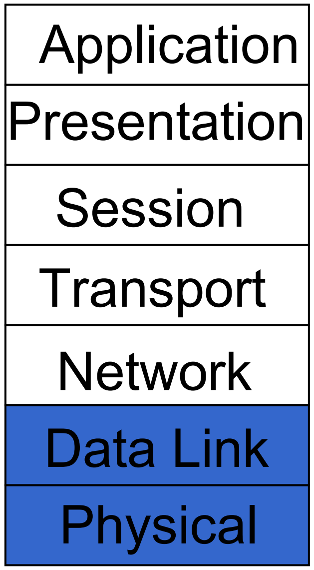
PHY and Link layers

- Key question: How do we send a message across a wire?

- The physical / link layers:
  1. Different kinds of media
  2. Encoding bits, messages
  3. Model of a link

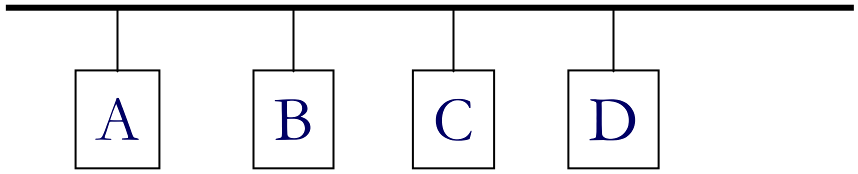


Application
Presentation
Session
Transport
Network
Data Link
Physical

Direct Link Networks

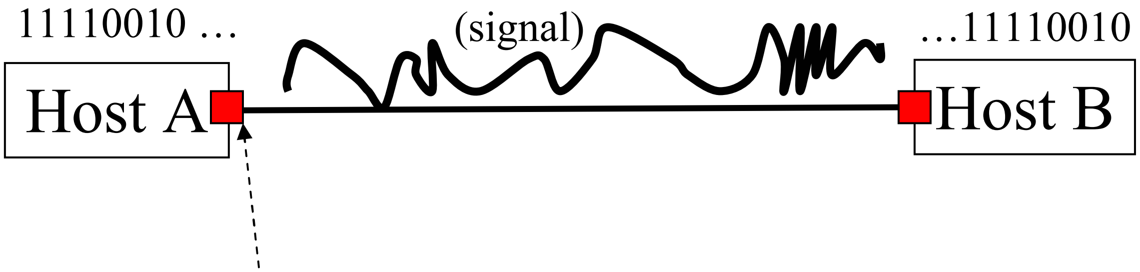
"Direct link" ⇒ no switching/routing

Point-to-point, e.g,
Gigabit Ethernet (GigE)



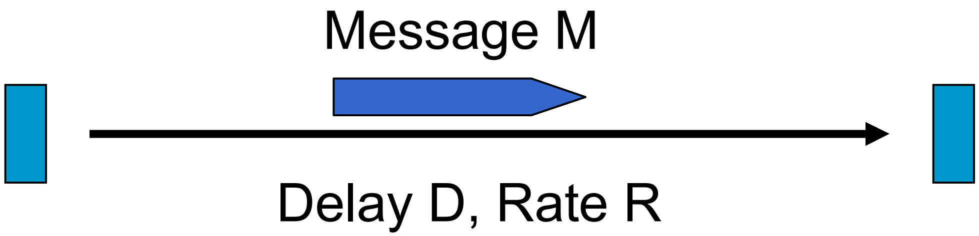
Broadcast / shared,
e.g., 802.11 (WiFi)

Relationship to the hardware



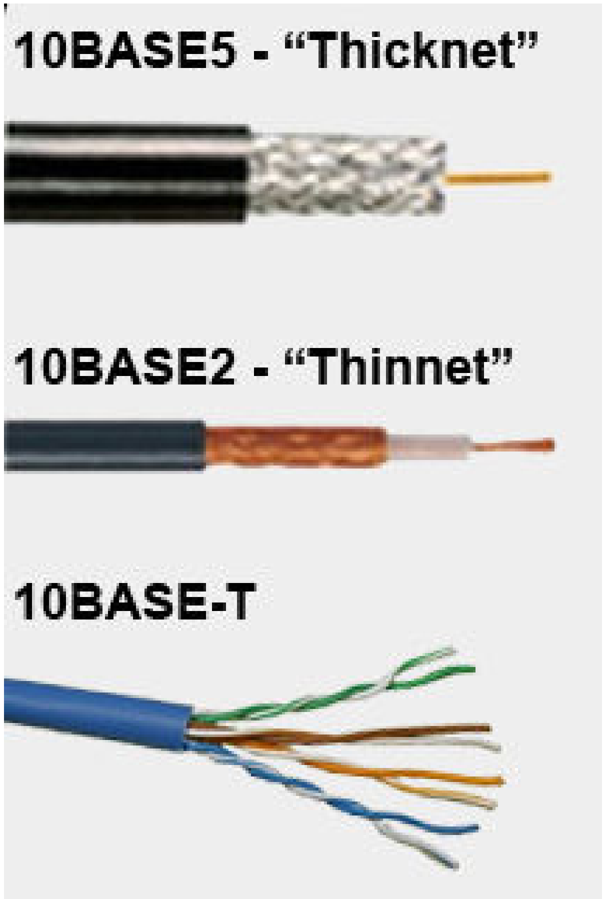
Network interface cards (NICs)
(also called “network adaptors”)

