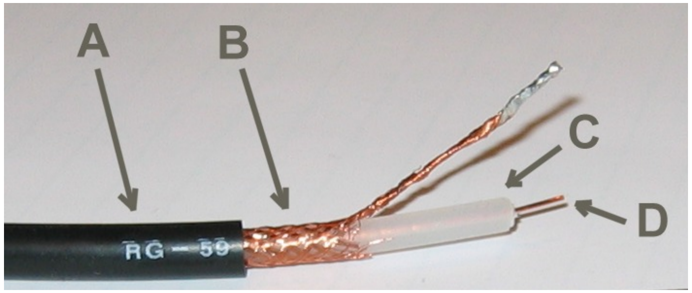
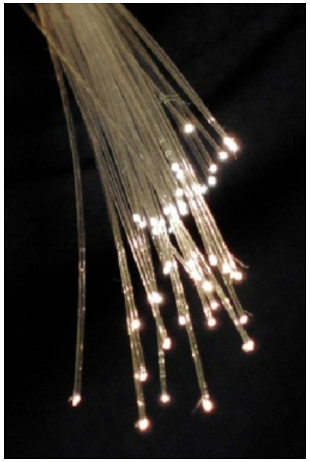
Physical connectivity



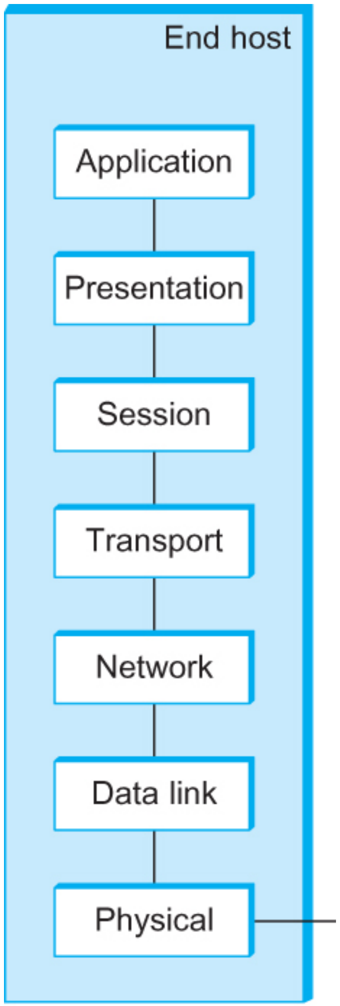


Overview

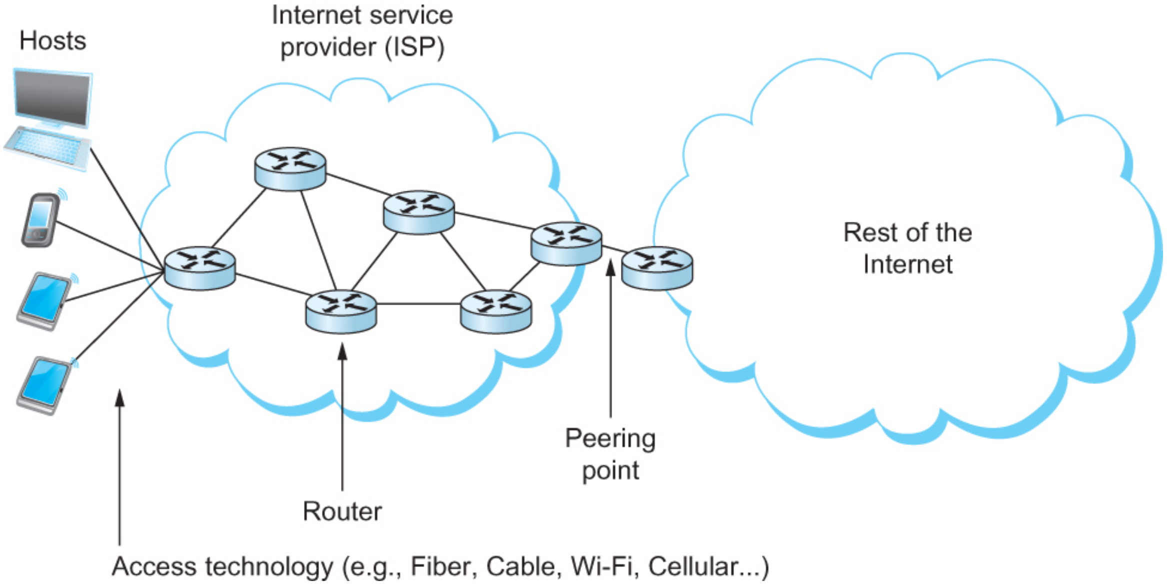
- Chapter 2:
  1. How do we transmit bits from one place to another?
  2. How do we aggregate bits into frames?
  3. How do we detect errors?
  4. How do we make links appear reliable?
  5. How do we share links between multiple hosts?

