02 - Physical Layer

Signal Modulation

Modem

- Modulation and demodulation of digital signal to analog to digital

Physical Layer

- possibly faulty, single hop, bit-pipe that connects 1 sender to possibly Many receivers; e.g., morse code:
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    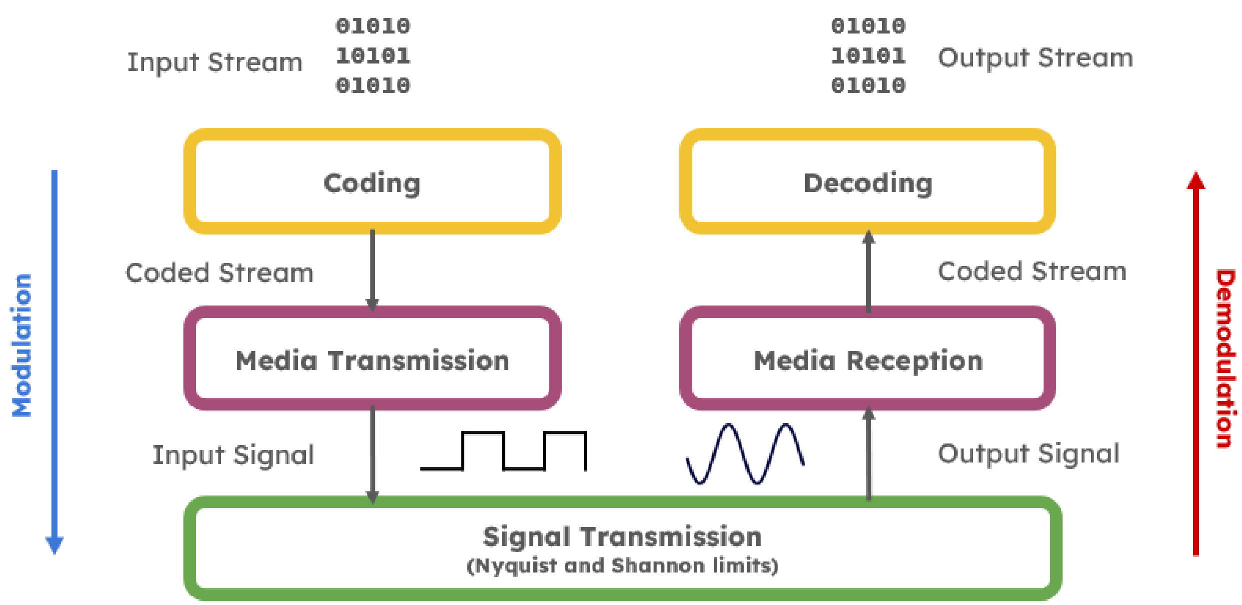

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- Constraints at every sublayer

Top Sublayer
How senders and receivers synchronize to sample analog signals to bits

Middle Sublayer
Properties of particular media — e.g. satellites, coaxial cable, fiber

Bottom Sublayer
Essential properties of the media (bandwidth, noise)
These influence data transmission rates (Nyquist, Shannon limits)

Bot Sublayer: Signal Transmission Limits

- transmission done on light: 0=low,1=high
- distortion is inevitable so:

How do we predict output of energy on channel?

Answer:
Fourier Analysis

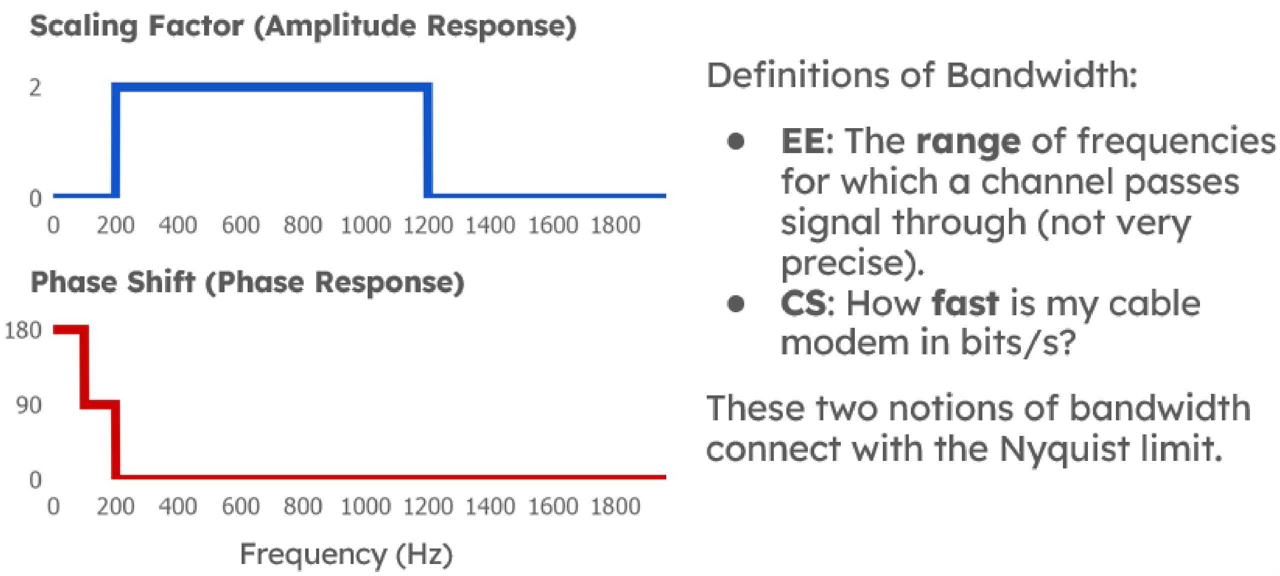
How does distortion affect maximum bit rate?