What really happens



Abstract link for our purposes

Wires



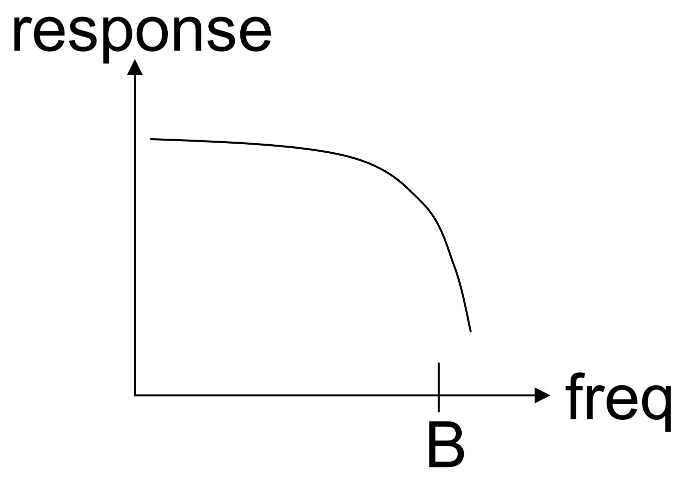
Now Cat 6, Cat 7 for GigE, four pairs

- Twisted pairs: twists reduce RF emission / crosstalk; also shielding can be added
- Coaxial cable: inner and outer ring conductor for superior noise immunity
- Many different specs/grades depending on application
- 100s of MHz for 100s of meters

Model of a wire

- Frequencies beyond cutoff highly attenuated
  - Bandwidth = passband (Hz)

- Signal also subject to:
  - Attenuation (repeaters)
  - Distortion (frequency and delay)
  - Noise (thermal, crosstalk, impulse)



EE: Bandwidth = width of frequency passband, measured in Hz

CS: Bandwidth = information carrying capacity, measured in bits/sec

(signals over a wire)

- If we send a waveform, what do we get out?
  - quiz on possibilities

- What do we want to get out?
  - quiz on fidelity

Fundamental Limits

- Nyquist rate on maximum symbols/second:

  $R < 2B$

  - Channel is bandwidth-limited to B

- Shannon capacity of a channel:

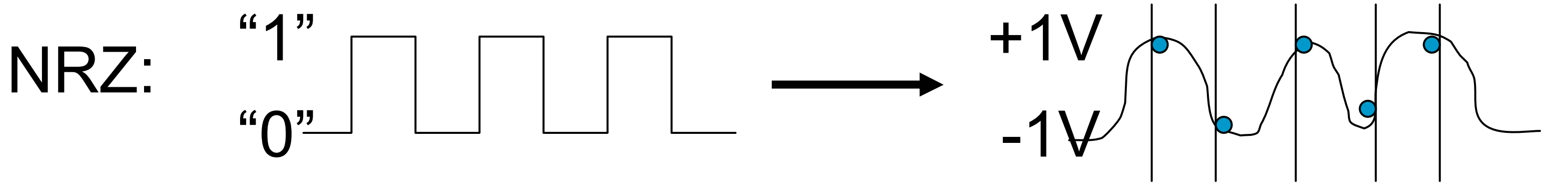
  $C = B \,.\, \log_2 ((S + N) / N)$

  - N is additive-white-Gaussian-noise (AWGN)

- Bandwidth and signal power define fundamental limits

Encoding Bits with Signals

- Generate analog waveform (e.g., voltage) from digital data at transmitter and sample to recover at receiver

