Lecture 5
Transmission

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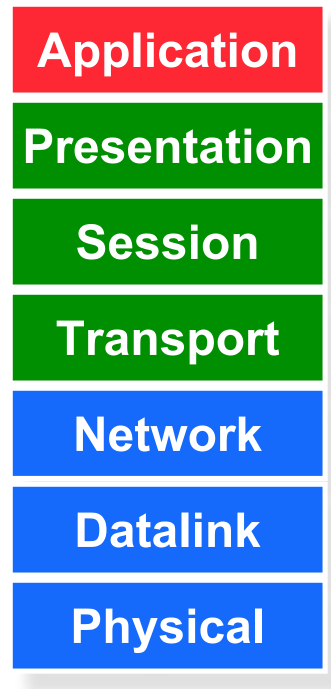
15-441 Networking, Spring 2005
http://www.cs.cmu.edu/~srini/15-441/S05

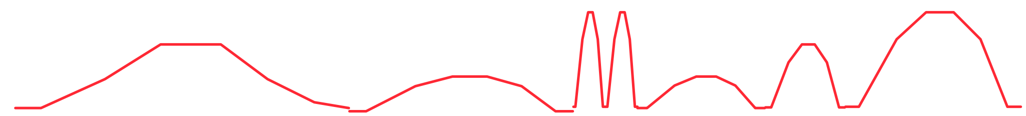
Physical and Datalink Layers: 3 Lectures

- Physical layer.
- Datalink layer introduction, framing, error coding, switched networks.
- Broadcast-networks, home networking.



From Signals to Packets

Analog Signal

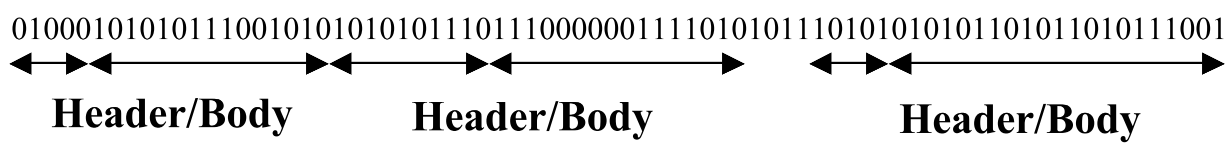


"Digital" Signal

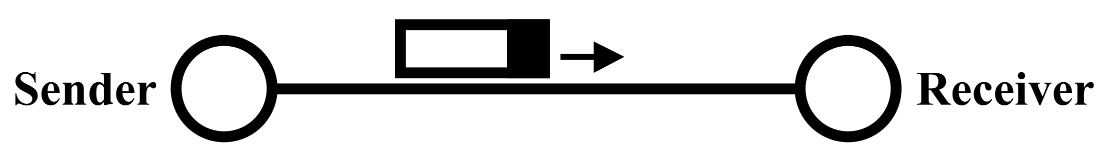
Bit Stream

0 0 1 0 1 1 1 0 0 0 1

Packets



Packet Transmission



Today's Lecture

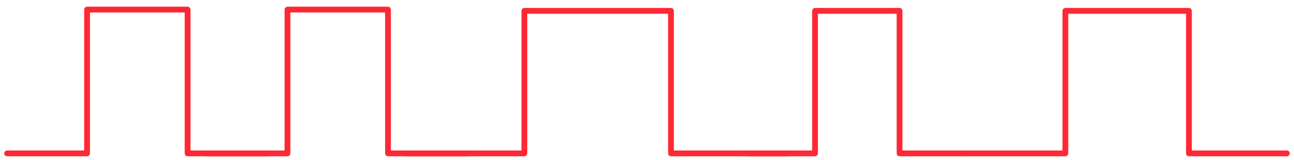
- Modulation.
- Bandwidth limitations.
- Frequency spectrum and its use.
- Multiplexing.
- Media: Copper, Fiber, Optical, Wireless.

- Coding.
- Framing.

Modulation

- Sender changes the nature of the signal in a way that the receiver can recognize.
  - » Similar to radio: AM or FM
- Digital transmission: encodes the values 0 or 1 in the signal.
  - » It is also possible to encode multi-valued symbols
- Amplitude modulation: change the strength of the signal, typically between on and off.
  - » Sender and receiver agree on a "rate"
  - » On means 1, Off means 0
- Similar: frequency or phase modulation.
- Can also combine method modulation types.