Overview

- Today:
  1. How do we transmit bits from one place to another?
     - Different transmission medium
     - Limits on transmission speed
     - Encoding bits onto the medium
  - Corresponds to OSI physical layer



A bird's-eye view



- All links conceptually the same
  - Both to end-user and to routers
  - But real details depend on physical link details

Transmission medium

- All links rely on electromagnetic radiation propagation through a medium
- Classes of transmission medium:
  - Guided media
    - Magnetic media
    - Cables
  - Unguided media
    - Wireless
    - Satellite

Magnetic media

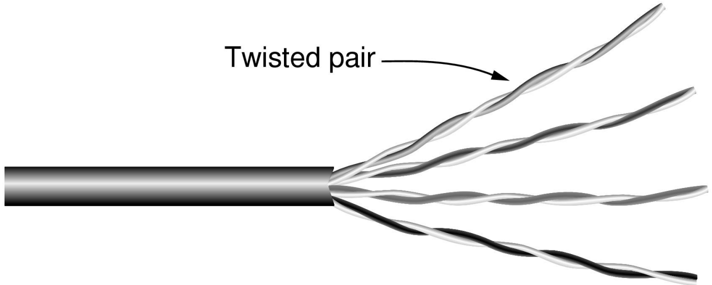
- Magnetic tape, removable media (DVD)
  - "sneakernet"
- Very high bandwidth for very low cost
  - 60 x 60 x 60 cm box holds 1000 800GB tapes
  - FedEx overnight, bandwidth: 70 Gbps
  - Cost: about 0.5 cents / GB

"Never underestimate the bandwidth of a station wagon full of tapes hurtling down the highway"

-Andrew Tanenbaum, Computer Networks 5th edition

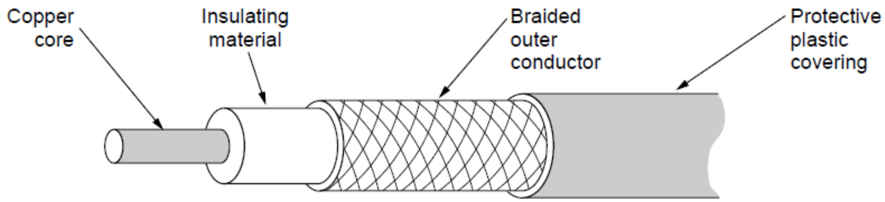
Twisted pairs

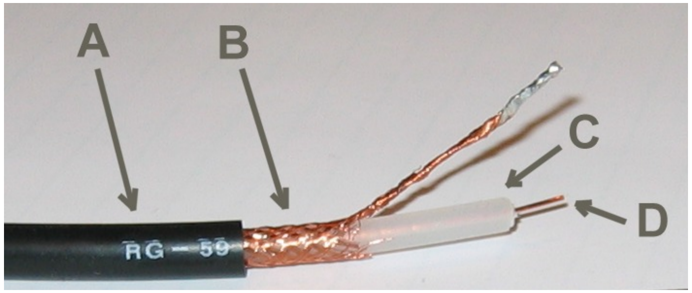
- Pairs of wires twisted together
  - Normally unshielded, just wires and insulation
  - Twists avoid wires becoming an antenna
  - Signal carried as difference in voltage between wires
    - Noise affects both wires similarly
  - Category 5 "cat 5" uses four pairs
    - 100 Mbps Ethernet uses two, one for reach direction
    - 1 Gbps Ethernet, all four in both directions simultaneously (cat 5e)
    - Bandwidth of 350 Mhz for cat 5e



Coaxial cable

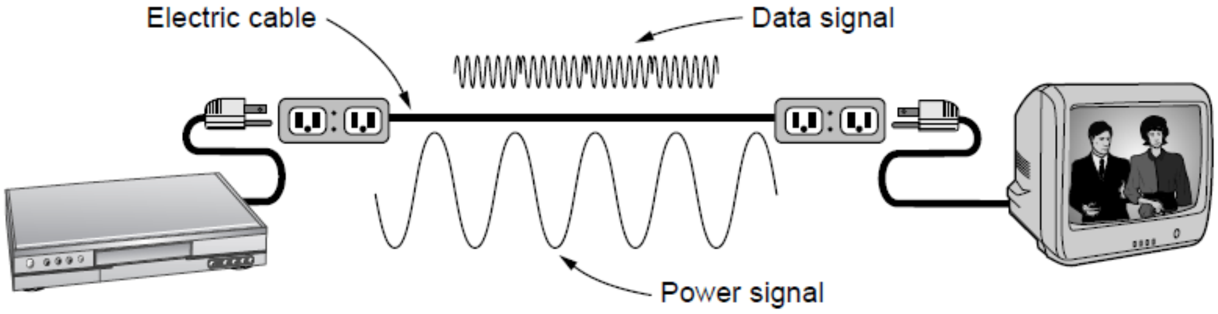
- Coaxial cable "coax"
  - Better shielding than unshielded twisted pair (UTP)
  - Longer distances
  - Greater bandwidth, up to a few GHz
  - Today, primarily last-mile
    - Yesterday: long-distance telephone trunks