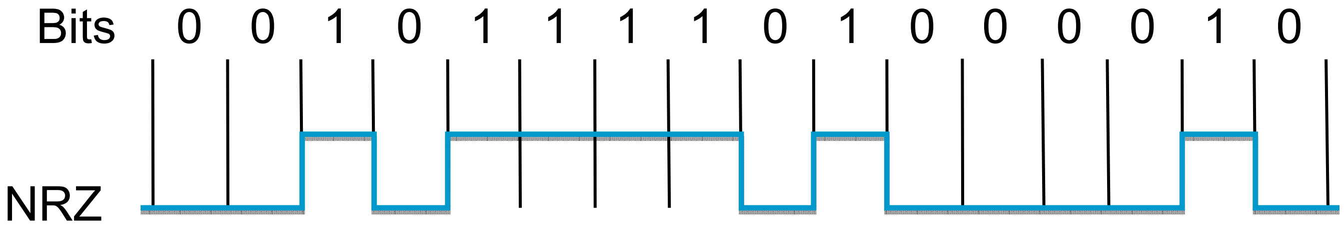


- We send/recover symbols that are mapped to bits
  - May have >2 different symbols, e.g., amplitudes
  - Thus distinguish symbol rate versus bit rate

- This is baseband transmission

NRZ

- Simplest encoding, NRZ (Non-return to zero)
    - Use high/low voltages, e.g., high = 1, low = 0



Issue: Clock recovery

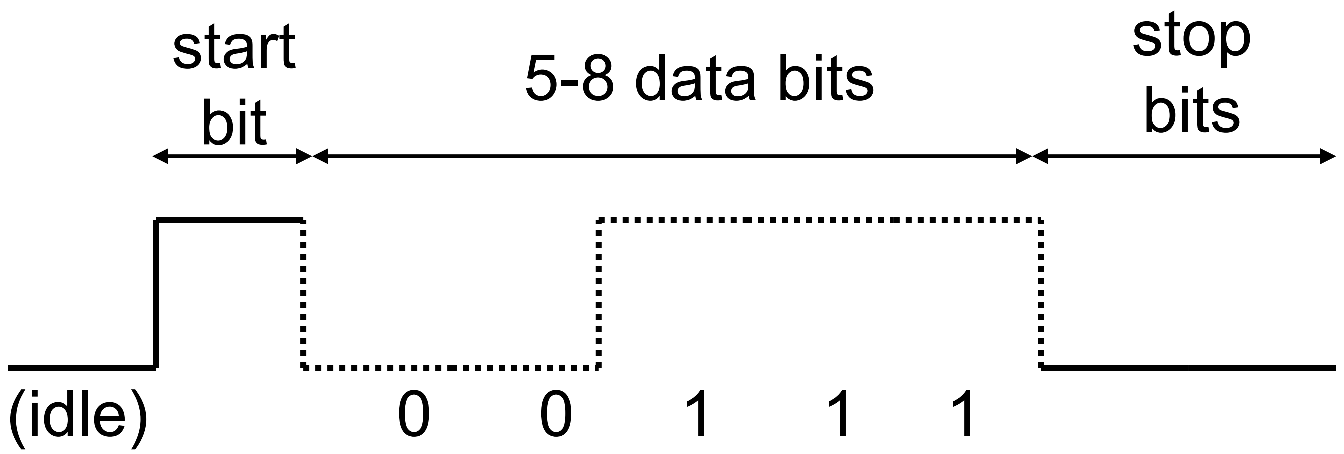
- Um, how many zeros was that again?

If sender and receiver have exact clocks no problem. But they don’t!

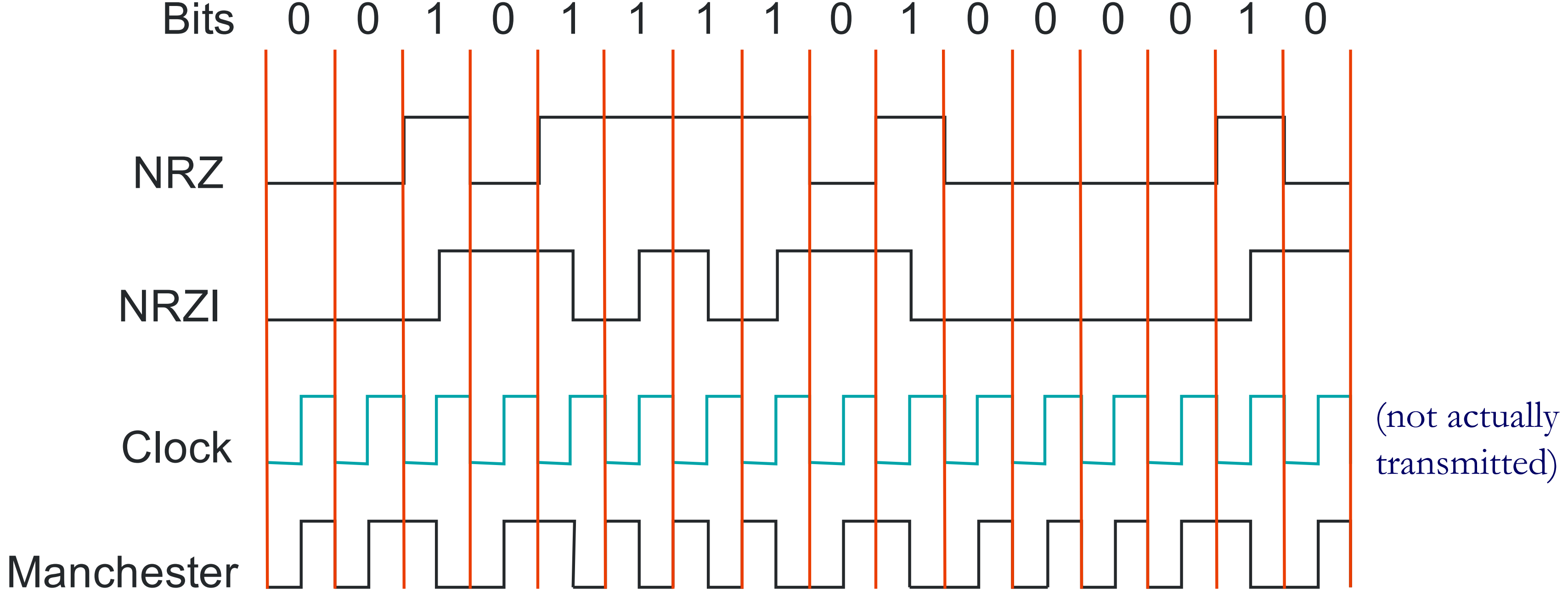
- Any brilliant ideas?
- 1.
- 2.
- 3.
- 4.