Answer:
Nyquist (sluggishness) and Shannon (noise) limits

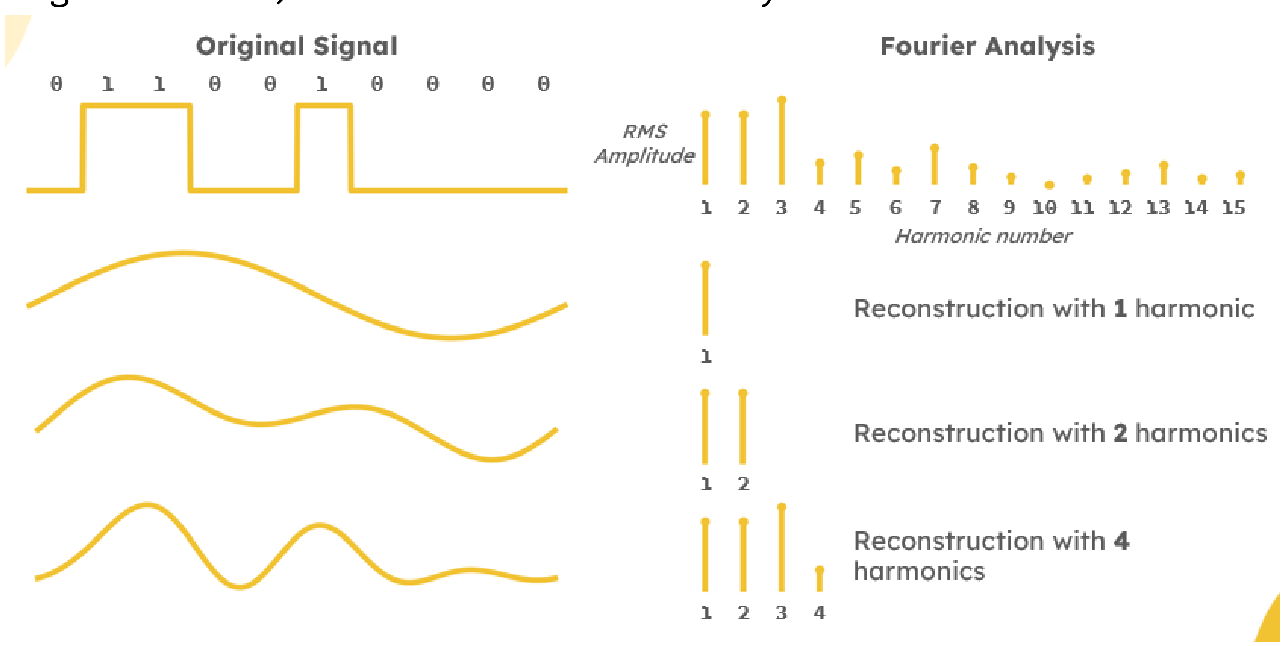
Fourier Analysis

- we can describe a channel by plotting the amplitude and phase of a signal S over all frequencies s.t. a wave of frequency f is scaled by fixed $a(f)$ (amplitude) and shifted by fixed $p(f)$ (phase)

- to then find the original signal, we write S as a sum of sine waves with diff frequencies using the amplitude and phase response to guage the difference and add the scaled sine waves to the fourier
- EE - range of signal freqs; CS - speed of cable modem in bits/s

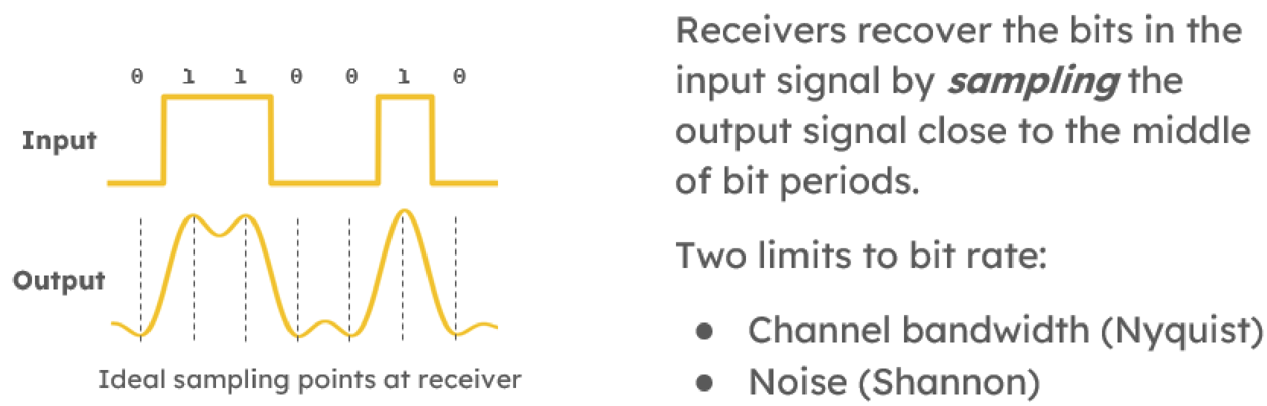


- higher bandwidth = higher fidelity (easier to distinguish high and low) = better bit recovery



- thus, lower bandwidth means more sluggish response as channels can't infer signals past a certain frequency

- most common noise is white noise - uniformly distributed across all freqs and normally distributed within a specific freq



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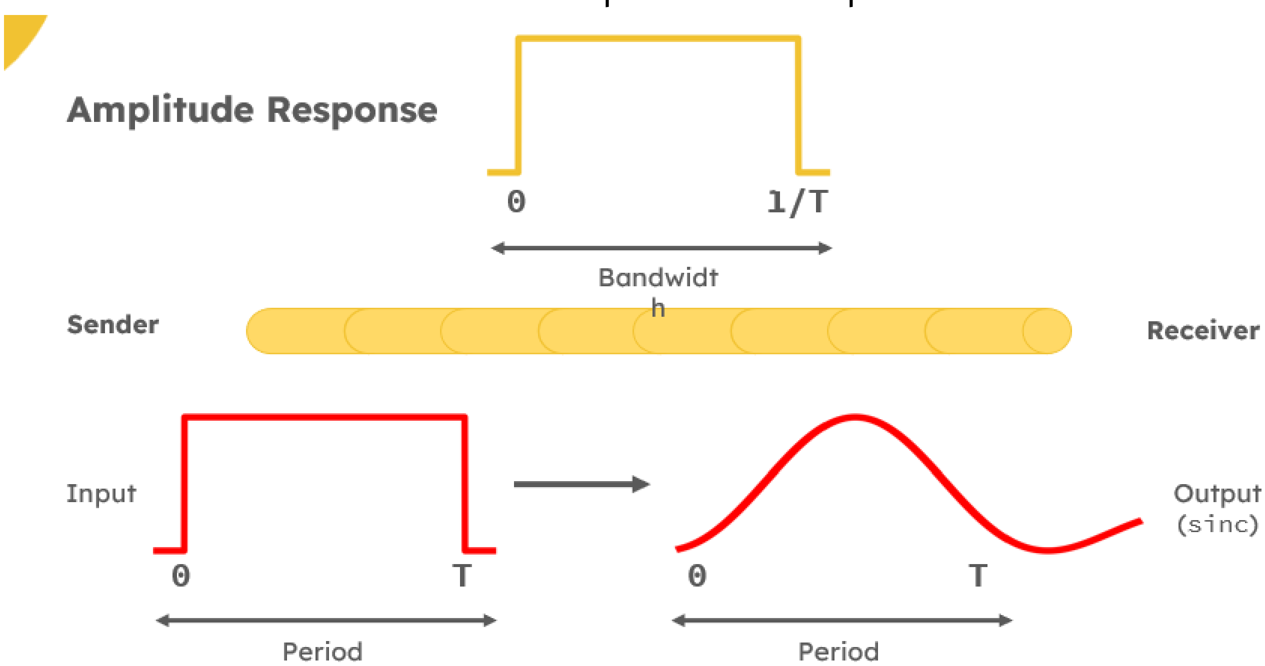
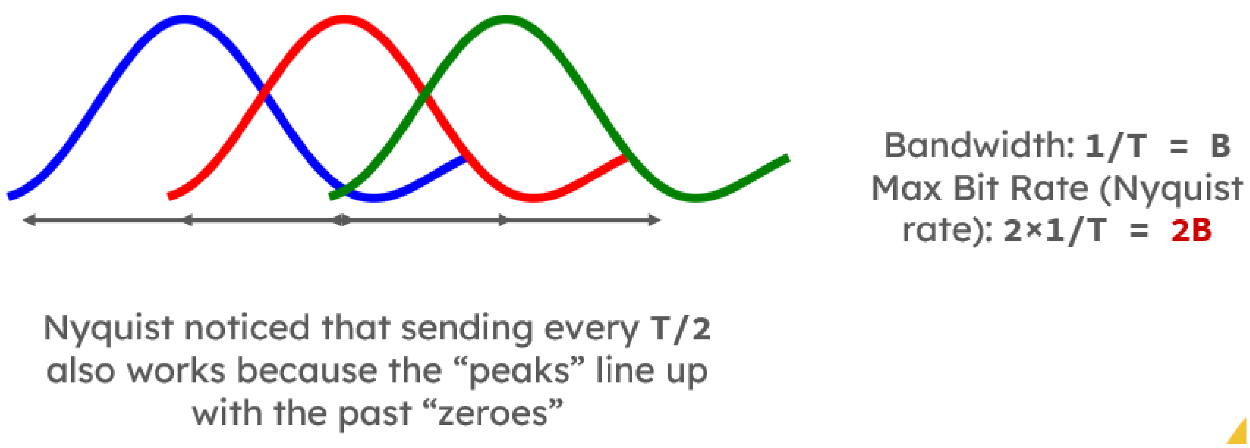
Nyquist Limit