Power lines

- Use existing power lines for networking
  - Advantages: no extra plug or radio
  - Disadvantages: wires vary in houses, vary with appliances, no twisting to cancel noise

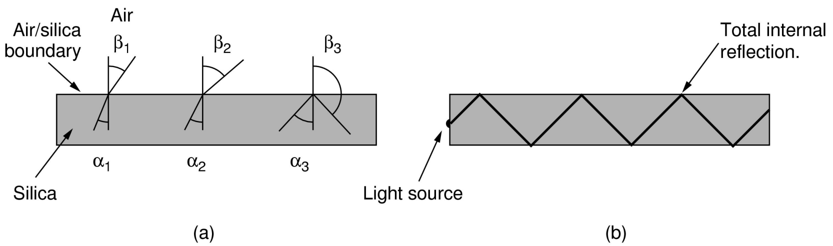


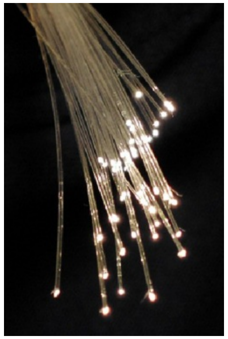
Computer industry improvements

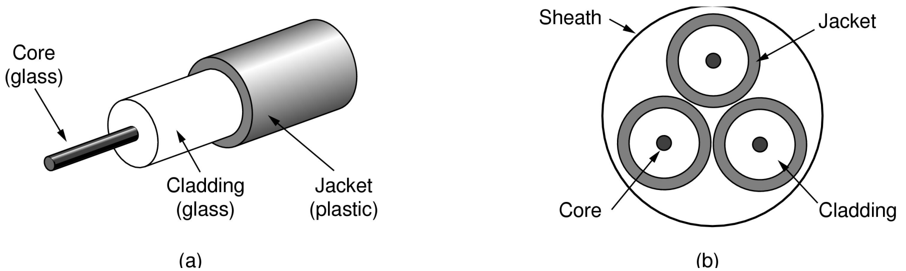
- Processing power
  - 1981 IBM PC, 4.77 Mhz
  - Today, 4-core CPU, 3 Ghz
  - Factor of 2500 increase
- Networking power
  - 1981, T3 telephone line, 45 Mbps
  - Today, modern long distance line, 100 Gbps
  - Factor of 2000 increase

Fiber optics

- Communication via light
  - Optical fibers conduct light
    - Via total internal reflection
  - Parts:
    - Light source (LED or semiconductor laser)
    - Transmission media (the glass fiber)
    - Detector (photodiode)
  - Very long distances (100km) without amplification
  - No interference from other cables
  - Difficult to tap