Send short messages

- Avoid timing problem by sending short, delimited data with a well-defined beginning
  - E.g., UARTs (typically used to connect your keyboard)



Embed clock in signal (Manchester)



- Signal is XOR of data (NRZ) and clock (transition per bit)
  - Low-to-high is 0; high-to-low is 1
  - Signal rate is twice the bit rate
- Advantage: self-clocking, Disadvantage: BW inefficiency

4B/5B Codes

- We want self-clocking transitions *and* efficiency …
- Solution: map data bits (which may lack transitions) into code bits (which are guaranteed to have them)

- 4B/5B code:
  - 0000 → 11110, 0001 → 01001, … 1111 → 11101
  - Never more than three consecutive 0s back-to-back
  - 80% efficiency, plus use “illegal” codes as markers

- Many more complex codes are available; some use multiple voltage level

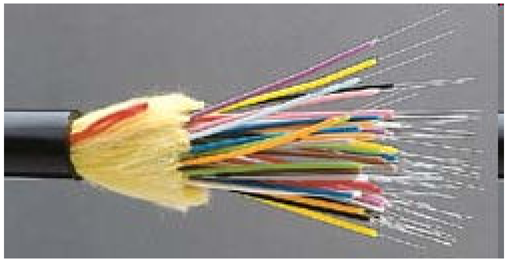
Scrambling

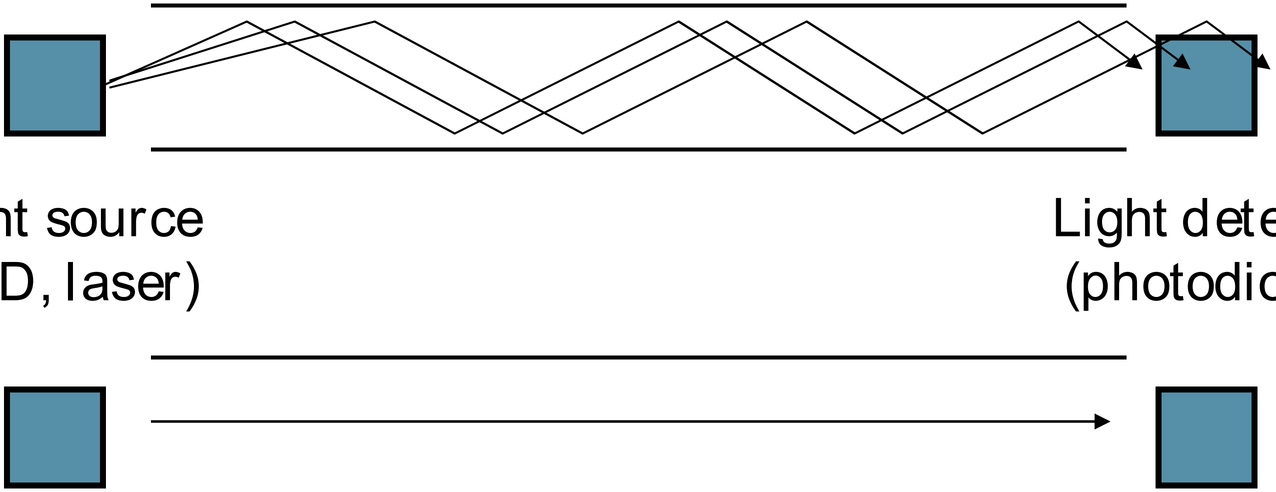
- XOR data with known pseudo-random sequence
  - Can generate cheaply with linear feedback shift registers (LFSR)
  - Causes transitions with reasonable probability
  - Also tends to whiten data (better for RF)