- Given a bandwidth for an amplitude response:



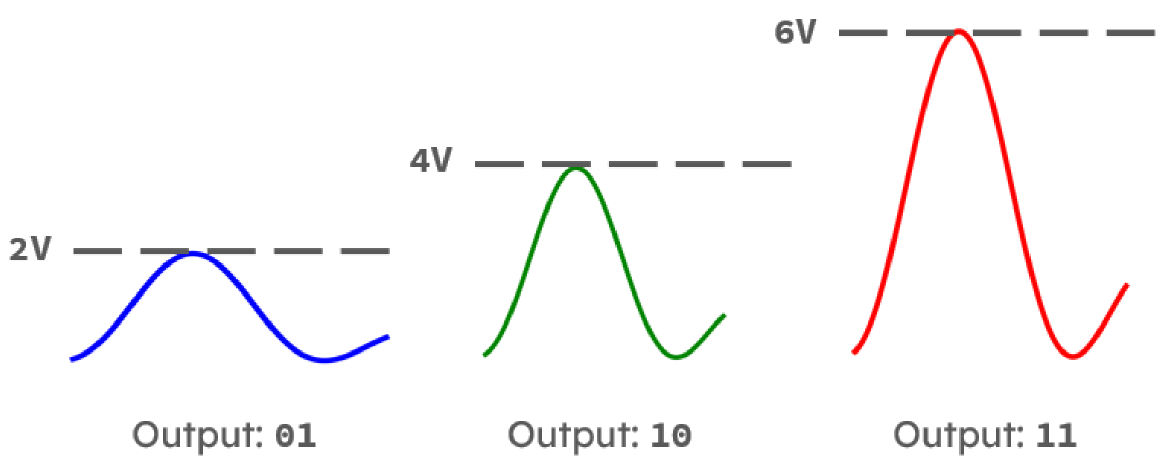
- we can send signals without intersymbol interference (ISI) up to a rate of **2xBandwidth** / second

- this is the limit of sending symbols not bits (baud rate)

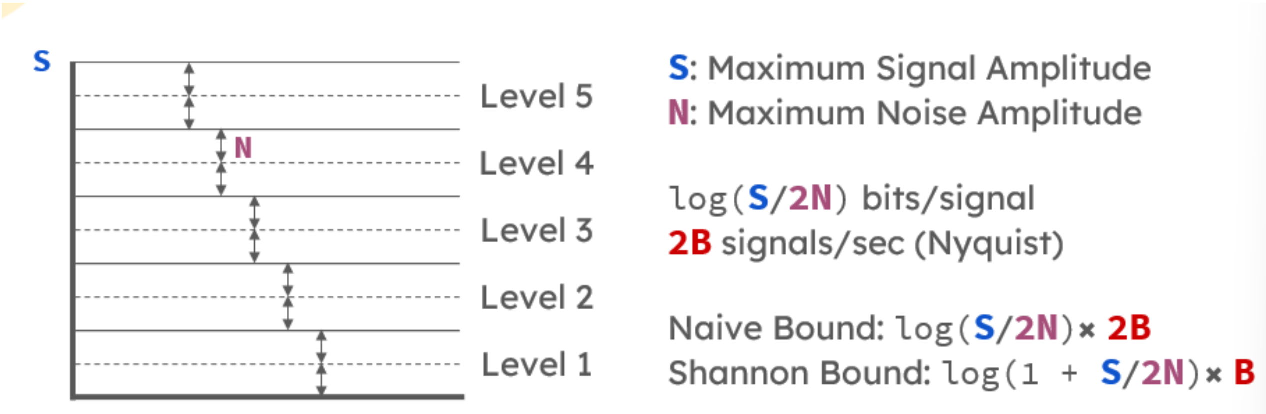


Shannon Limit

- speed of transmission depends on noise and bandwidth
- see that we can send multiple bits over a single wave:



- Thus baud rate for L signal levels is = $\log L \times 2B$
- noise messes with the amplitudes, so we set Shannon bounds



The real Shannon bound `log(1 + S/2N)` × **B** is slightly different than the naive bound `log(S/2N)` × **2B** since our simple model was only for a simple coding and for fixed deterministic noise.

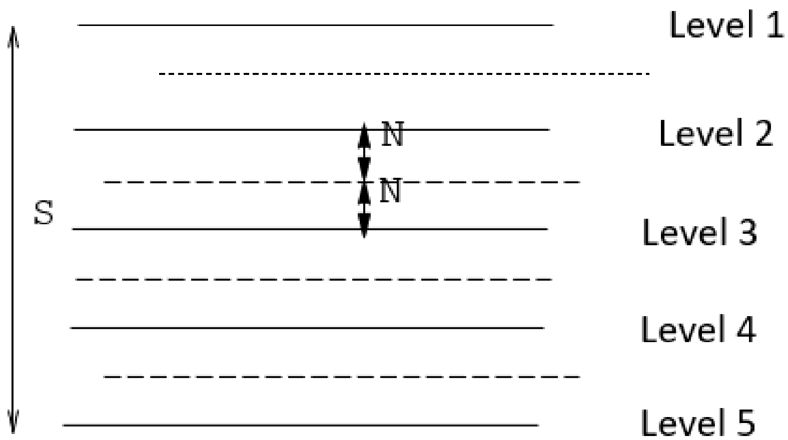
The Shannon bound works for any coding scheme (frequency, phase modulation) and for Gaussian additive noise; needs a deep probabilistic argument.

For example, a telephone line (not DSL) with

- a signal-to-noise ratio of **30 dB** and
- bandwidth of **3 kHz**,

we get a maximum data rate of **30 kbps**.

