe and Latency (*delay*) is like the length of the pipe
  - With a bandwidth of *100 Mbps* and delay of *50 ms*

    100×10^6 bits/second x 50×10^{-3} seconds = 5×10^6 bits
  - We can transmit 5×10^6 bits before the first bit reaches the other end of the link
  - Thus, we can say this link's *capacity* is 5×10^6 bits
  - Due to the way the capacity is calculated, it is often referred to as the *bandwidth-delay product*

Link Utilization

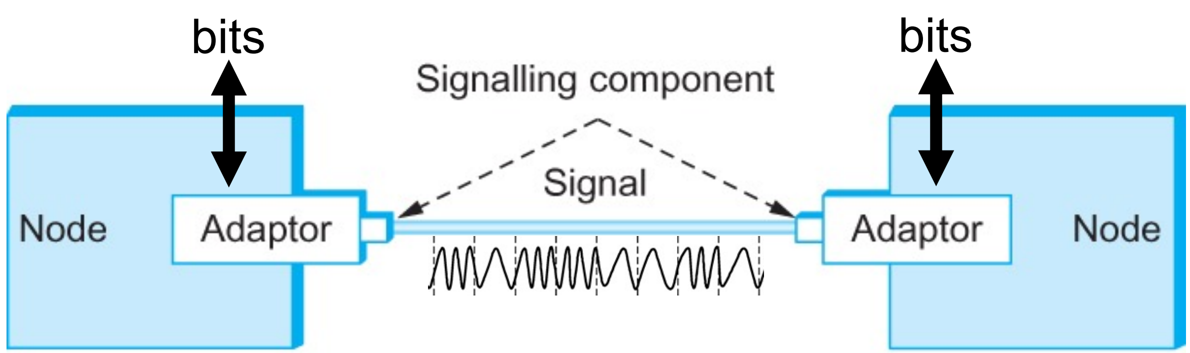
- After calculating the bandwidth-delay product of a link (i.e., its *theoretical* capacity), we can determine the link's *utilization* by comparing that to the number of bits we are transmitting
  - Assume a link with a capacity of 5×10^6 bits and we intend to send one 1 KB frame (8,000 bits)
  - This is only $8{,}000/5 \times 10^6$ = *0.16%* of the total capacity of the link
  - At 100 Mbps, it will take $8{,}000/100 \times 10^6$ seconds to transmit the entire frame: 0.08 ms
    - Thus, the link will be idle for the 49.02 ms it takes the frame to get to the other end of the link (ignoring ACK)

Digital Modulation and Multiplexing

- *Modulation* converts bits into signals
  - Baseband Transmission - encodes bits
  - Passband Transmission - shares media
- *Multiplexing* allows multiple users to share a passband channel
  - Frequency Division Multiplexing
  - Time Division Multiplexing
  - Code Division Multiple Access

Encoding

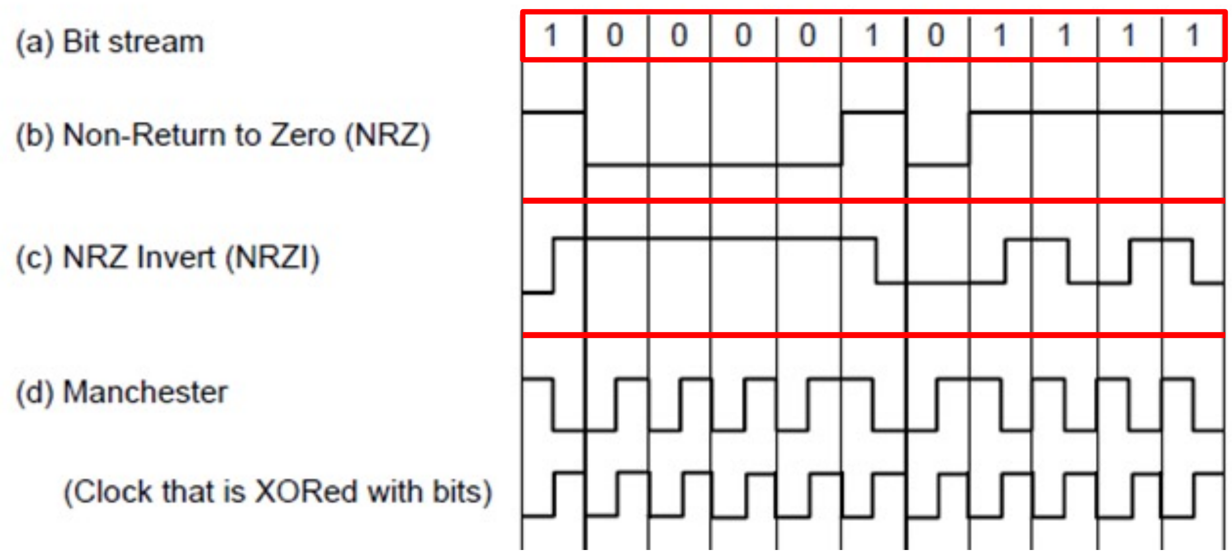
- Encoding: a method for converting binary data into electromagnetic signals
  - performed in the signaling component within the network adapter



Signals travel between signaling components

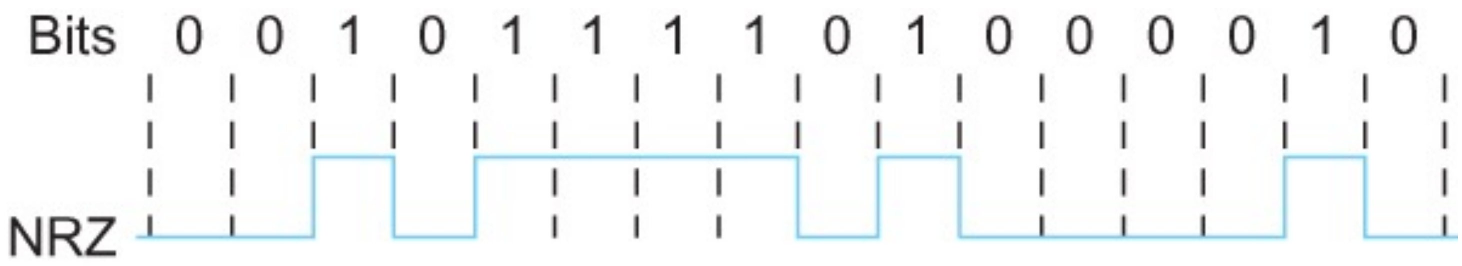
Baseband Transmission

- Encoding produces symbols that represent one or more bits and those symbols can be converted into electromagnetic signals



Encoding

- One method is Non-Return to Zero (NRZ)
  - a high amplitude signal is = 1
  - a low amplitude signal is = 0
  - the bit stream shown below is represented by using the NRZ method to send 1's and 0's



NRZ encoding of a bit stream

A Problem with NRZ

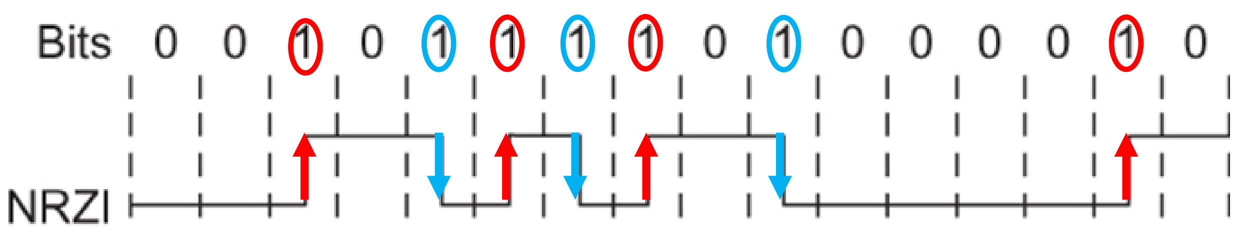
- Baseline wander
  - The receiver keeps an average of the signals it has seen so far and uses that average to distinguish between low and high signals
    - When the signal that is received is significantly higher than the average, it is considered to be a 1, otherwise it is 0
  - Too many consecutive 0’s or 1’s may cause the average to drift up or down, making it difficult to detect the difference between 0 & 1