- Reverse at receiver by XORing with same sequence

Fiber Optic Cable

- Long, thin, pure strand of glass
  - light propagated with total internal reflection
  - enormous bandwidth available (terabits)





Multi-Mode

Light source
(LED, laser)

Light detector
(photodiode)

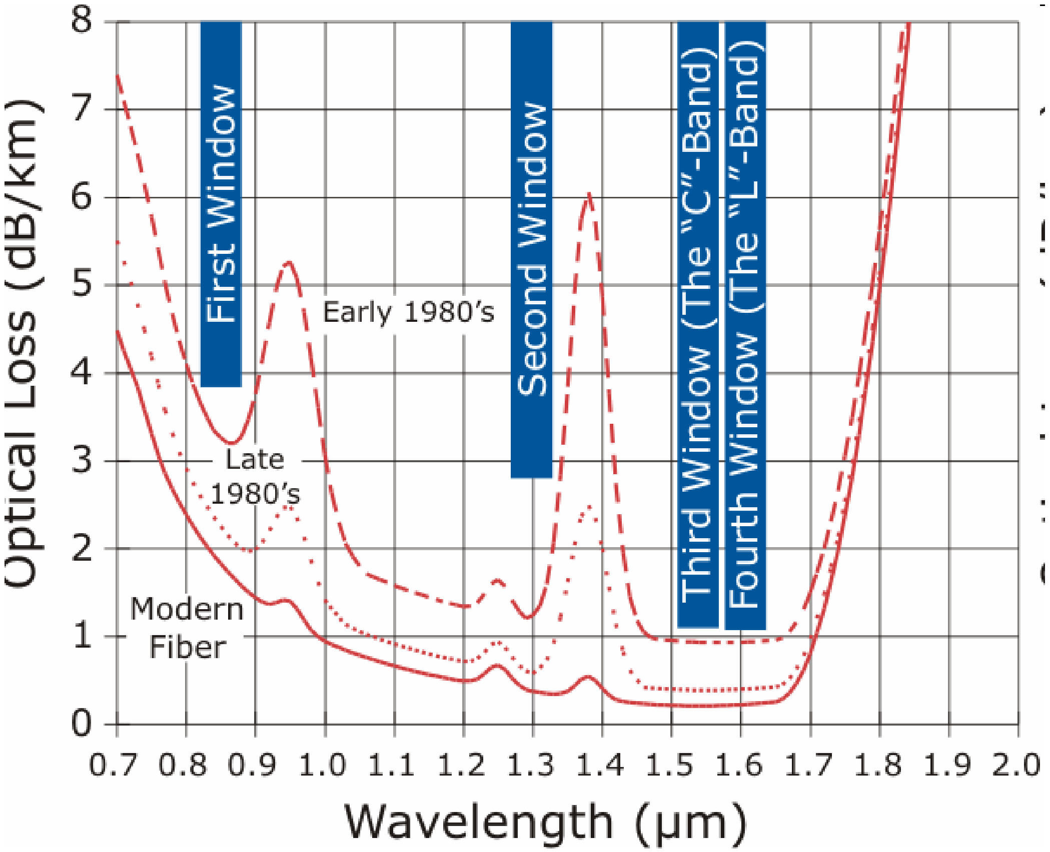
Single-Mode

Light source
(LED, laser)

Light detector
(photodiode)