- Shannon bound



S = Maximum Signal Amplitude

N = Maximum Noise Amplitude

log(S/2N) bits per signal

2 B signals/sec (Nyquist)

Naive Bound = 2 B log(S/2N)

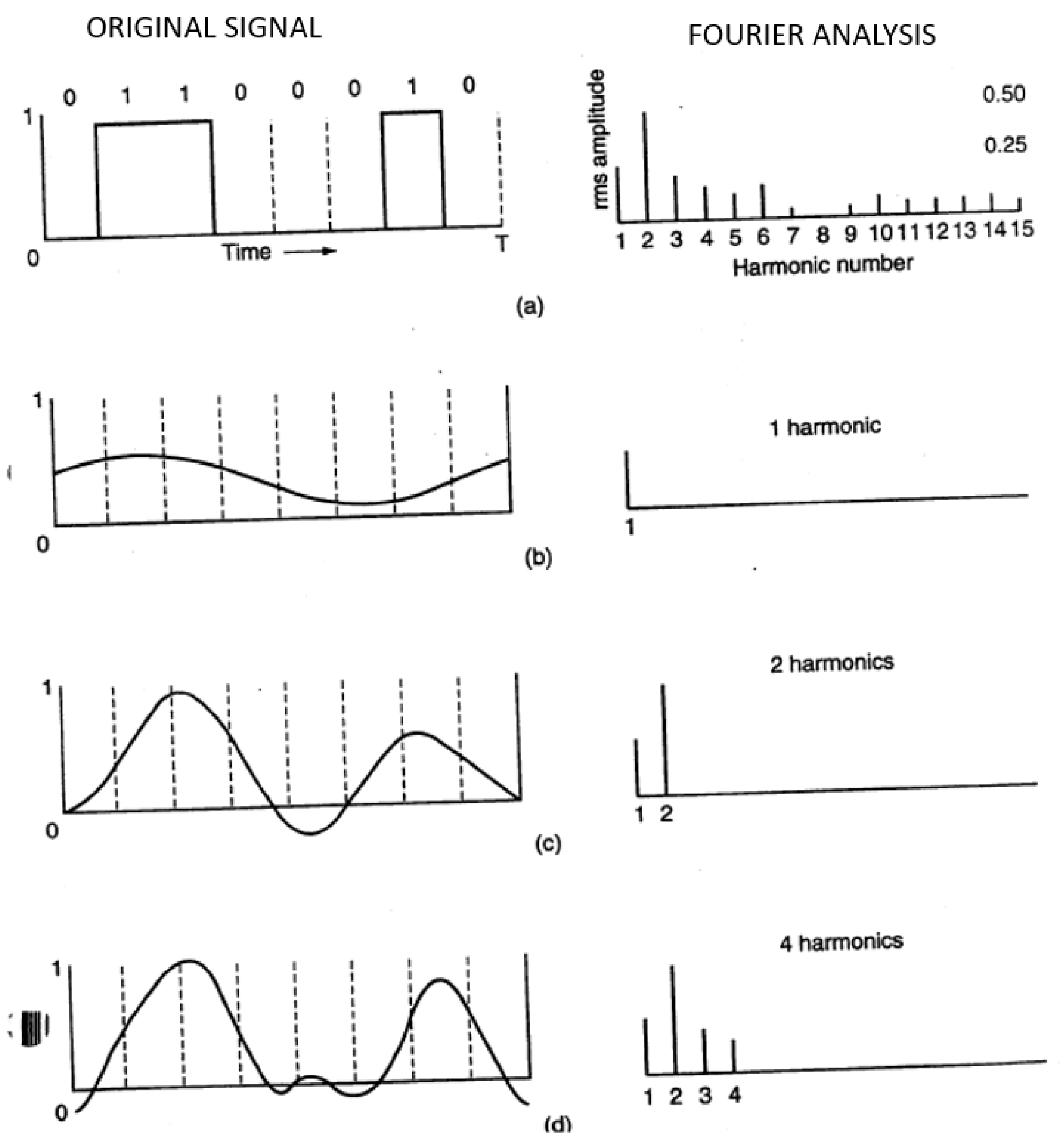
Shannon Bound = B log(1 + S/2N)

Nyquist-Shannon Sampling Thm

https://youtu.be/Jv5FU8oUWEY?si=Y2GXnNIvty9OEfAa

- Due to aliasing from too low of a sampling frequency, we may only capture the orginal signal accuratley if the sampling frequency $f_s > 2 \cdot f_{\max}$ is greater than twice the max frequency of the original signal
- this is why audio recorders record at 44.1 kHz (a little more than twice the max frequency humans can hear)

- larger bandwidth = better recovery

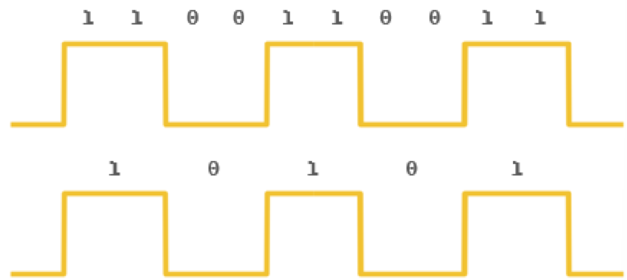


Top Sublayer: Clock Recovery

- b/c clocks drift, we hve initial training bits. to anti-alias, we need transitions in clock voltage
- we need signal transitions bw multiple clock cycles of the same signal to know that the clock has ticked

How can we initially sync the sender clock with the receiver clock?
Initial Training Bits

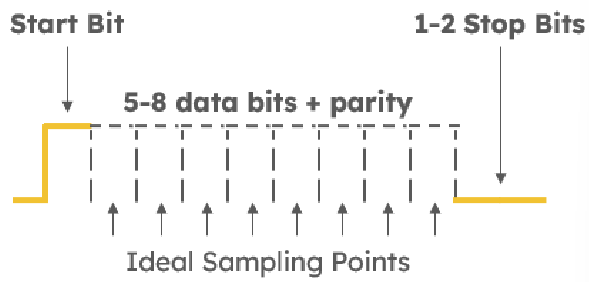
Problem: All real physical clocks drift over time, which is crucial at high speeds. Small drift leads to sampling errors. How do we keep in sync?
Transitions



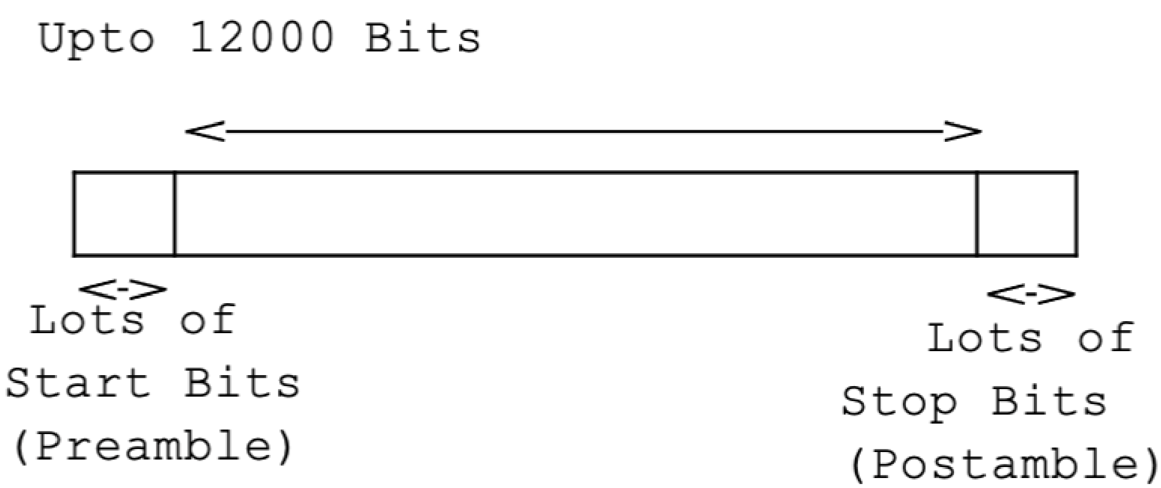
- we add start and stop bits

Codes a character (5-7 bits) at a time (ASCII with parity bit).