Another Problem with NRZ

- Clock recovery (clock synchronization)
  - The sender transmits a bit at regular intervals, but the receiver must synchronize to that by keeping track of the time between the arrival of new bits
    - If the sender and receiver are not in sync, the receiver may fail to recognize that a new bit has arrived
  - Frequent transitions between high and low are necessary to ensure that the receiver “knows” when the next bit will arrive
    - It is easier to tell when a new bit has arrived if it is different from the last bit to arrive, thus long sequences of 0’s or 1’s can result in a loss of synchronization and a loss of data

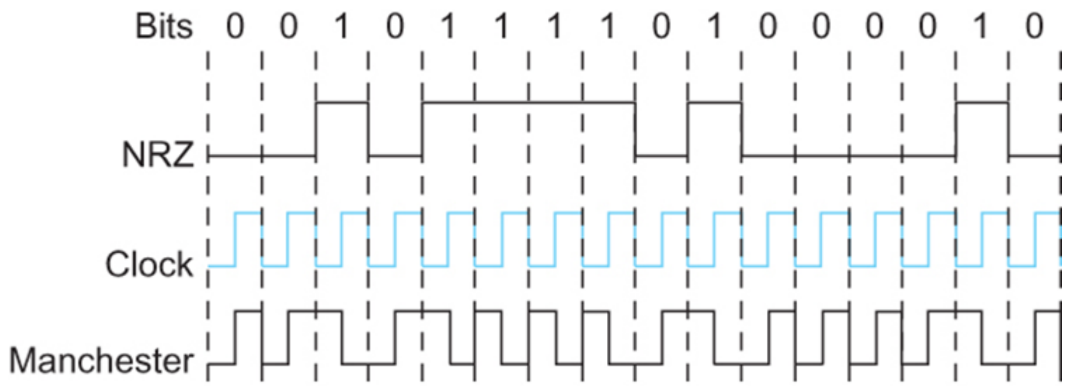
Encoding

- Non Return to Zero *Inverted* (NRZI)
  – Sender makes a transition from the current signal to the opposite signal to encode a 1 and stays at the current signal to encode a 0
    - This mitigates the problem of having too many repeated bits, but assumes a roughly equal number of 0's & 1's



Encoding

- Manchester encoding
  - Merges an internal clock with the signal by calculating the XOR (eXclusive OR) of the clock pulses with the NRZ encoded data
    - The *direction* of the transition indicates 0 or 1
    - 0 is represented by a low→ high transition
    - 1 is represented by a high→ low transition

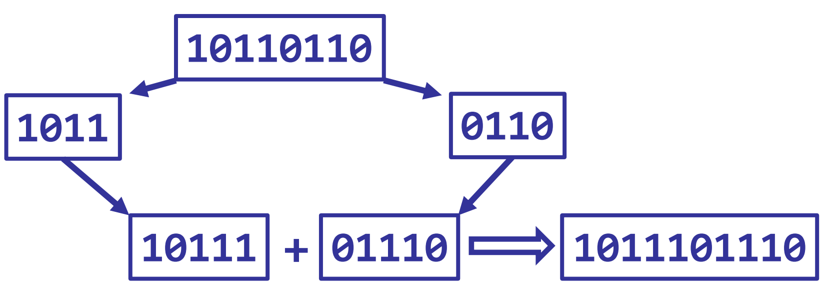


Another Way to do Encoding

- 4B/5B encoding
  - Inserts extra bits into the bit stream to break up the long sequences of 0’s and 1’s
  - Every 4-bits of actual data are encoded in a 5-bit code that is transmitted to the receiver
    - 5-bit codes are selected in such a way that each one has no more than one leading 0 (zero) and no more than two trailing 0’s.
    - Thus, no pair of 5-bit codes results in more than three consecutive 0’s

4B/5B: 4-Bit Data Symbol, 5-Bit Code

- Each byte is *split* into two 4-bit values
- Each of those 4-bit values is mapped to its corresponding 5-bit code
  - Thus, any byte value can be represented by a unique 10-bit number



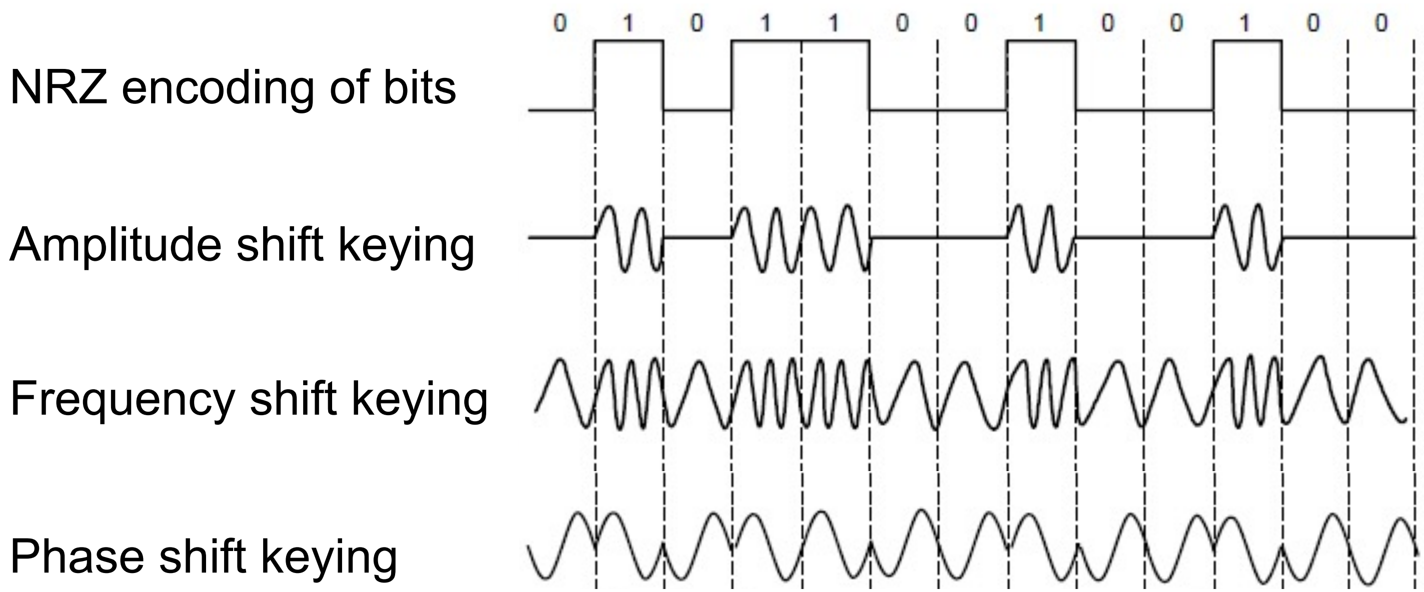
4-bit data	5-bit code
0000	11110
0001	01001
0010	10100
0011	10101
0100	01010
0101	01011
0110	01110
0111	01111
1000	10010
1001	10011
1010	10110
1011	10111
1100	11010
1101	11011
1110	11100
1111	11101

Encoding More than Just Bits

- 4B/5B encoding
  - 5 bits allows 32 different combinations
  - 16 of them are used to encode the 4 bits
  - Some of the remaining combinations are used for control or error signals
    - 11111 – used when the line is idle
    - 00000 – used when the line is dead
    - 00100 – means to halt transmission
    - 6 more codes used for control signals
      - the 7 remaining codes are not used because they would produce too many consecutive 0's