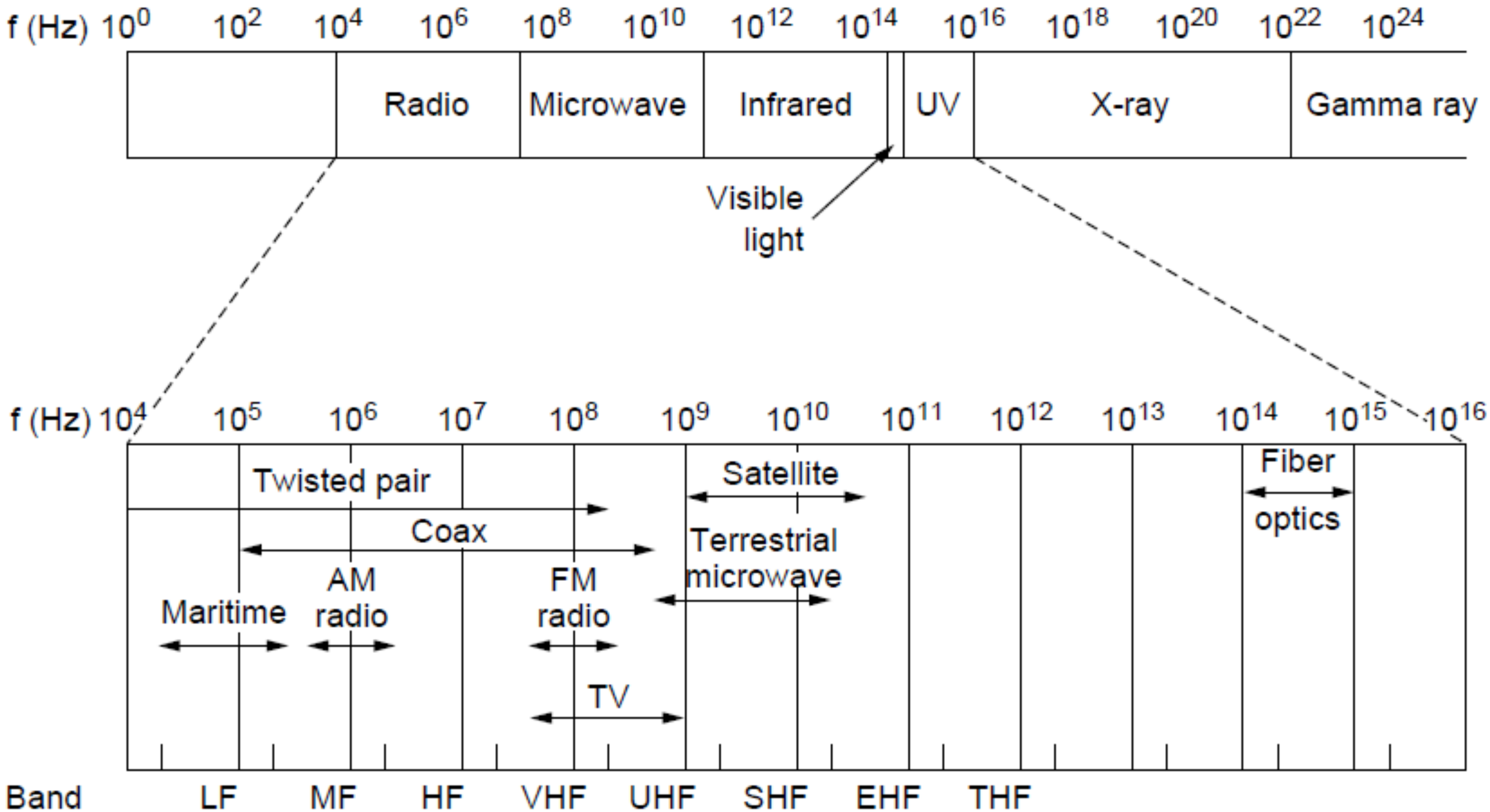




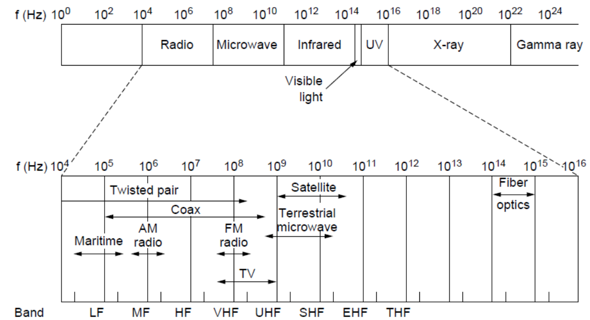
Fiber versus copper

- Fiber advantages
  - Higher bandwidth than copper
  - Lower attenuation, requires fewer repeaters
  - Not affected by electromagnetic interference
  - Thinner and lighter
  - Difficult to tap
- Fiber disadvantages
  - Less familiar technology
  - Damaged if bent too much
  - Fiber interfaces more expensive than electrical

Electromagnetic spectrum



Radio transmission



- Advantages:
  - Easy to generate
  - Penetrates buildings
  - Omnidirectional, no alignment of transmitter and receiver
  - Travels long distances
    - Signal drops same fraction as distance doubles
    - VLF, LF, MF bands follow curvature of earth
    - HF band bound off ionosphere

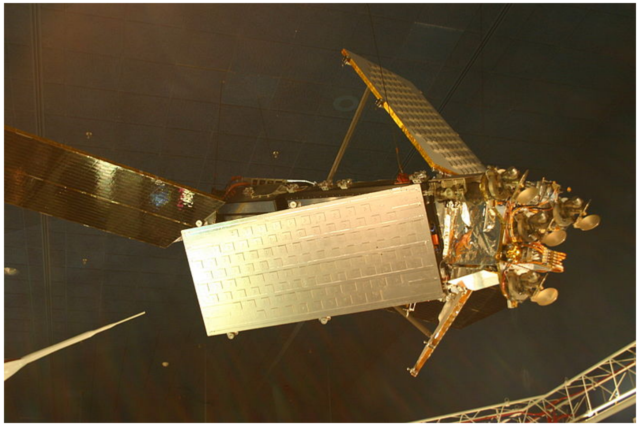
- Disadvantages:
  - Interference with other users
  - Strictly controlled by governments
  - Low bandwidth