Amplitude and Frequency Modulation

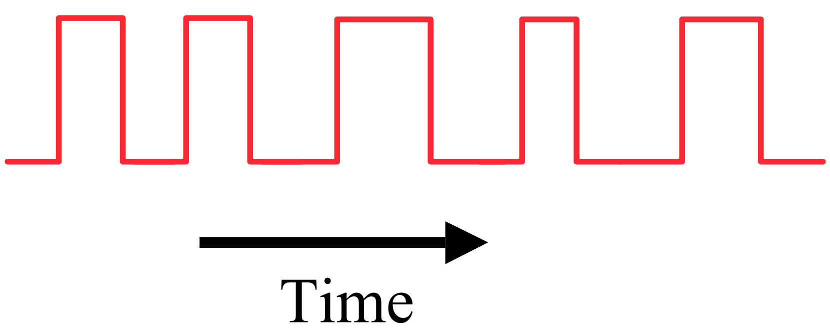


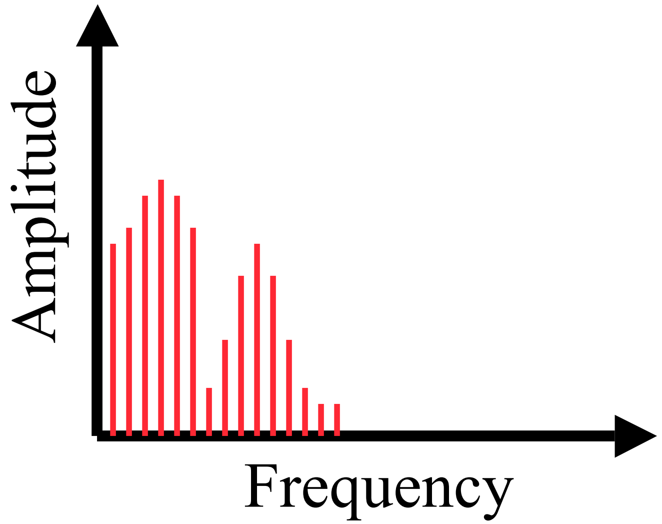
0 0 1 1 0 0 1 1 0 0 0 1 1 1 0 0 0 1 1 0 0 0 1 1 1 0