Passband Transmission

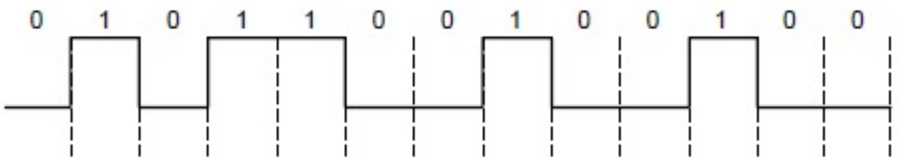
Techniques for modulating the *amplitude*, *frequency* or *phase* of a carrier signal to transmit bits within a certain frequency band



Passband Transmission

Non-Return to Zero encodes the binary data as **0** or **1**

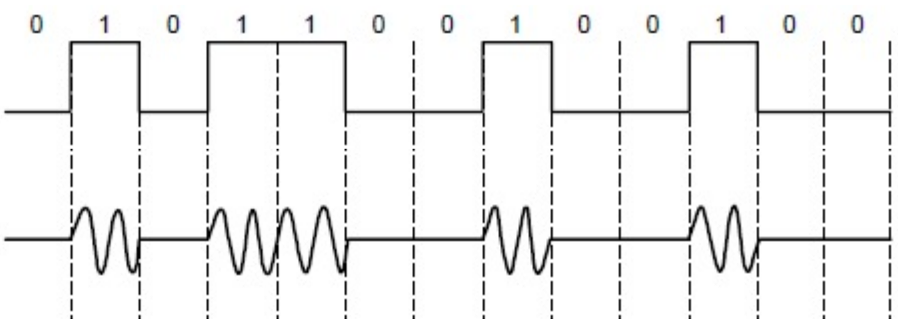
NRZ encoding of bits



Amplitude shift keying (ASK) transmits those bits by sending a signal to represent a **1**, or no signal for a **0**

NRZ encoding of bits

Amplitude shift keying (ASK)

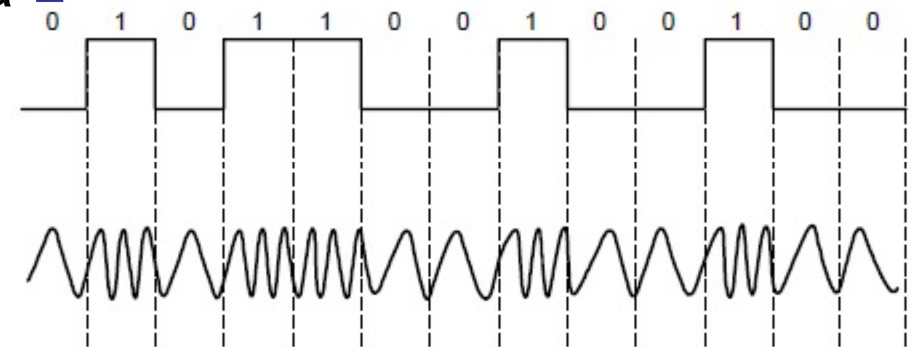


Passband Transmission

Frequency shift keying (FSK) uses different *frequencies* to represent a **0** or a **1**

NRZ encoding of bits

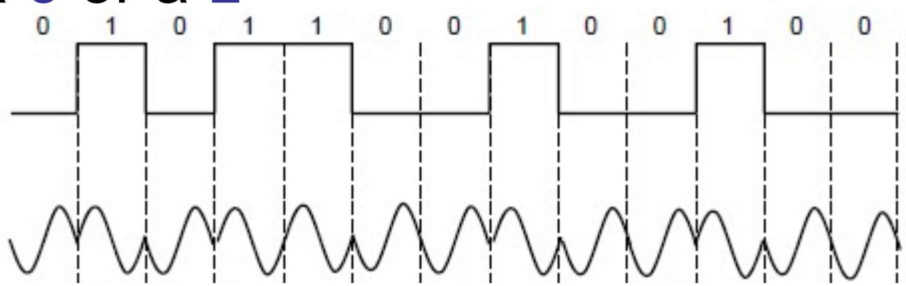
Frequency shift keying (FSK)



Phase shift keying (PSK) changes the *phase* of the signal to represent a **0** or a **1**

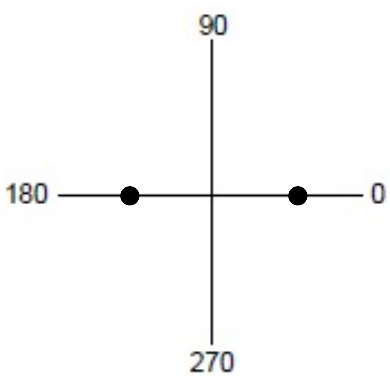
NRZ encoding of bits

Phase shift keying (PSK)

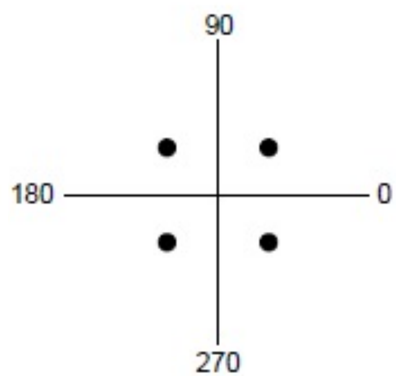


Passband Transmission

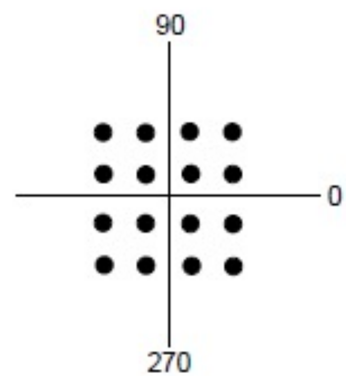
Constellation diagrams represent *phase shift* modulation and *amplitude* modulation of bits:



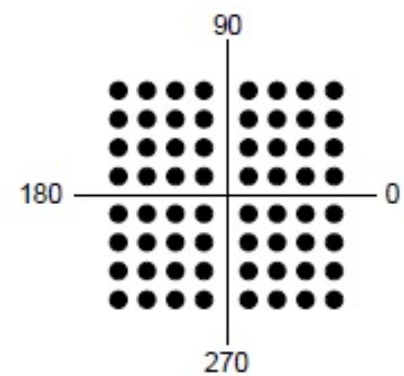
Binary PSK
2 combinations,
represents 1 bit



Quad PSK
4 combinations,
represents 2 bits



Quad AM-16
16 combinations,
represents 4 bits



Quad AM-64
64 combinations,
represents 6 bits

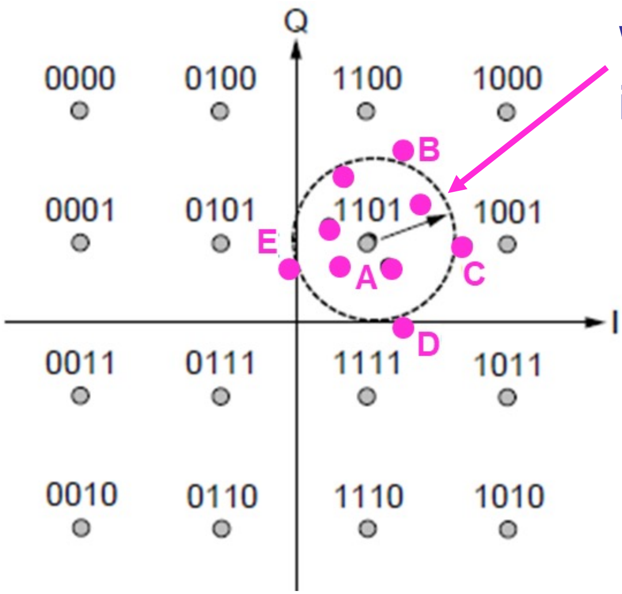
BPSK and QPSK
vary only in phase

Quad AM varies in both
amplitude and phase

Passband Transmission

Gray-coding Quad AM assigns bits to symbols

- small errors in amplitude and/or phase (inside circle) stay within the threshold for the correct bit pattern
- larger errors will move toward combinations that result in a change to only one bit of the 4-bit value