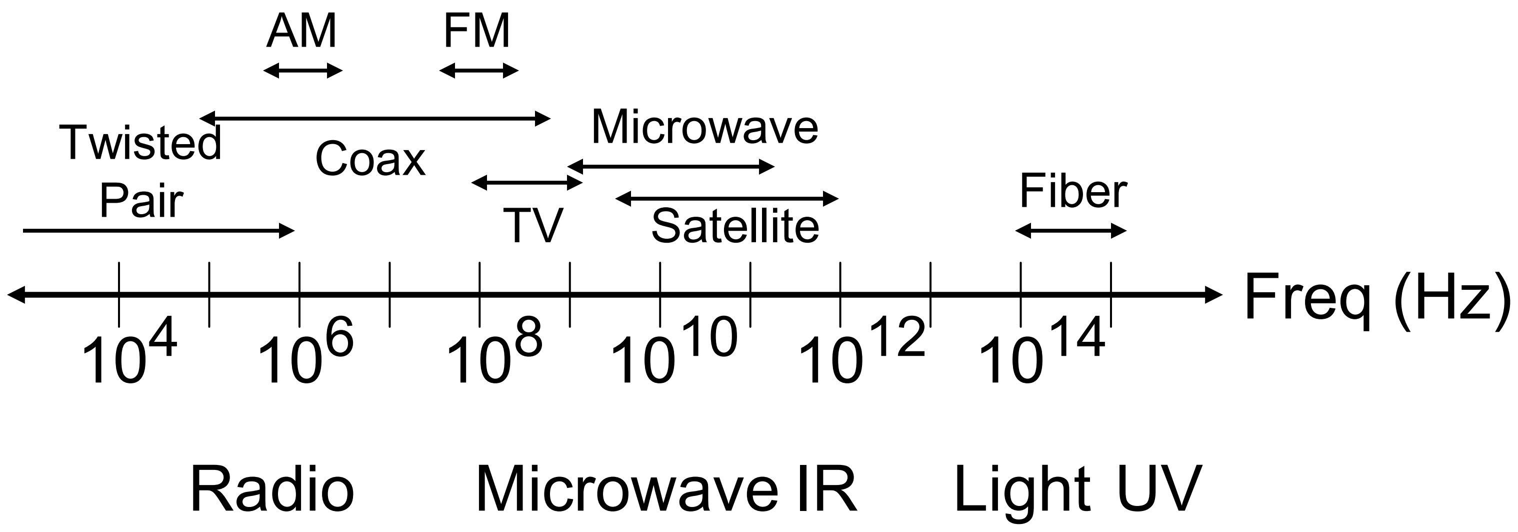
Attenuation of optic fiber

- Enormous bandwidth in each window



Wireless

- Different frequencies have different properties
  - Tend to bounce off object >> wavelength
  - Antenna size related to wavelength
  - Higher frequencies more directional, e.g., light
  - Signals subject to atmospheric/environmental effects



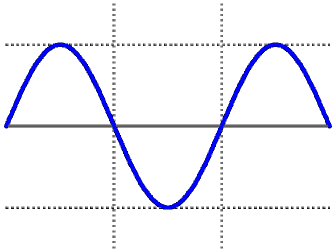
US Frequency Allocations

- http://www.ntia.doc.gov/osmhome/allochrt.pdf

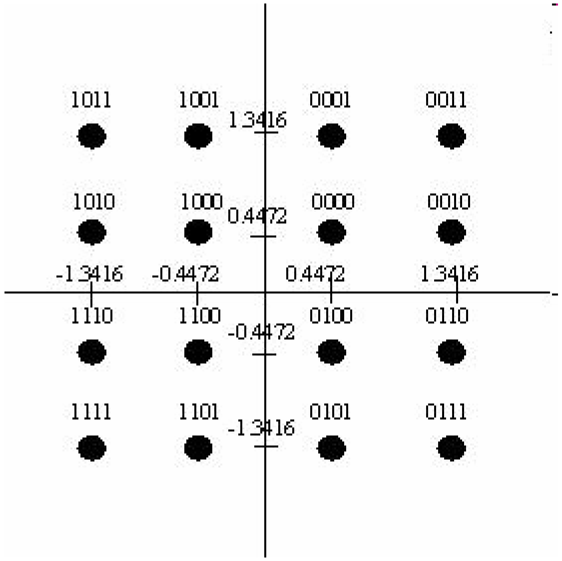
Modulation

- For wireless, fiber, need to encode signal by modulating carrier wave … can't propagate at baseband

- Modulate: can change
  - Amplitude
  - Phase/frequency



  - BPSK, QPSK … QAM
  - Express as constellation



QAM 16 constellation
in HSPDA

Framing

- Need to send message, not just bits
  - Requires that we synchronize on the start of message reception at the far end of the link
  - Complete Link layer messages are called <u>frames</u>

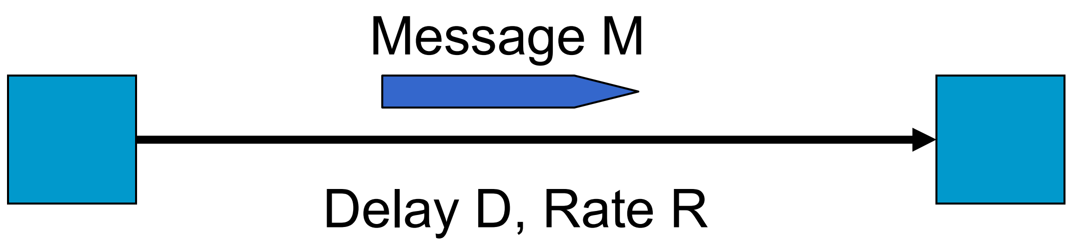
- Common approach: Sentinels
  - Look for special sequence that marks start of frame, e.g., preamble in 802.11, 0x7E in PPP
  - May escape or “stuff” this code within the data region, e.g., PPP
    - Like a C compiler: A quotation mark (“) is a string sentinel, so (\”) means (“)
  - May give length of frame with header, e.g., SONET, 802.11

Model of a Link

- Abstract model is typically all we will need
- Other parameters that are important:
  - The kind and frequency of errors (bit error rate, BER)
  - Whether the media is broadcast or not

Message Latency

- How long does it take to send a message?