0 1 1 0 1 1 0 0 0 1

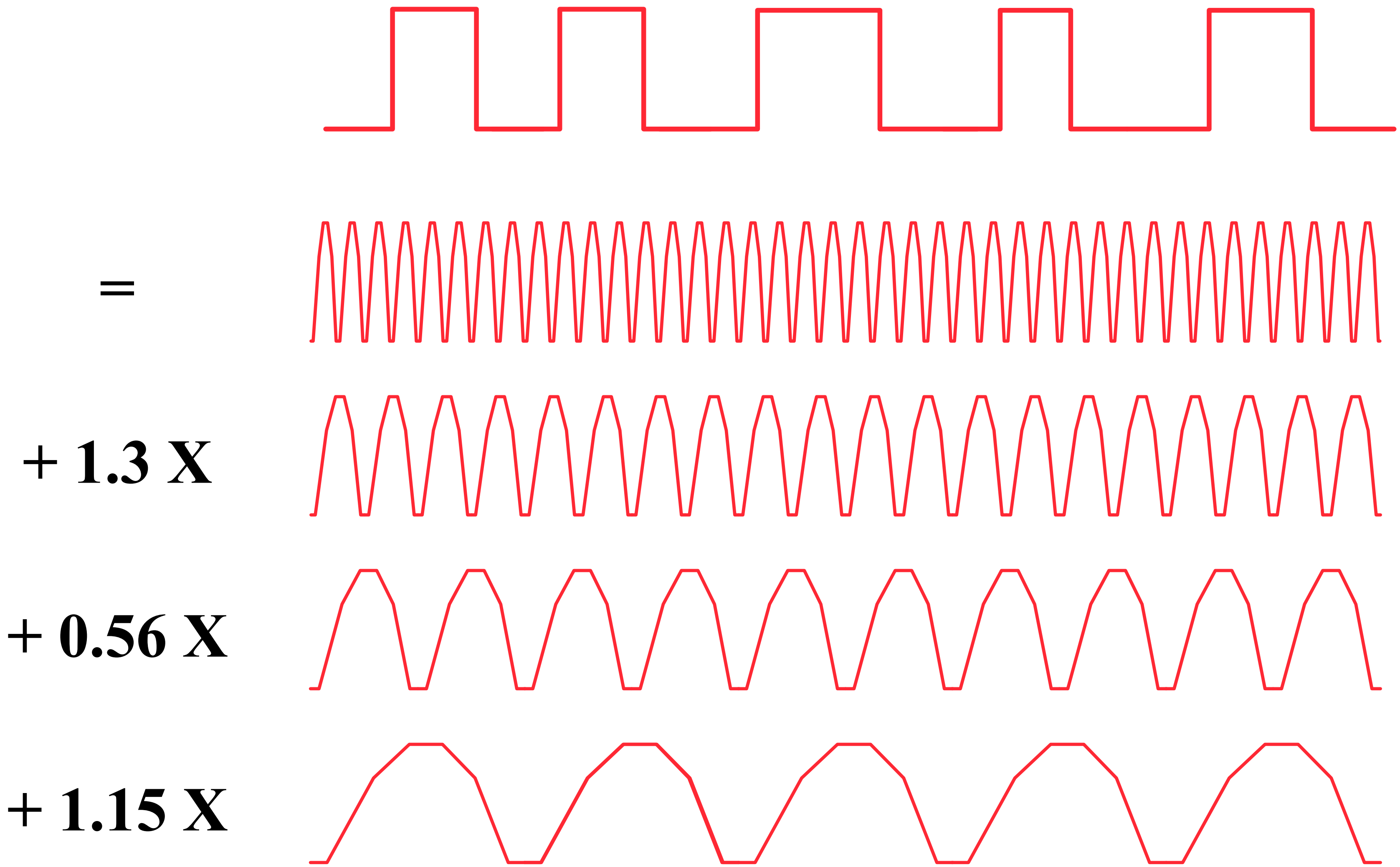
The Frequency Domain

- A (periodic) signal can be viewed as a sum of sine waves of different strengths.
  - » Corresponds to energy at a certain frequency
- Every signal has an equivalent representation in the frequency domain.
  - » What frequencies are present and what is their strength (energy)
- Again: Similar to radio and TV signals.





Signal = Sum of Waves

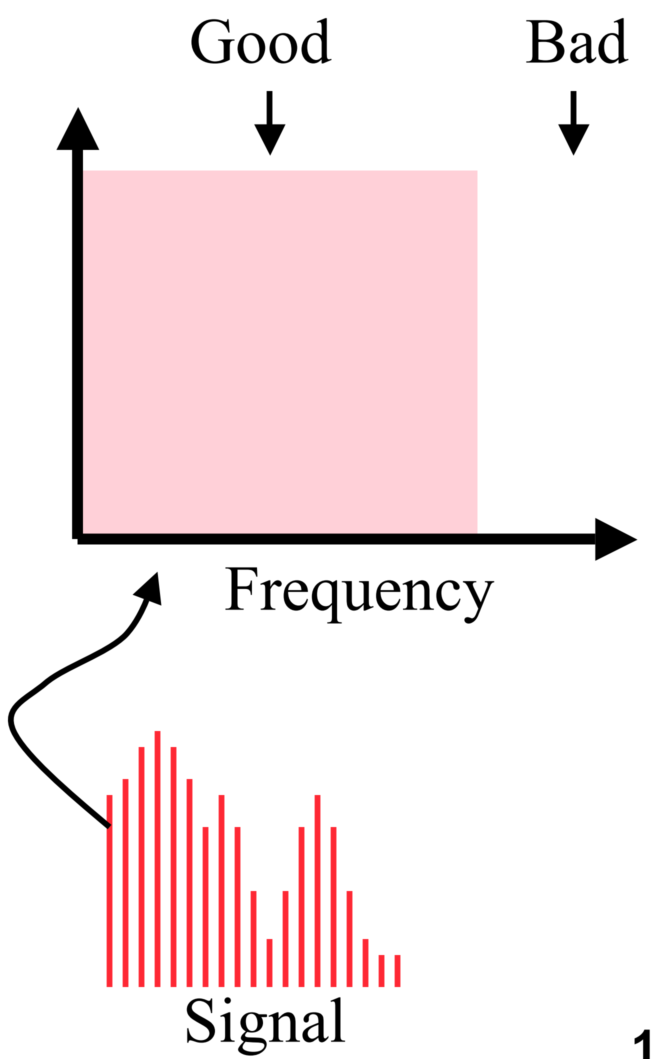


Why Do We Care?

- How much bandwidth can I get out of a specific wire (transmission medium)?
- What limits the physical size of the network?
- How can multiple hosts communicate over the same wire at the same time?
- How can I manage bandwidth on a transmission medium?
- How do the properties of copper, fiber, and wireless compare?