Within the circle, still recognized as `1101`, if it is outside the circle an error occurred

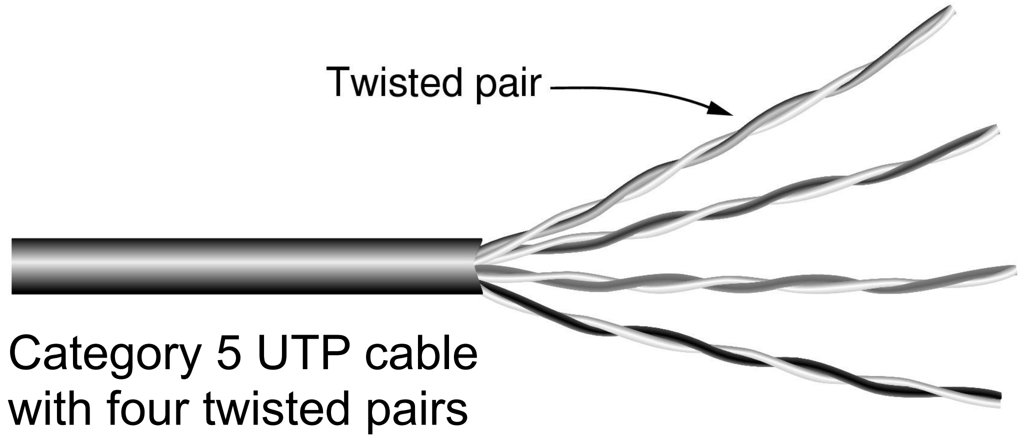
When 1101 is sent:

Point	Decodes as	Bit errors
A	1101	0
B	1100	1
C	1001	1
D	1111	1
E	0101	1

Gray code: adjacent values assigned so they will differ in only one bit position

Twisted Pair

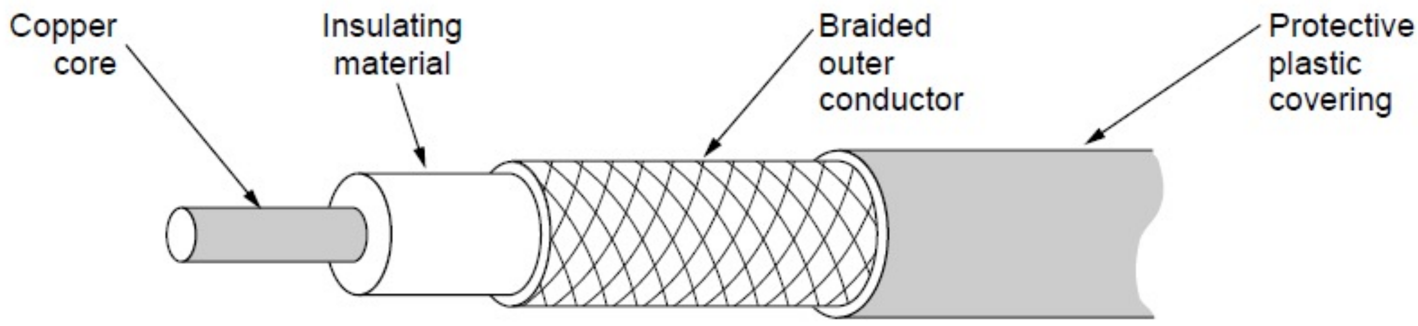
- Commonly used in LANs, telephone lines
  - Twisting the pair of wires around each other reduces the interference caused by radiated signals without the extra expense of shielding the cables



Coaxial Cable ("Co-ax")

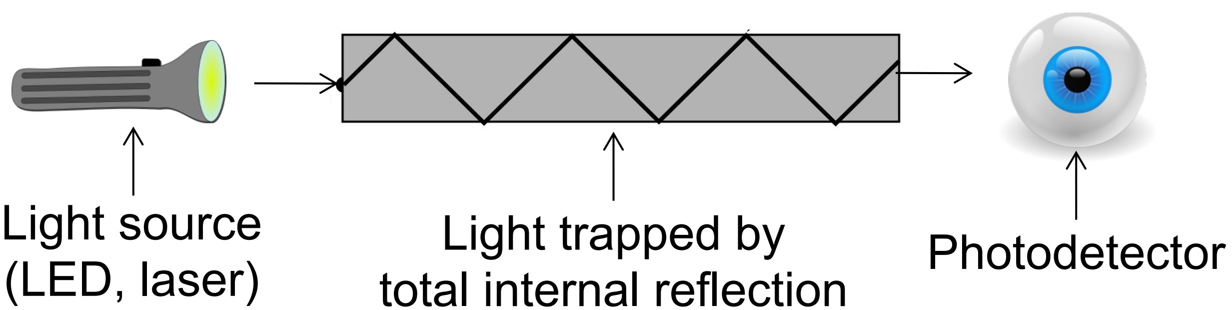
Provides better shielding and more bandwidth for transmitting signals over longer distances and at higher rates than twisted pair cables

- Outer conductor also acts as a shield to block interference from other cables
- However, it is more expensive to make and it doesn't bend around corners as easily



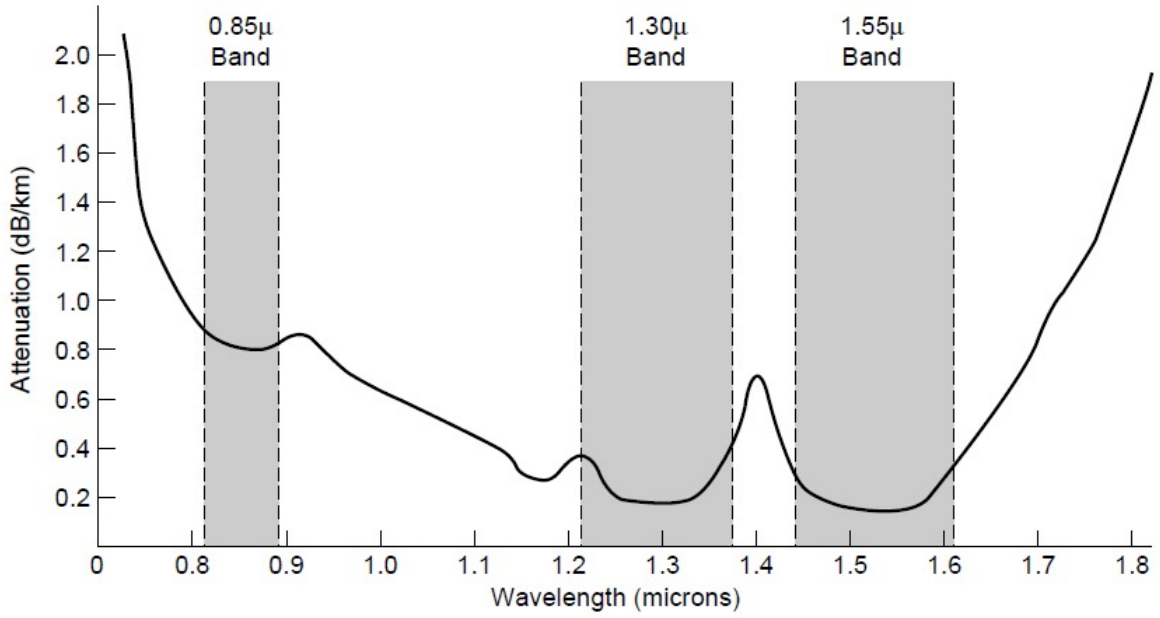
Fiber Optic Cables

- Commonly used to support high data rates over long distances with greatly reduced risk of interference
  - Used for long distance network links and Fiber-to-the-Home
  - Light carried in very long, thin strand of glass