Characters are framed using a start bit and one or two stop bits.
1 is encoded as *low voltage*
0 is encoded as *high voltage*



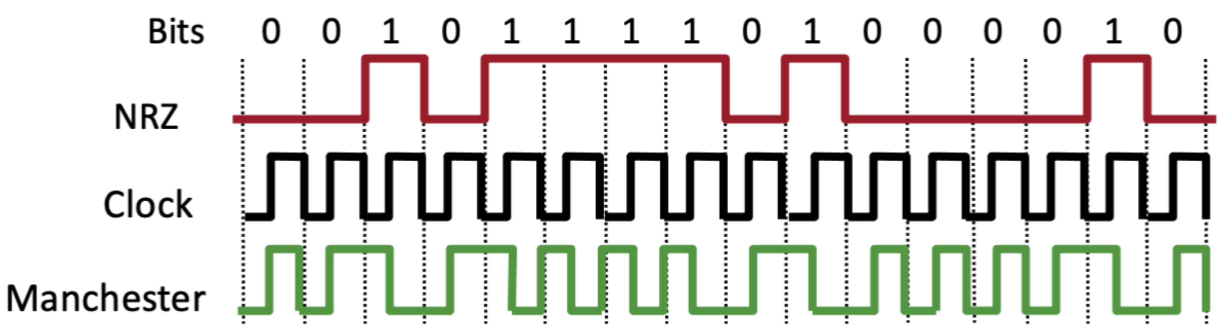
- asynchronous tranmision of bits over signal don't require robust start and stop, usually jusst 1-2 trailing stop bits
- synch. transmission needs better clock tolerance → sophisticated coding, ususally of the form:



- synch. does this to reduce receiver clock startup overhead (knowing when to start the receiver clock is expensive which iss a blocker to assynch transmission, instead long leading and trailing bits wrapping the message)

Manchester encoding

- encodes the transition of the signal/data itself, e.g. hi→lo : 1, lo→hi : 0
- this helps with getting the phase matching easier - with asyc you have 1 transition to sync sender and receiver clock, but with manchester you have a preamble of transitioons of form 010101 ... 11
- solves clock recovery problem but 50% efficient as it encodes 1/2 bit per transition



Receiver code

- usually use phase locked loops to speed up or slow receiver clock to lock in phase

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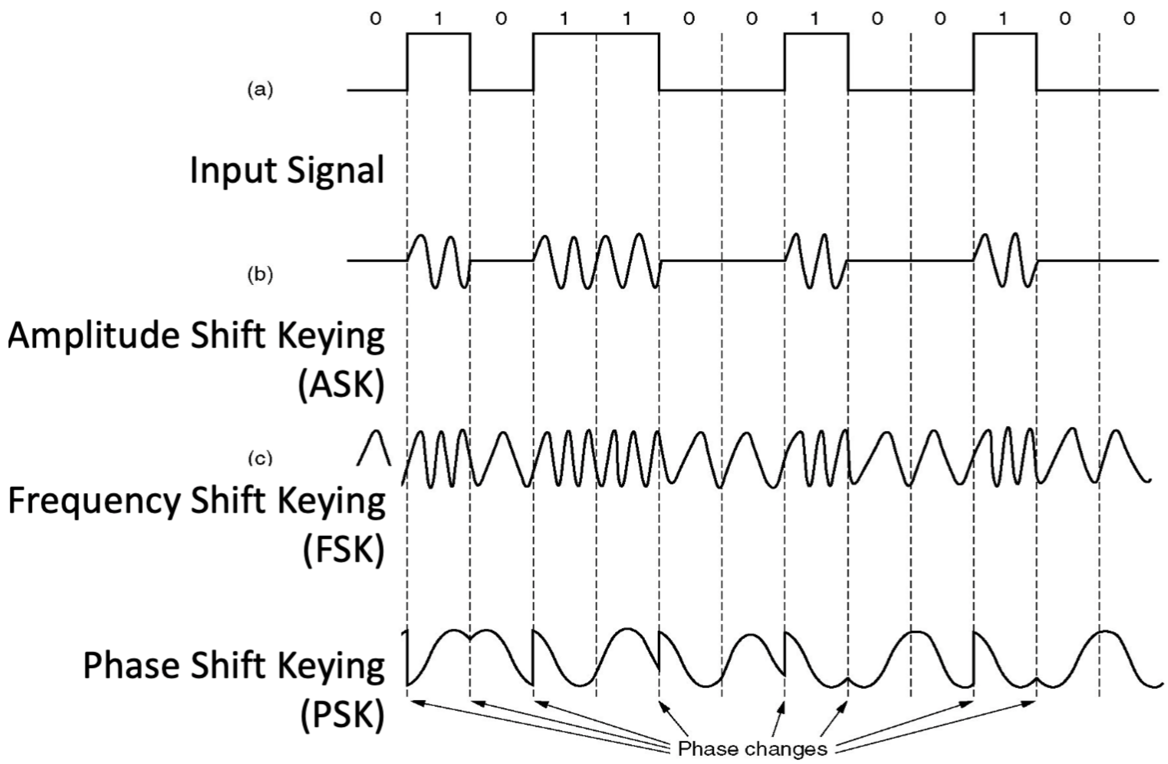
Data Structures:
C[0..10];  ARRAY, to store bits in current character