- Two terms:
  - Propagation delay = distance / speed of signal in media
    - How quickly a message travels over the wire
    - 2/3c for copper wire
  - Transmission delay = message (bits) / rate (bps)
    - How quickly you can inject the message onto the wire
  - Propagation delay tells you when the FIRST bit arrives, Transmission delay tells you when the LAST bit arrives.
- Later we will see queuing delay …

One-way Latency

Dialup with a modem:

  - D = 10ms, R = 56Kbps, M = 1024 bytes
  - Latency = 10ms + (1024 x 8)/(56 x 1024) sec = 153ms!

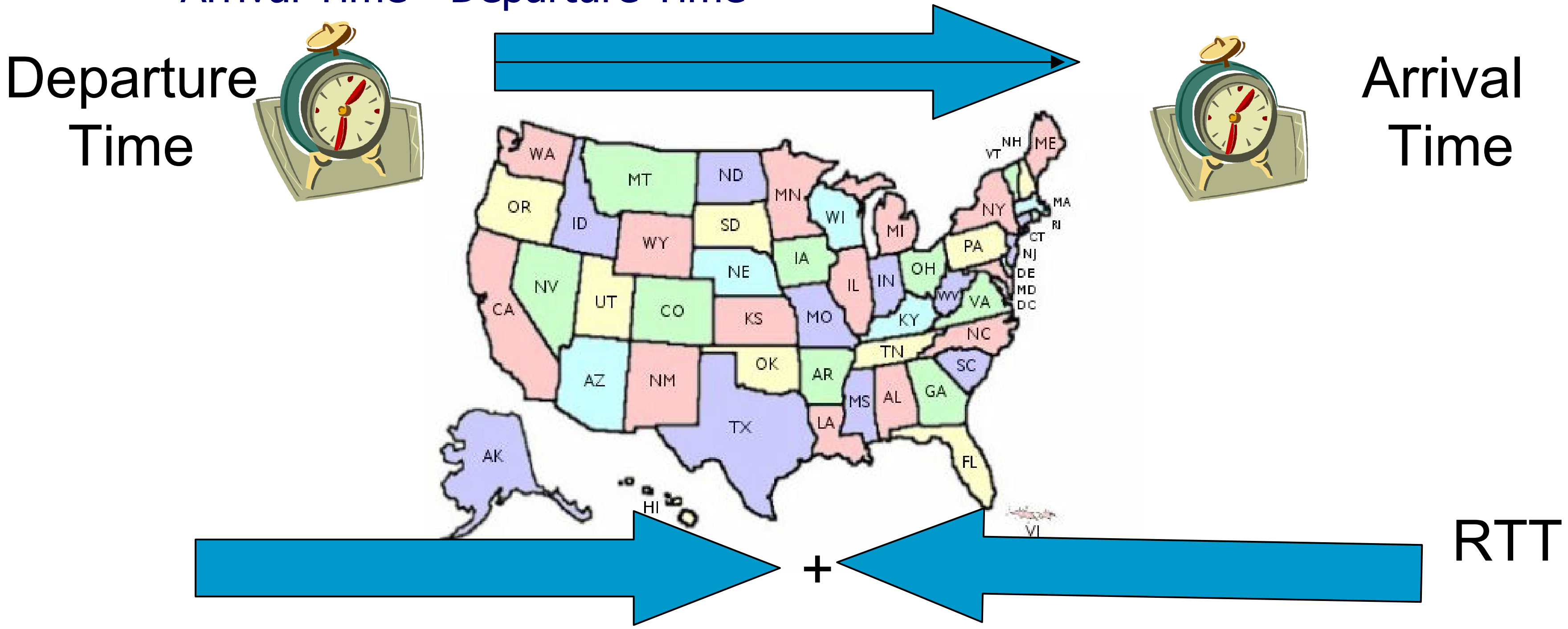
Cross-country with T3 (45Mbps) line:

  - D = 50ms, R = 45Mbps, M = 1024 bytes
  - Latency = 50ms + (1024 x 8) / (45 x 1024*1024) sec = 50ms!