Fiber Optic Cables

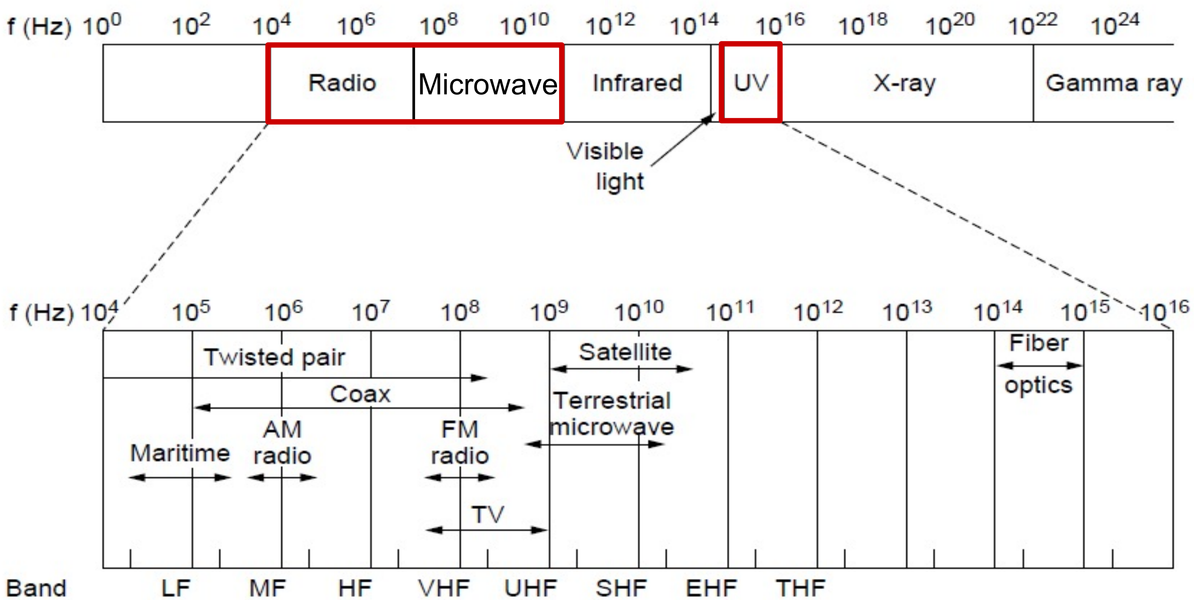
Fiber has enormous bandwidth (up to TeraHz) with tiny signal loss and supports very high data rates over long distances



Electromagnetic Spectrum

Networks use a range of frequency bands:

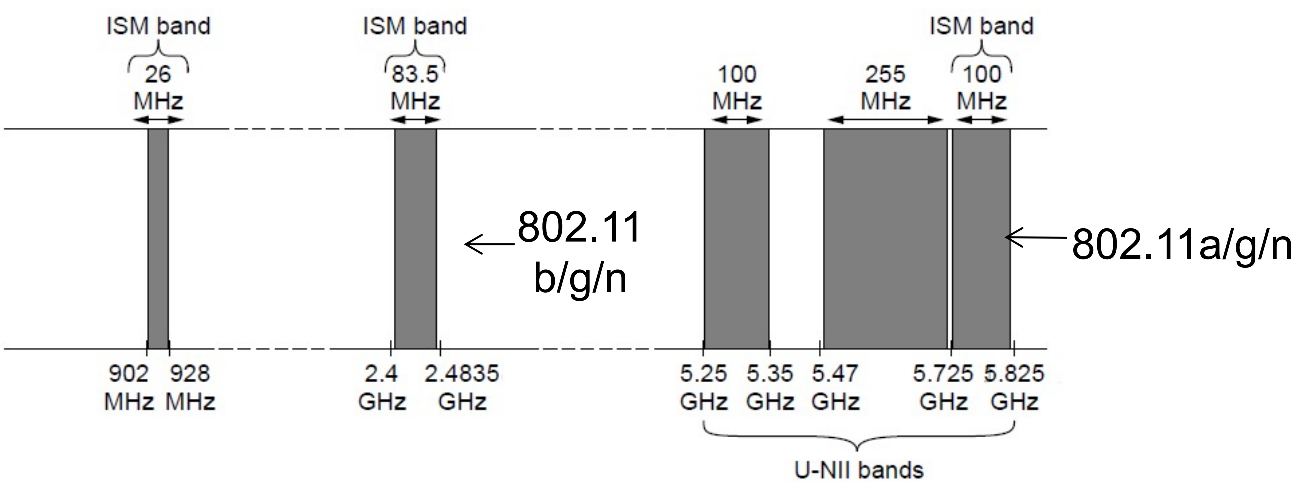
- Radio band: wide-area broadcast, RFID
- Microwave band: LANs and 3G/4G, IoT devices
- Fiber Optic often uses light in the UV-range



Electromagnetic Spectrum

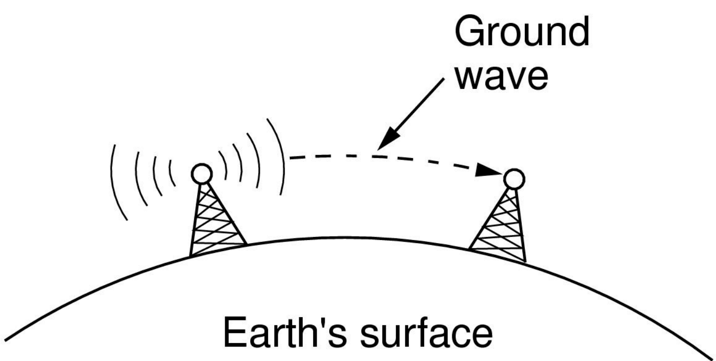
There are special frequency bands for *Industrial, Scientific, Medical* (ISM) communications:

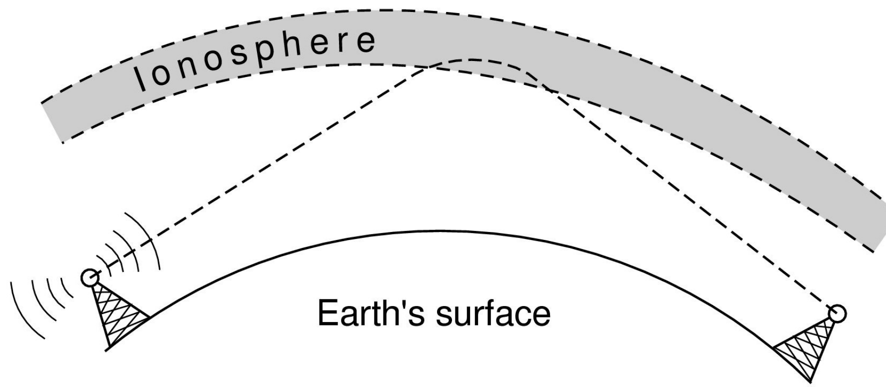
- No license required for use at low power
- Widely used for home/business/IoT networking
  - WiFi, Bluetooth, Zigbee, Z-wave, etc. (not cellular phones)



Radio Transmission

Radio signals penetrate buildings well and propagate for long distances but do exhibit path loss (i.e., signals weaken over distances)





In the VLF, LF, and MF bands, radio waves follow the curvature of the earth

In the HF band, radio waves bounce off the ionosphere.