Microwave

- Microwave transmission
  - Above 100 Mhz waves go in straight line
  - Focus into a beam with parabolic antenna
  - Use to be heart of long-distance telephone system
    - MCI = Microwave Communications, Inc.
  - Advantages:
    - No right of way needed to lay cable
    - Relatively inexpensive compared to laying cable
  - Disadvantages:
    - Earth gets in the way, 100 m tower → needs towers every 80 km
    - Refraction off low-lying atmosphere, multipath fading
    - Above 4 Ghz, absorbed by water

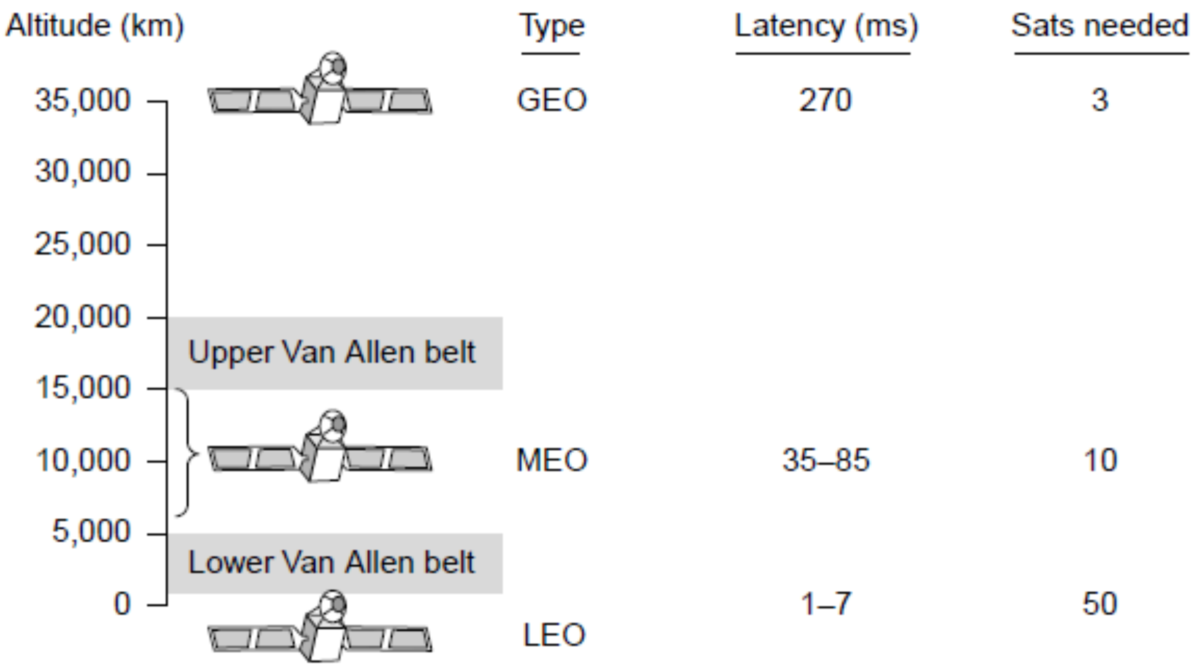
Satellite

- Communication satellites
  - Big microwave repeater in the sky
  - Transponders listen to portion of spectrum
  - Beams signal back to earth on different frequency
    - Wide beam, cover large portion of Earth
    - Spot beams, area a few hundred km in diameter



Satellite placement

- Geostationary satellites (GEO)
- Medium-Earth orbit (MEO)
- Low-Earth orbit (LEO)



Geostationary orbit

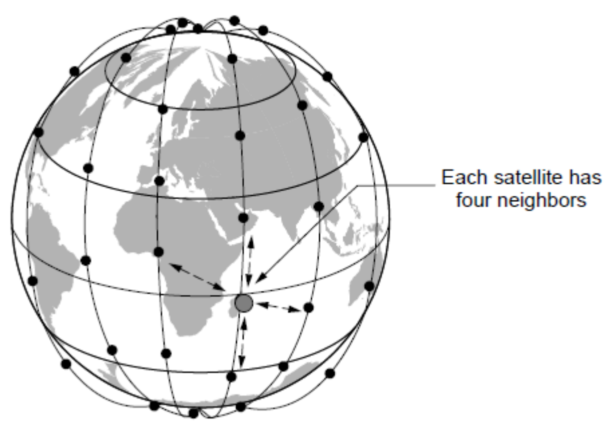
- Geostationary satellites
  - At altitude of 35,800km, satellite appears to remain motionless
  - Examples: DirecTV, Dish Network, HughesNet, WildBlue
  - Advantages:
    - No need to track, always in view
    - Inherently broadcast media
  - Disadvantage:
    - Long latency due to great distance
    - Only 180 or so in sky at once
    - Inherently broadcast media