On Transition:
   StartTimer (1/2 bit)
   For (i = 0 to 10) do
      Wait (TimerExpiry);
      C[i] = SampleSignal;
      StartTimer (1 bit)
   End;
   If (C[0] = 1) and (C[9] = C[10] = 0) then Output C[1..8]
```

Broadband Coding

- baseband coding uses binary energy levels, e.g. light or voltage
- broadband modules the data/information on a carrier wave at some frequency
- modulation can be Frequency Shift Keying (FSK) - high freq = 1, low freq = 0; or Amplitude Shift Keying (ASK), or QAM (mix), or similar e.g. Phase Shift Keying (PSK)



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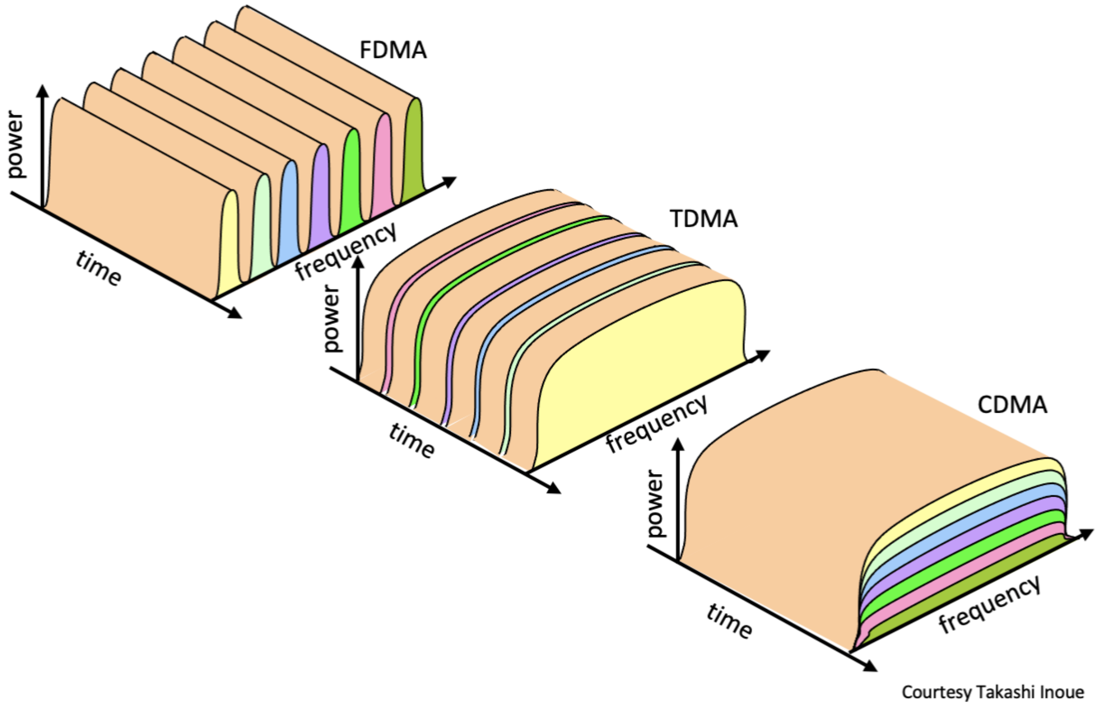
- TODO: three levers of modulation - FDMA, TDMA, CDMA



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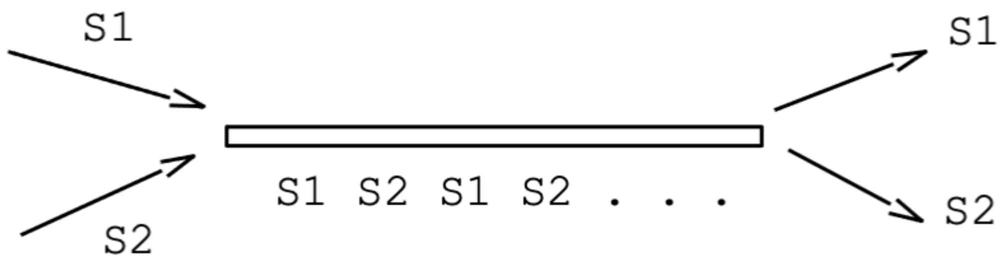
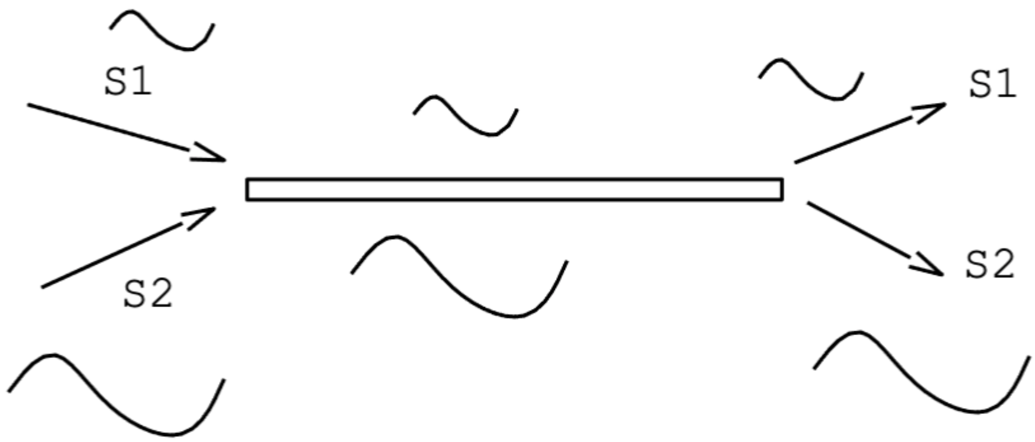
- TODO: Signal Multiplexing - Time Division Mux (TDM), Freq Div Mux (FDM)



TIME DIVISION MULTIPLEXING (TDM)



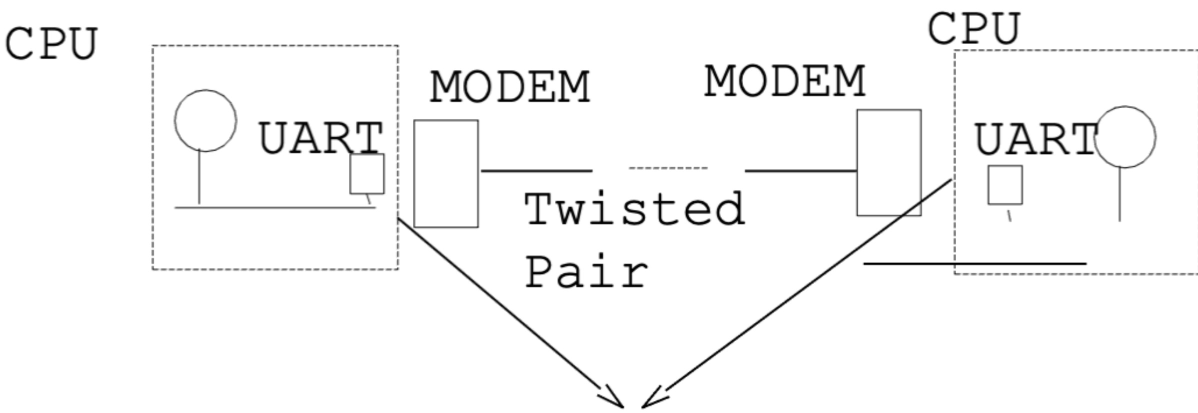
FREQUENCY DIVISION MULTIPLEXING (FDM)

Middle Sublayer: Media

- hardware tech to best convert digital to analog signal
  - important to consider due to hardware limitations on bandwidth, etc.

- Low Bandwidth led to tight encoding: Early Phone lines, not needed on LANs
- Broadcast LANs led to use of Multicast: Initialization and free copies, to IP multicast.
- Building wiring led to Switching: Wiring closets to hubs to switches.
- Fiber a game changer: Point-to-point fibers led to rings and then switches
- Fiber changes telephony: Long haul telephone network becomes digital.
- Wireless leads to low bandwidths again: Laptops. Need Ipv6 compression on wireless!

Twisted Pair Coax

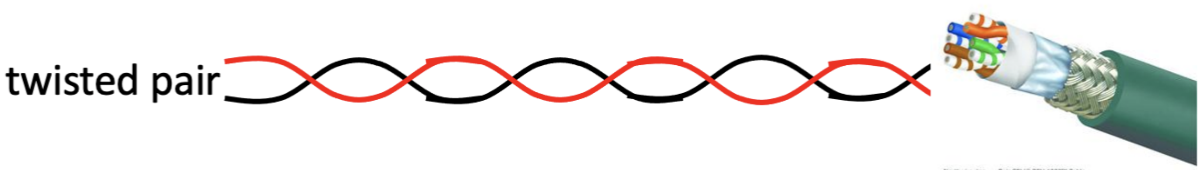


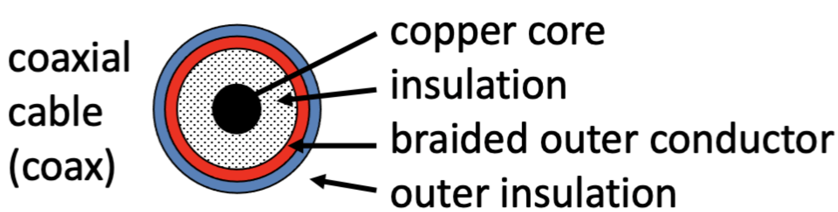
RS-232

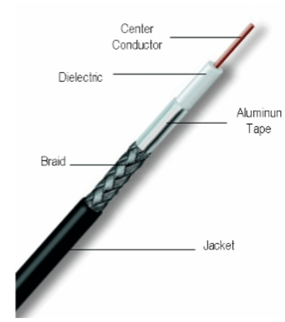
Low bandwidth

Cheap, Easy to Install

- Typical examples
  - Category 5/6 Twisted Pair 10M-10Gbps 50-100m