Wireless vs. Wires/Fiber

Wireless:

+ Easy and inexpensive to deploy
+ Naturally supports mobility
+ Naturally supports broadcast
- Transmissions interfere and must be managed
- Signal strengths and data rates can vary greatly

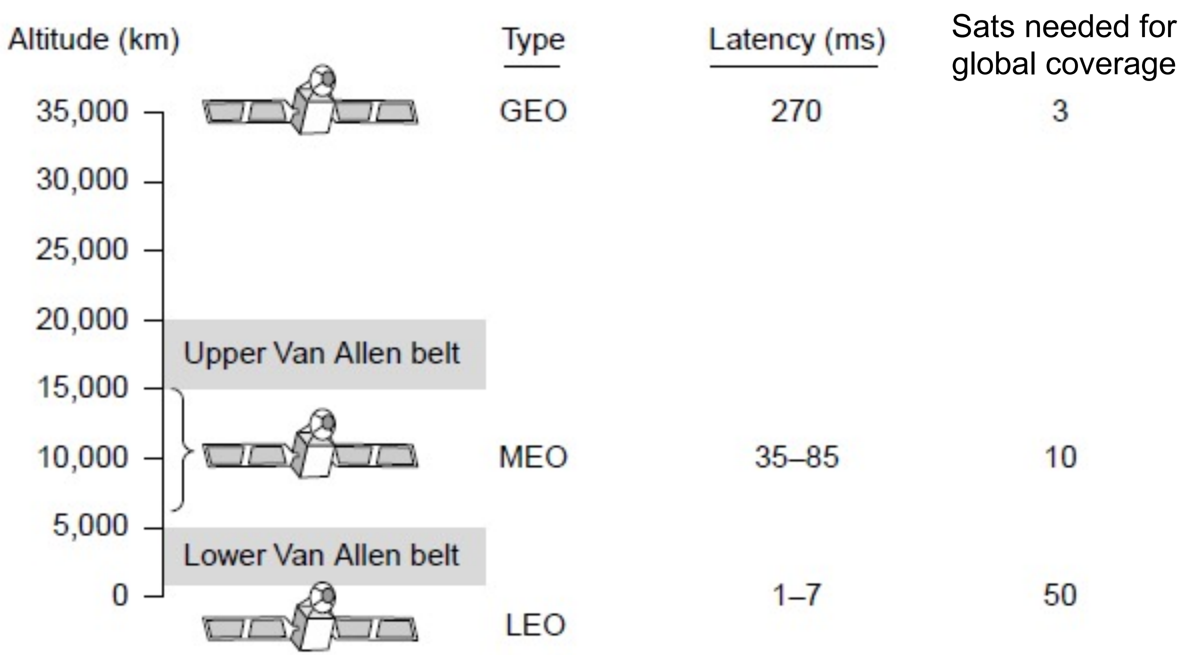
Wires / Optical Fiber:

+ Easy to engineer a fixed data rate over point-to-point links
- Can be expensive to deploy, esp. over distances
- Doesn't readily support mobility or broadcast

Kinds of Satellites

Satellites and their properties vary by altitude:

- Geostationary (GEO), Medium-Earth Orbit (MEO), and Low-Earth Orbit (LEO)

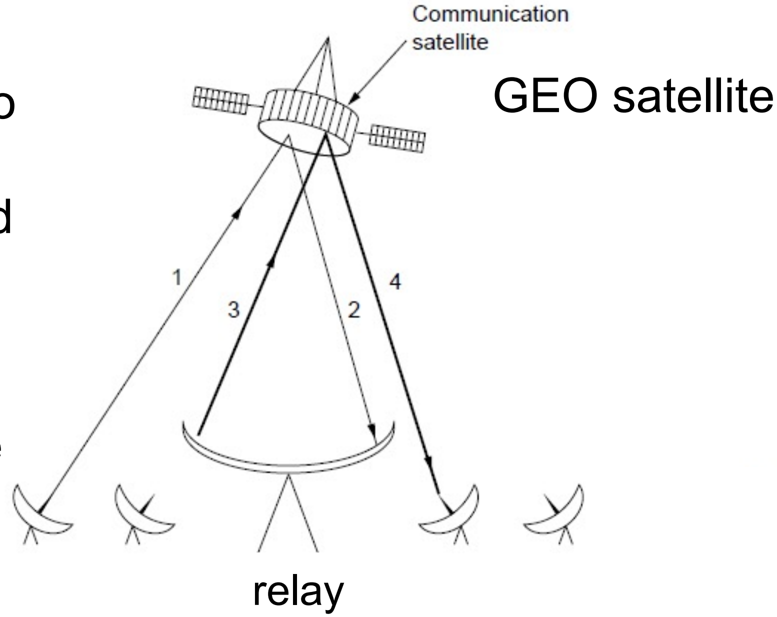


Geostationary Satellites

Geostationary (GEO) satellites orbit 35,000 km (22,240 miles) above a fixed location

- Relay nodes can retransmit signals to extend the range
- Bands in the GHz range (L, S, C, Ku, Ka) are used but may be affected by local interference or signal fading due to rain

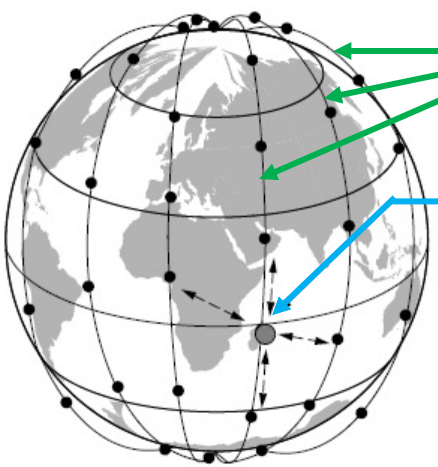
- The concept of using satellites to relay signals between different parts of Earth was first published by Arthur C. Clarke in 1945
- It takes *240ms to 270ms* for the signal to travel up to the satellite and back to a ground station



Low Earth Orbit Satellites

Systems such as *Iridium* use many LEO satellites for coverage of all areas on Earth

- LEO altitudes are 100 to 1,200 miles, reducing the round-trip time for audio communications
- However, satellites move across the sky and must handover users similar to the way cell towers do



The Iridium satellites form six necklaces around the earth.

Each satellite can handover users to one of its four neighbors.

Satellite vs. Fiber

Satellite:

+ Once in their orbital location, can support communications at most locations on Earth
+ Can broadcast signals to large regions
- Bandwidth is limited to pre-set channels
- Many sources of interference at receive point

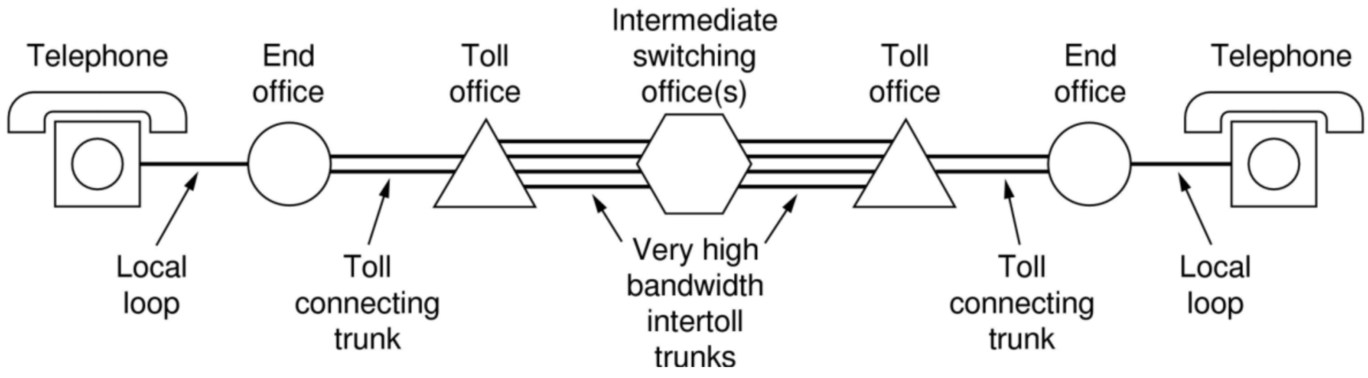
Optical Fiber:

+ Enormous bandwidth over long distances
- Installation can be expensive & time consuming

Structure of the Telephone System

A hierarchical system for voice communications:

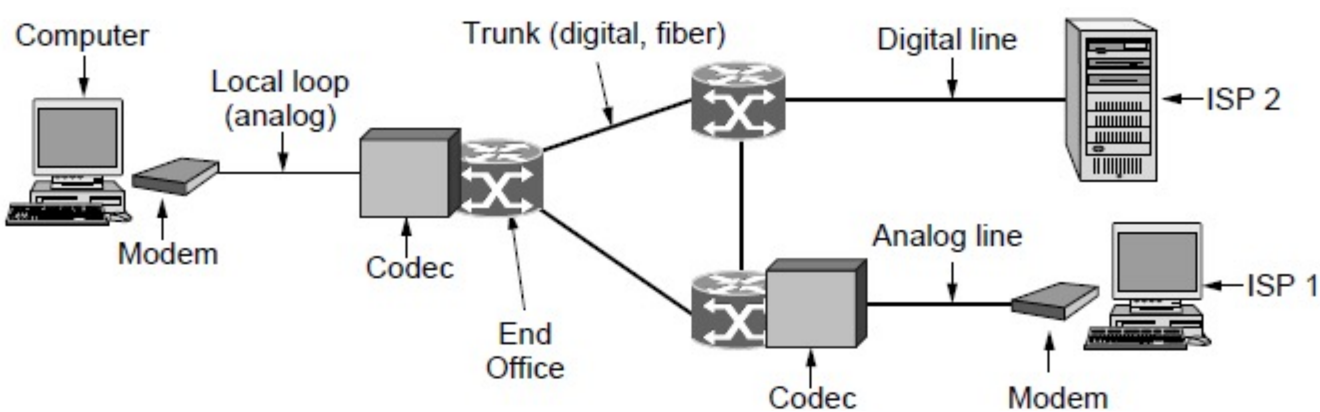
- Called POTS (Plain Old Telephone System)
- Local loops mostly use analog twisted pairs connecting to wired phones and devices
- Trunks: digital fiber optic links that connect calls originating on local loops over long distances
- Switching offices: route calls between trunks



Local Loop: Dial-up Modems

Telephone modems sent digital data over a 3.3 KHz analog voice channel in the POTS

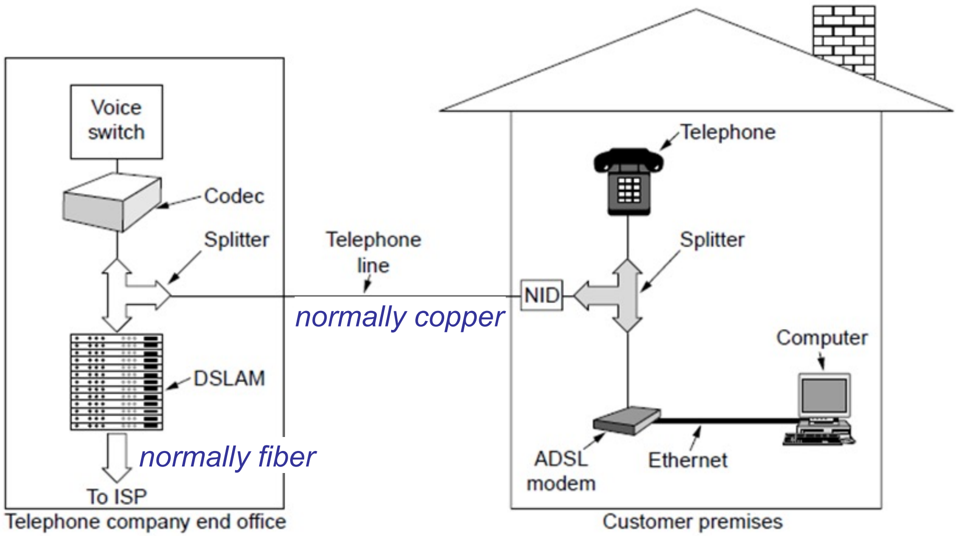
- Originally used frequency modulation for data rates up to 2400 bps
- Upgraded to phase shift modulation to support data rates up to 56 kbps



Local Loop: Digital Subscriber Lines

Digital Subscriber Line (DSL) transmits data to the local office using frequencies that are not used for voice communications on POTS

Telephones and computers both attach to the same twisted-pair line, but operating on different channels. Computers get greater bandwidth than with modems.

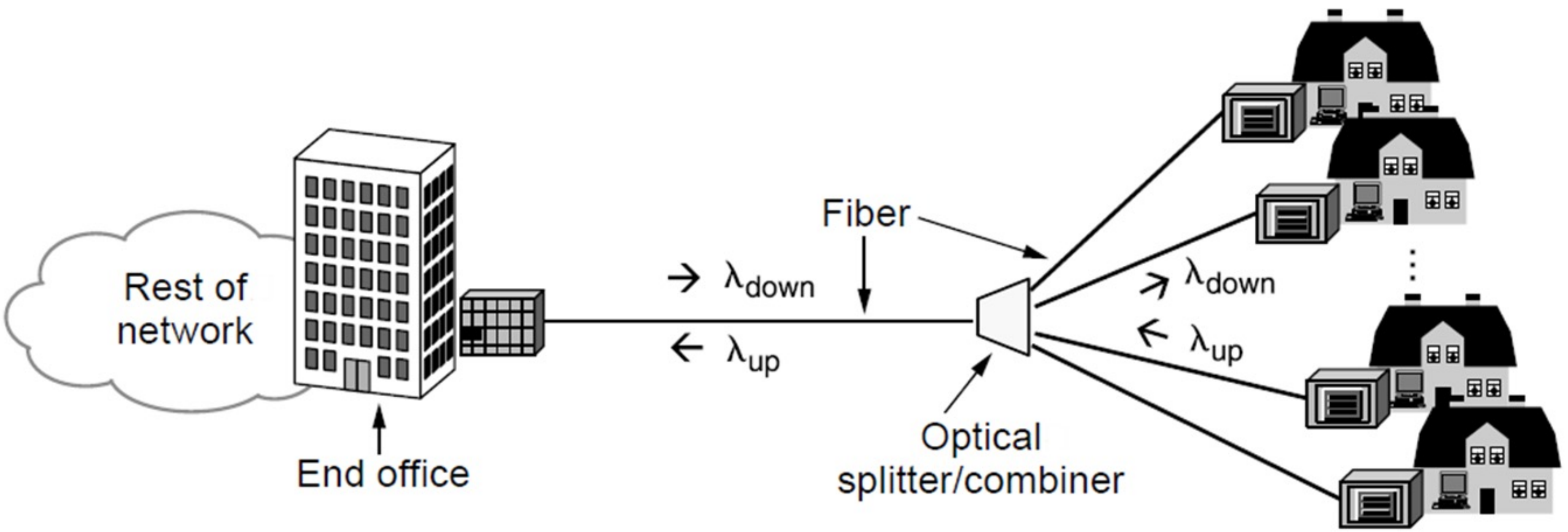


ADSL is a newer, faster version of DSL

Local Loop: Fiber To The Home

Fiber To The Home (FTTH) broadband relies on the deployment of fiber optic cables to provide higher data rates to customers

- One frequency band can be shared between homes



Generations of mobile telephone systems

1G, analog voice

- Example: AMPS (Advanced Mobile Phone System) deployed from 1980s, Frequency Division Modulation