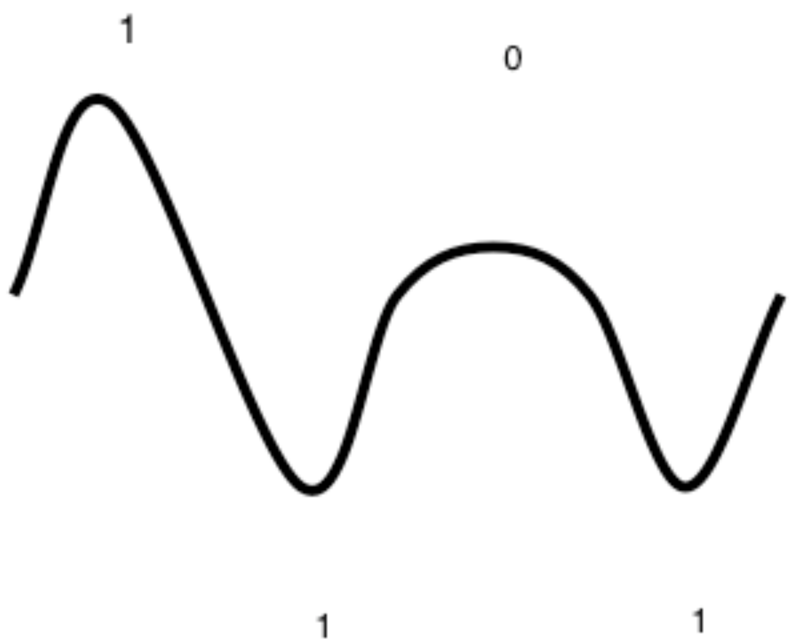
Transmission Channel Considerations

- **Every medium supports transmission in a certain frequency range.**
  - **Outside this range, effects such as attenuation, .. degrade the signal too much**
- **Transmission and receive hardware will try to maximize the useful bandwidth in this frequency band.**
  - **Tradeoffs between cost, distance, bit rate**
- **As technology improves, these parameters change, even for the same wire.**
  - **Thanks to our EE friends**



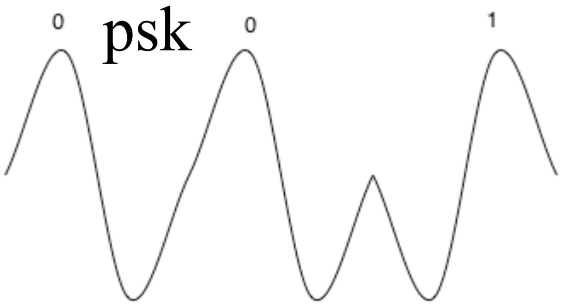
The Nyquist Limit

- A noiseless channel of width H can at most transmit a binary signal at a rate 2 x H.
  - » E.g. a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second
  - » Assumes binary amplitude encoding

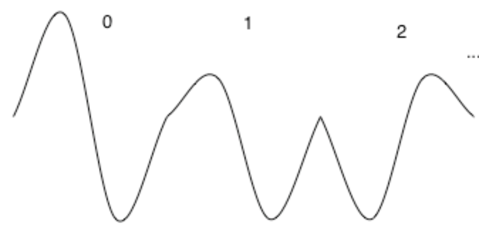


Past the Nyquist Limit

- **More aggressive encoding can increase the channel bandwidth.**
  - » **Example: modems**
    - – **Same *frequency* - number of symbols per second**
    - – **Symbols have more possible values**