Medium-Earth orbit

- Medium-Earth orbit satellites
  - Around 6 hours to circle Earth
  - Must be tracked as they move through sky
  - Lower so less powerful transmitter needed
  - Examples: GPS global positioning system (USA), Galileo (EU), GLONASS (Russia)

Low-Earth orbit

- Low-Earth orbit satellites
  - Rapid motion across sky
  - Large number needed for complete system
  - Close to ground, low latency and low power
  - Cheaper launch cost
  - Examples: Globalstar, Iridium, weather satellites



Satellite versus fiber

- Satellite advantages
  - Rapid deployment
    - Disaster response
    - Military communication
  - When terrestrial infrastructure poorly developed
  - Broadcasting is essential
    - TV or radio broadcast

Using the link

- Transmission speed is limited!
  - Shannon-Hartley Theorem
    - Upper bound to the capacity of a link as a function of the channel bandwidth and the signal-to-noise

$$C = B \log_2(1 + S/N)$$

where C is achievable capacity in bits-per-second (bps)

B is bandwidth of channel (Hz)

S is the average signal power

N is the average noise power

Link capacity

- Signal-to-noise ratio (SNR), expressed in decibels

  $SNR = 10 \log_{10}(S/N)$

- Example:
  - Channel capacity of a voice-grade phone line
  - Frequencies of 300 Hz to 3300 Hz
  - SNR of 30 dB, $30 = 10 \log_{10}(S/N)$

$C = B \log_2(1 + S/N)$

$B = 3000$ Hz

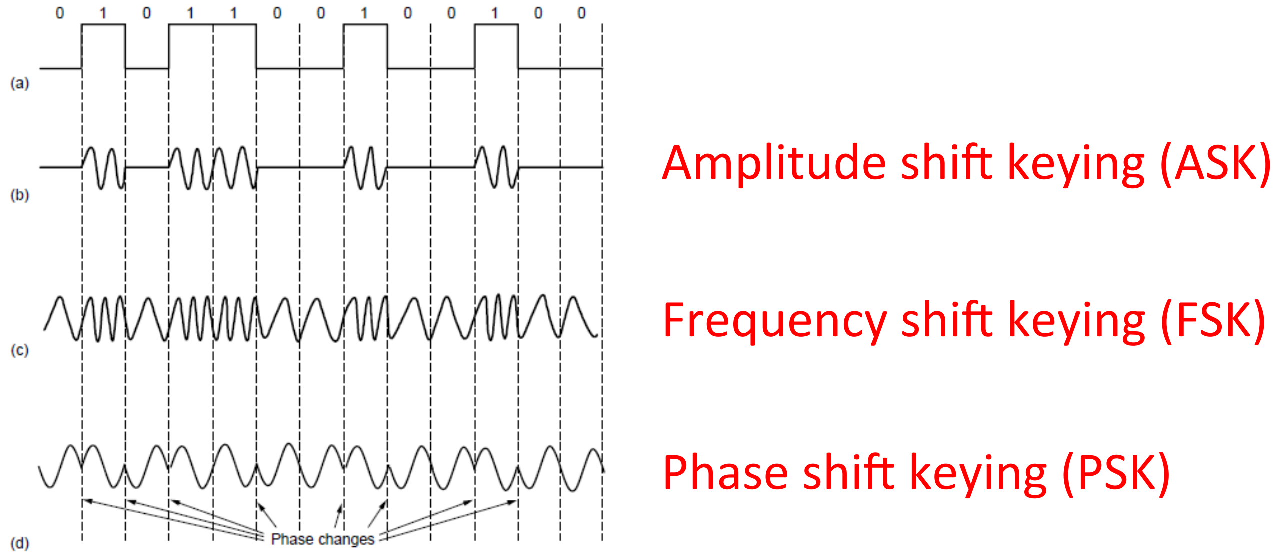
$S/N = 1000$

$C = 3000 \log_2(1001) = 30$ kbps

Service	Bandwidth (typical)
Dial-up	28–56 kbps
ISDN	64–128 kbps
DSL	128 kbps–100 Mbps
CATV (cable TV)	1–40 Mbps
FTTH (fibre to the home)	50 Mbps–1 Gbps