2G, analog voice and digital data

- Example: GSM (Global System for Mobile Comm.) deployed from 1990s, modulation based on QPSK

3G, digital voice and data

- Example: UMTS (Universal Mobile Telecomm. System) deployed from 2000s, modulation based on CDMA

4G, digital data including voice

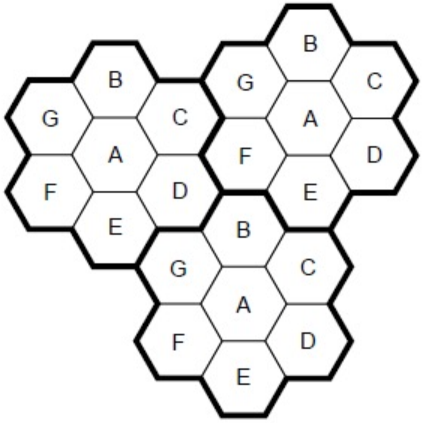
- Example: LTE (Long Term Evolution) deployed from 2010s, modulation based on OFDM

5G, update of 4G - higher bandwidth

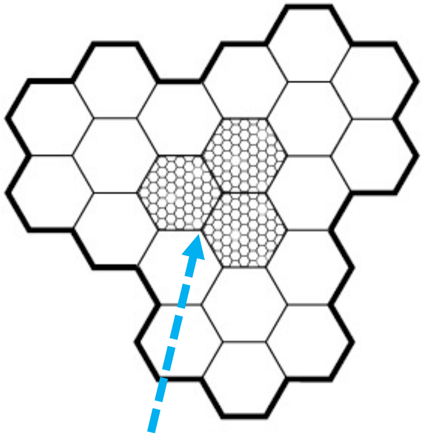
Cellular mobile phone systems

All based on spatial regions called *cells*

- Each mobile uses a different frequency in a cell
- Handoff occurs when moving between cells
- Frequencies are allocated across non-adjacent cells
- To support more mobiles, smaller cells can be used



Frequency allocation pattern ensures no adjacent cells



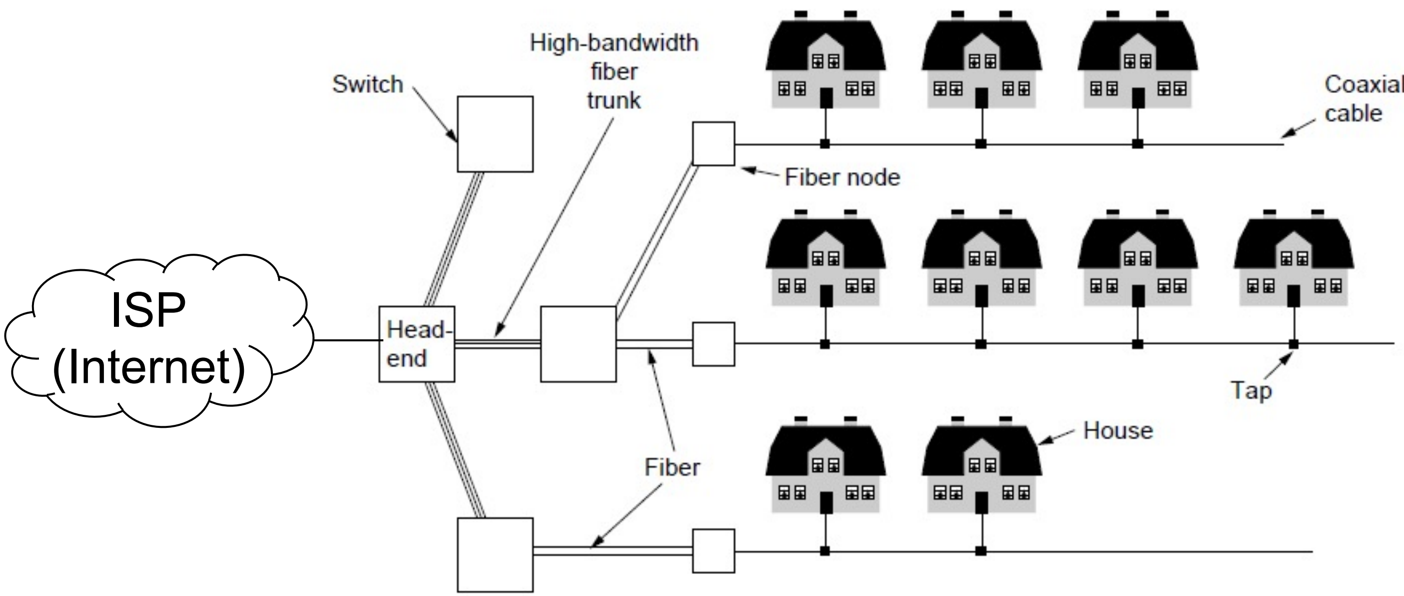
Smaller cells for densely populated regions

5G uses this approach

Internet over Cable

Internet connections delivered over an existing cable TV system

– Data is sent on the shared cable from the head-end, *not* on a dedicated line per subscriber (DSL)



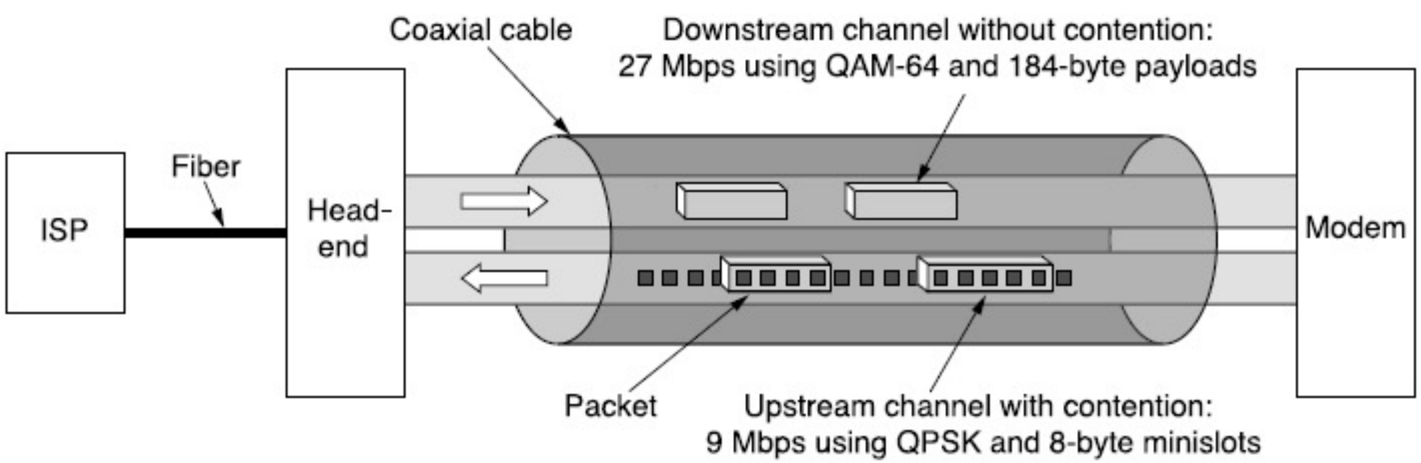
Spectrum Allocation

Upstream and downstream data use frequency channels not being used for TV channels

Cable Modems

Cable modems at customer premises implement the physical layer

- QPSK/QAM is used in timeslots on frequencies that are assigned for upstream/downstream data



Cable vs. ADSL

Cable:

+ Uses coaxial cable to customers
- Data is broadcast to all customers (less secure)
- Bandwidth is shared over customers so may vary

ADSL:

+ Bandwidth is dedicated for each customer
+ Point-to-point link does not broadcast data
- Uses twisted pair to customers