Psk
+
AM



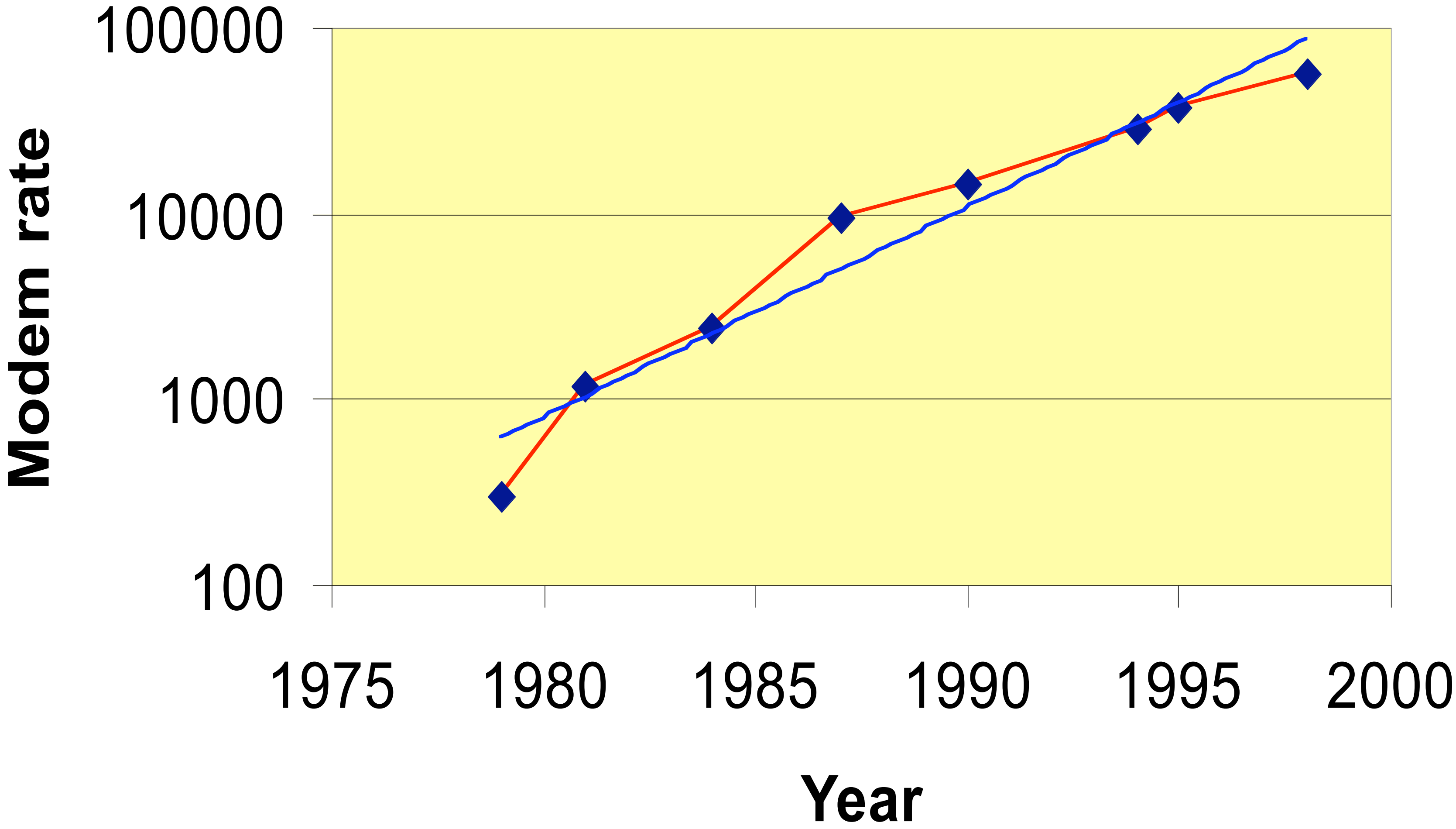
- **Every transmission medium supports transmission in a certain frequency range.**
  - » **The channel bandwidth is determined by the transmission medium and the quality of the transmitter and receivers**
  - » **Channel capacity increases over time**

Capacity of a Noisy Channel

- Can’t add infinite symbols - you have to be able to tell them apart. This is where noise comes in.

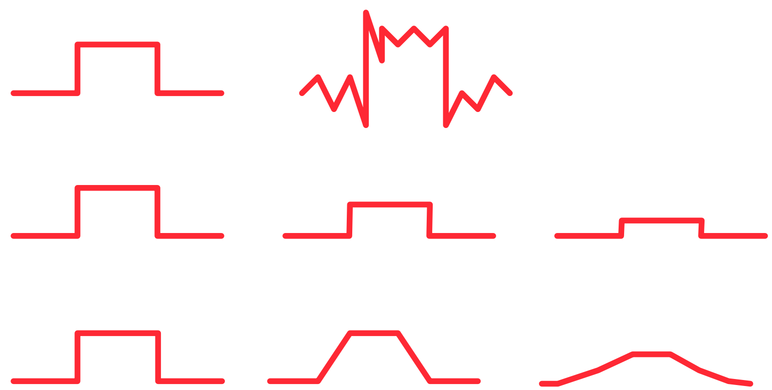
- Shannon’s theorem:
  - » C = B x log(1 + S/N)
  - » C: maximum capacity (bps)
  - » B: channel bandwidth (Hz)
  - » S/N: signal to noise ratio of the channel
    - – Often expressed in decibels (db). 10 log(S/N).
- Example:
  - » Local loop bandwidth: 3200 Hz
  - » Typical S/N: 1000 (30db)
  - » What is the upper limit on capacity?
    - – Modems: Teleco internally converts to 56kbit/s digital signal, which sets a limit on B and the S/N.