Encoding bits

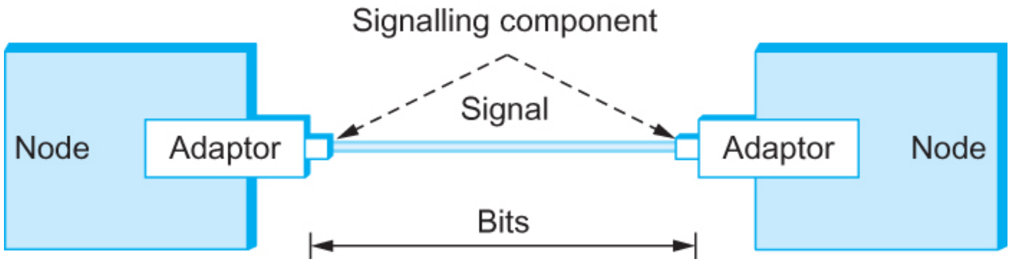
- Physical links allow us to propagate signals
- Modulate signal on link

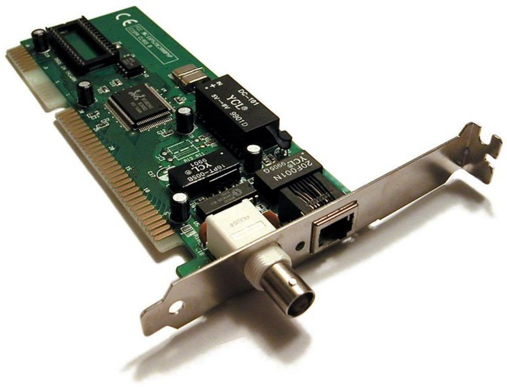


- We'll ignore the modulation details
  - Assume two discrete signals: high and low

Encoding bits

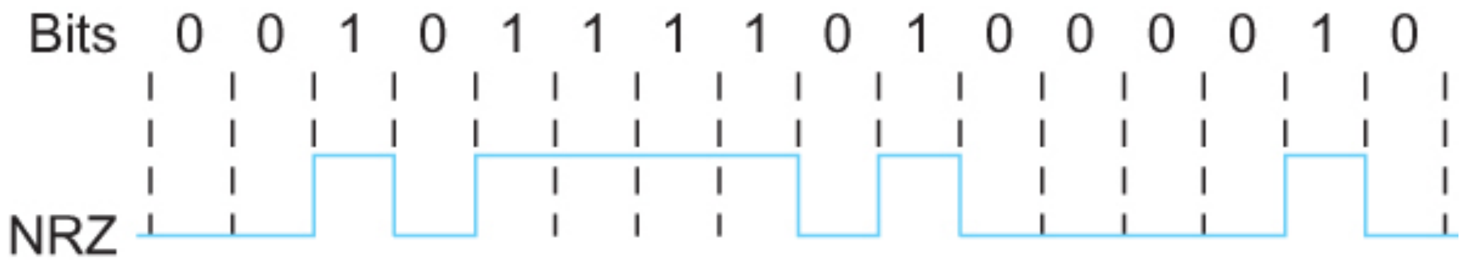
- Network adapter
  - Hardware the connects node to link
  - Send: encodes bits into signal
  - Receive: decodes signal into bits





Non-return to zero

- Non-return to zero (NRZ)
  - Use the obvious mapping:
    - Data value 1 high signal
    - Data value 0 low signal