  - Coaxial Cable 10-100Mbps 200m

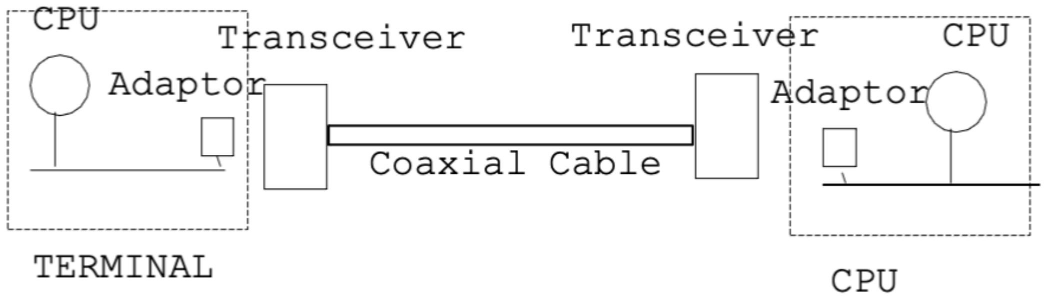






- twisted pair today
  - Standard twisted pair is limited by loading cables by telephone company to 4 Mhz. Shannon limit is around 56 Kbps (not counting compression). Two alternatives:
  - Better quality twisted pair cables for local area networks e.g., Cat 3 (10 Mbps, Manchester), Cat 5 (100 Mbps, 100 Mhz bandwidth uses 4-5 coding)
  - Telephone company removes loading cables, reduces your length, and gives you ADSL. Asymmetrical.

Baseband Coax (Ethernet)



High bandwidth (10-100 MHz)

Hard to tap,

Expensive to Install

Small Distance (1 - 3 km)

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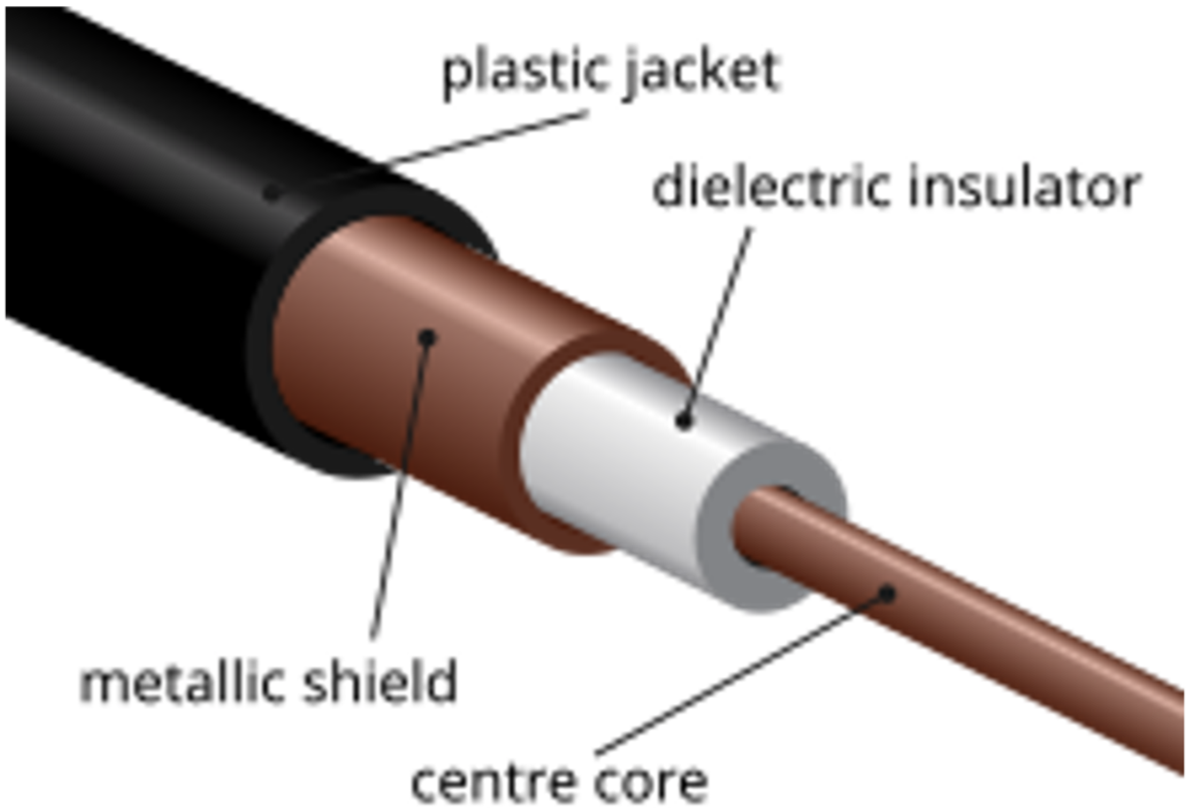

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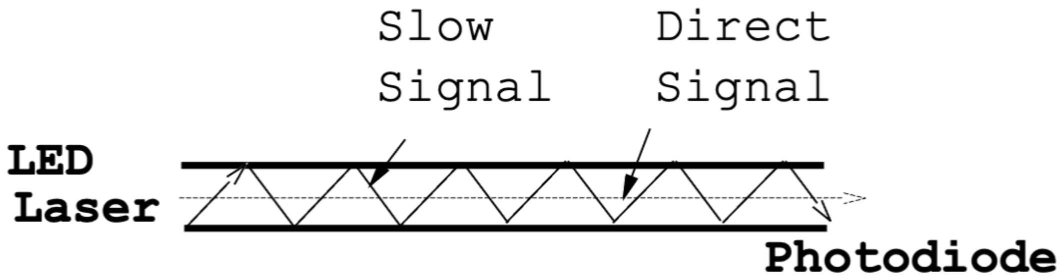
- baseband coax today:
  - Coaxial cable has high bandwidth. Used for original 10 Mbps Ethernet but very clunky. Twisted pair (e.g. Cat 5) used today.
  - Cable still used in cable networks for cable TV and for data via cable modems. Divide bandwidth into 6 Mhz channels for each TV channel and one 6 Mhz channel for downstream data. Theoretically can reach 30 Mbps but beware other users and bandwidth limits. Upstream much less.

Fiber Optic

- unidirectional



Huge Bandwidth (10 Million Mhz!)

Almost Imposible to Tap

Point-to-point Secure

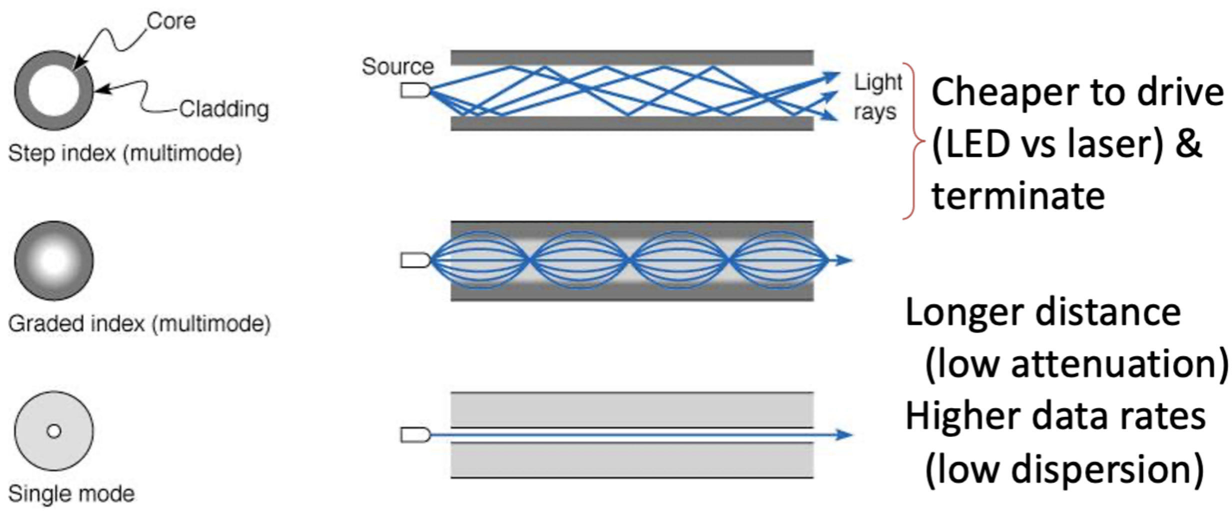
Excellent Electrical Isolation

Thin and Easy to Install

Optics still expensive

Unidirectional

- Typical examples
  - Multimode Fiber 100Mbps-10Gb 500-2000m
  - Single Mode Fiber 1-100Gbps 100m-40km



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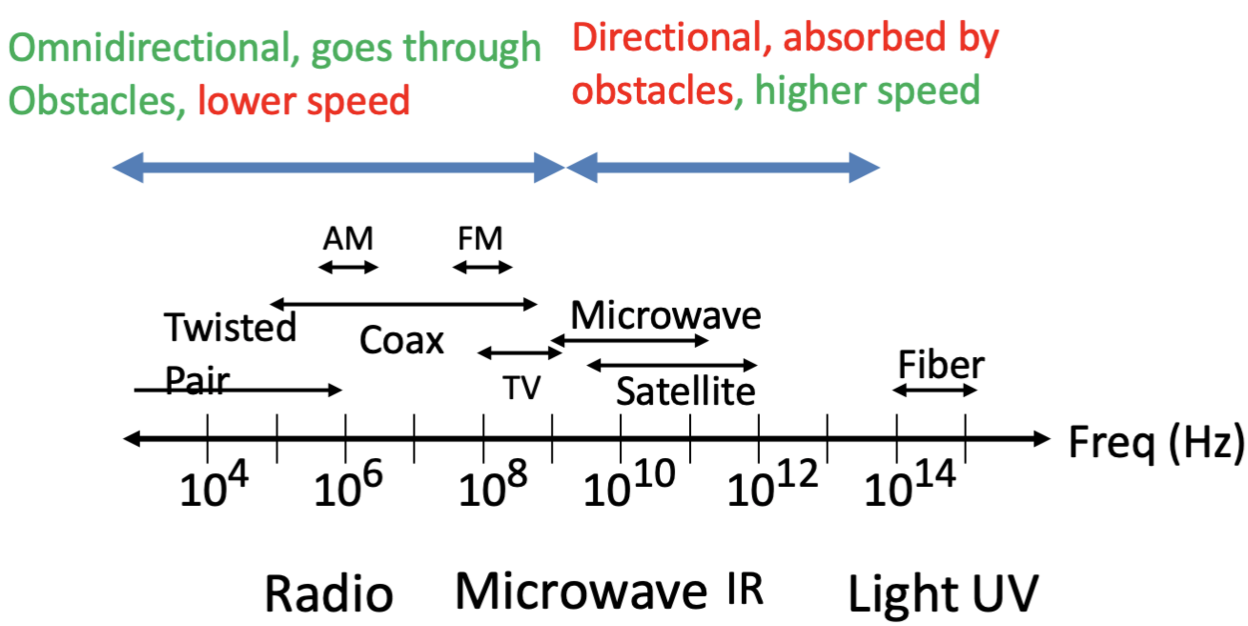
- visible light disperse through reflections in glass due to different wavelengths traveling at diff speeds → sol: monochromatic light (lasers)

Wireless