- Either a slow link or long wire makes for large latency

Latency and RTT

- Latency is typically the one way delay over a link
  - Arrival Time - Departure Time



- The round trip time (RTT) is twice the one way delay
  - Measure of how long to signal and get a response

Throughput

- Measure of system’s ability to “pump out” data
  - NOT the same as bandwidth
- Throughput = Transfer Size / Transfer Time
  - E.g., “I transferred 1000 bytes in 1 second on a 100Mb/s link”
    - BW?
    - Throughput?
- Transfer Time = SUM OF
  - Time to get started shipping the bits
  - Time to ship the bits
  - Time to get a response if necessary

Messages Occupy Space On the Wire

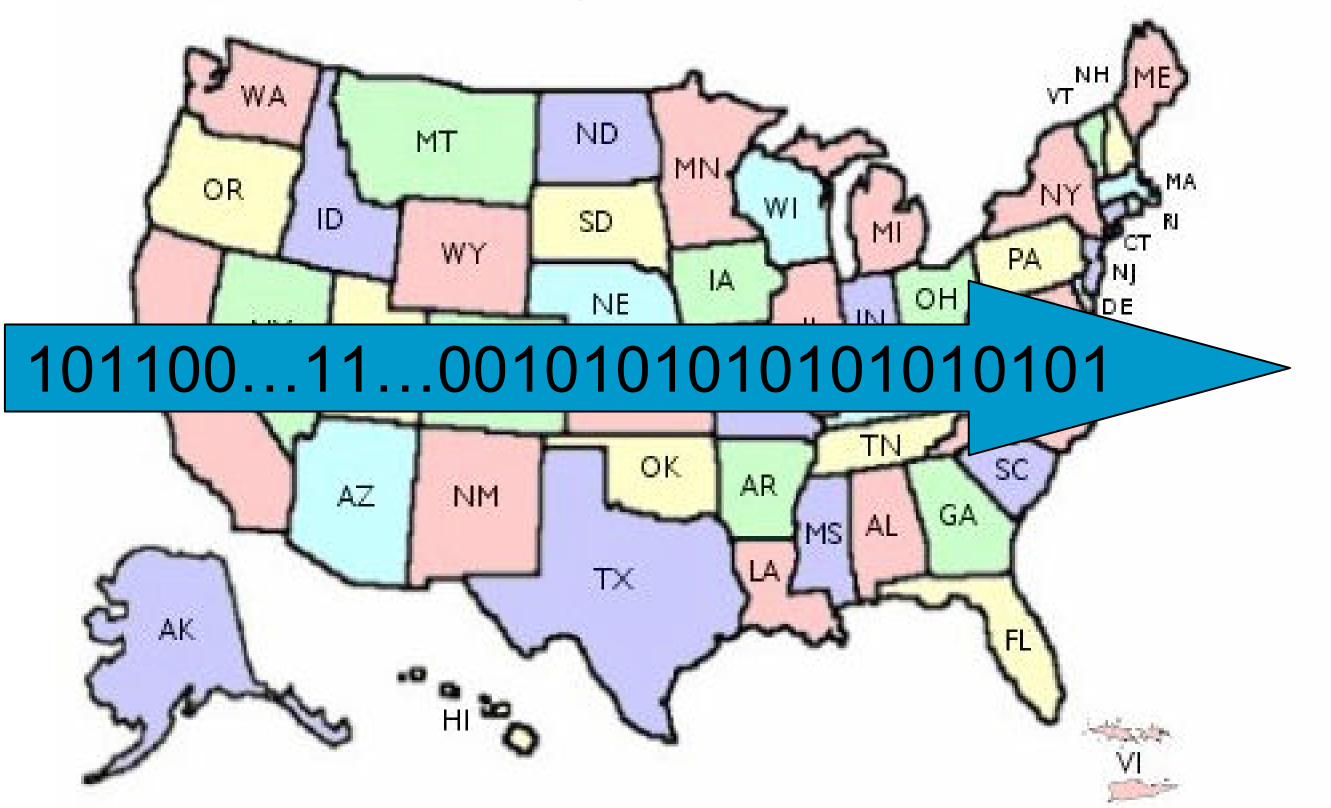
- Consider a 1b/s network.

- Suppose latency is 16 seconds.
  - How many bits can the network “store”
  - This is the BANDWIDTH-DELAY product
  - Measure of “data in flight.”
  - 1b/s * 16s = 16b

- Tells us how much data can be sent before a receiver sees any of it.
  - Twice B.D. tells us how much data we could send before hearing back from the receiver something related to the first bit sent.
  - What are the implications of high B.D.?

A More Realistic Example

BD = 50ms * 45Mbps = 2.25 * 10^6 = 280KB



We’ll see why this is important when we learn about TCP