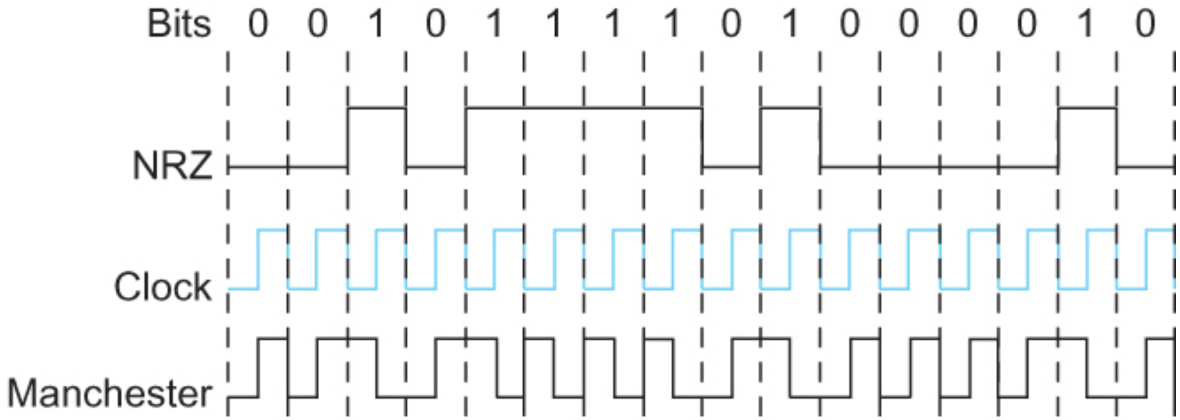


Problems with NRZ

- Non-return to zero (NRZ)
  - Problem 1: baseline wander
    - Receiver keeps average of signal seen thus far
    - Uses average to determine high versus low
    - Too many consecutive 0s or 1s, biases average
  - Problem 2: clock recovery
    - Encoding and decoding driven by clock
    - Synchronization required between sender and receiver
      - Adjust clock on transition from high-to-low or low-to-high
    - Too many consecutive 0s or 1s, clocks diverge

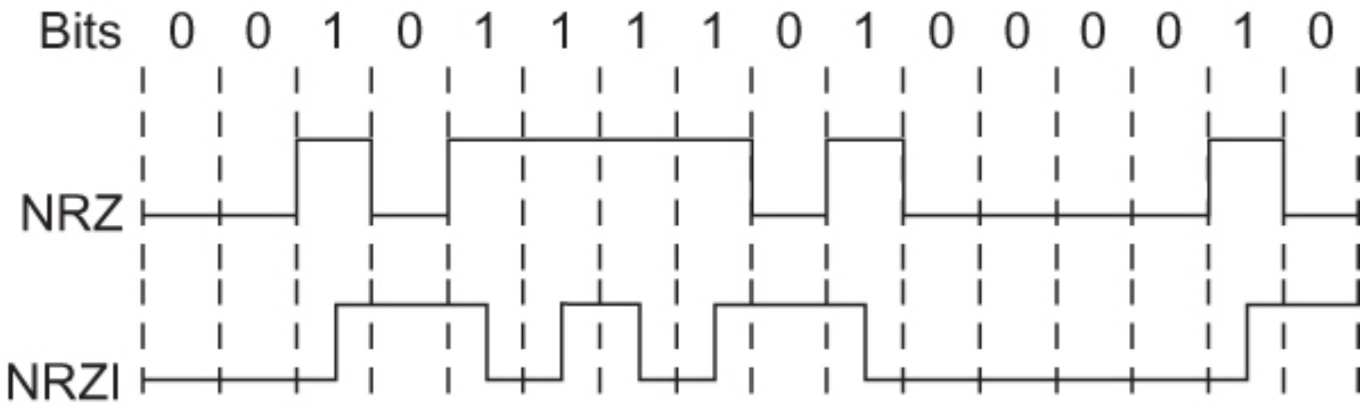
Manchester encoding

- Manchester encoding
  - XOR bits with clock signal
  - 0 bit is low-to-high transition
  - 1 bit is high-to-low transition
  - Disadvantage: requires twice the bit rate
  - Used in 10 Mbps Ethernet



Non-return to zero inverted

- Non-return to zero inverted (NRZI)
  - To send a 1: transition from current level
  - To sent a 0: stay at current level
  - Solves consecutive 1s problem
  - Still have problem for consecutive 0s



4B/5B encoding

- 4B/5B encoding
  - Every 4 bits encoded as 5 bits
  - Avoid runs of 0s, choose code words smartly:
    - No more than one leading 0
    - No more than two trailing 0s
    - Thus no pair of code words has > three consecutive 0s
  - Transmit using NRZI (avoids runs of 1s)
  - 80% efficiency
  - Used in 100 Mbps Ethernet

4B/5B encoding

- 4-bit signal = 16 possibilities
- 5-bit code word = 32 possibilities
  - 11111 idle link
  - 00000 dead link
  - 00100 halt
  - 6 valid remaining:
    - Control symbols

Data (4B)	Codeword (5B)	Data (4B)	Codeword (5B)
0000	11110	1000	10010
0001	01001	1001	10011
0010	10100	1010	10110
0011	10101	1011	10111
0100	01010	1100	11010
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101

Other encoding

- 8B/10B encoding
  - Similar idea as 4B/5B
  - Encode 8 bits using 10 bits
  - At most 5 consecutive 0s or 1s
  - 80% efficiency
  - Used in Gigabit Ethernet, SATA, USB 3.0, etc.
- 64B/66B encoding
  - More efficient that 4B/5B, 8B/10B
  - Used in 10 Gigabit Ethernet

Summary

- Physical connectivity
  - Twisted pair, coax, fiber
  - Terrestrial radio, microwave
  - Satellite
- Encoding bits
  - Must be clever to avoid problems
  - NRZI plus code: 4B/5B, 8B/10B, etc.