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- requires spectrum allocation - trying to allocate like a spatial resource does not work as spectrum is time and power shared → whitespace comms
- radiowave - cheap, good bandwidth, avoids ROW, long diistance (100km), issues with raiin
- satellite - avoids ROW, good bandwidth, world wide distance, expensive, large latency
  - LEO - orbit at varying speeds, cell
  - geostationary much farther = higher latency, but regionally stationary
- types of wireless protocols (not including 5G)
  - 802.11: Wireless LANs using a wireless access point (AP) at hot spot using unlicensed frequency band 2.4 to 4.485 Ghz (radio frequency) 100 metres. 11 Mbps with 802.11b. Needs hotspot but becoming common and very cheap!
  - Bluetooth: ad hoc personal area networks with no AP. Master-slave. 4 Mbps
  - WiMax: broader geographical range smaller bandwidth of a few Mbps
  - 3 G (Cellular telephone networks carrying data) at a few Mbps such as EVDO. Unlimited geographical range and true mobility

802.11b (a/c?)

- AP configured with SSID, with channel number 1 to 11. non overlapping channels, e.g. 1,6,11 can be used to triple bandwidth → ssends beacon w/ SSID payload

- each mobiile/client scans all 11 channels looking for SSID beaacons
- issues with hidden terminal problem - mobile A and B can communicate to AP, but not between themselves

Media summary

Medium	Speed	Distance Span	Pros	Cons
Twisted Pair	1 Mps -1 G (Cat 1 – Cat 5)	1 – 2 Km	Cheap, easy to install	Low distance
Digital Coax	10-100 Mbps	1- 2 km	broadcast	Hard to install in building
Analog Coax	100-500 Mbps	100 Km	Cable companies Use it now	Expensive amplifiers
Fiber	Terabits	100 km	Security, low noise, BW	No broadcast, Needs digging
Microwave	10-100 Mbps	100 km	Bypass, no right Of way need	Fog outages
Satellite	100-500 Mbps	worldwide	Cost independent of distance	250 msec delay Antenna size
RF/Infrared	1 – 100 Mbps, < 4 Mbps	1 km 3 m	wireless	Obstacles for infrared