Example: Modem Rates



Limits to Speed and Distance

- Noise: “random” energy is added to the signal.
- Attenuation: some of the energy in the signal leaks away.
- Dispersion: attenuation and propagation speed are frequency dependent.
  - Changes the shape of the signal



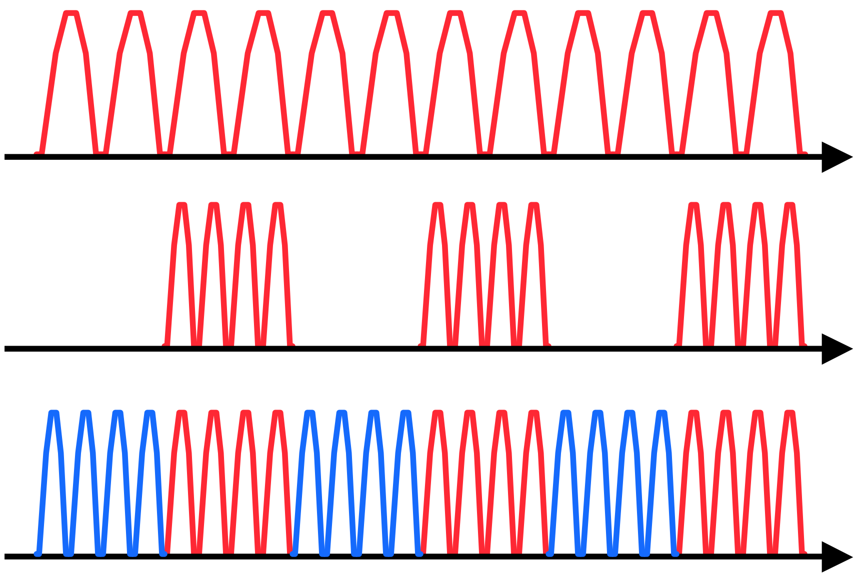
- Effects limit the data rate that a channel can sustain.
  - But affects different technologies in different ways
- Effects become worse with distance.
  - Tradeoff between data rate and distance

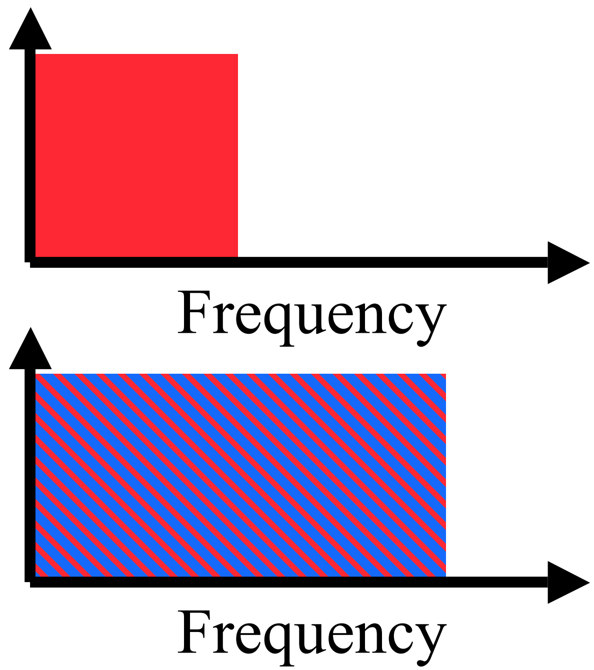
Supporting Multiple Channels

- Multiple channels can coexist if they transmit at a different frequency, or at a different time, or in a different part of the space.
  - » Three dimensional space: frequency, space, time
- Space can be limited using wires or using transmit power of wireless transmitters.
- Frequency multiplexing means that different users use a different part of the spectrum.
  - » Again, similar to radio: 95.5 versus 102.5 station
- Controlling time is a datalink protocol issue.
  - » Media Access Control (MAC): who gets to send when?

Time Division Multiplexing

- Different users use the wire at different points in time.
- Aggregate bandwidth also requires more spectrum.

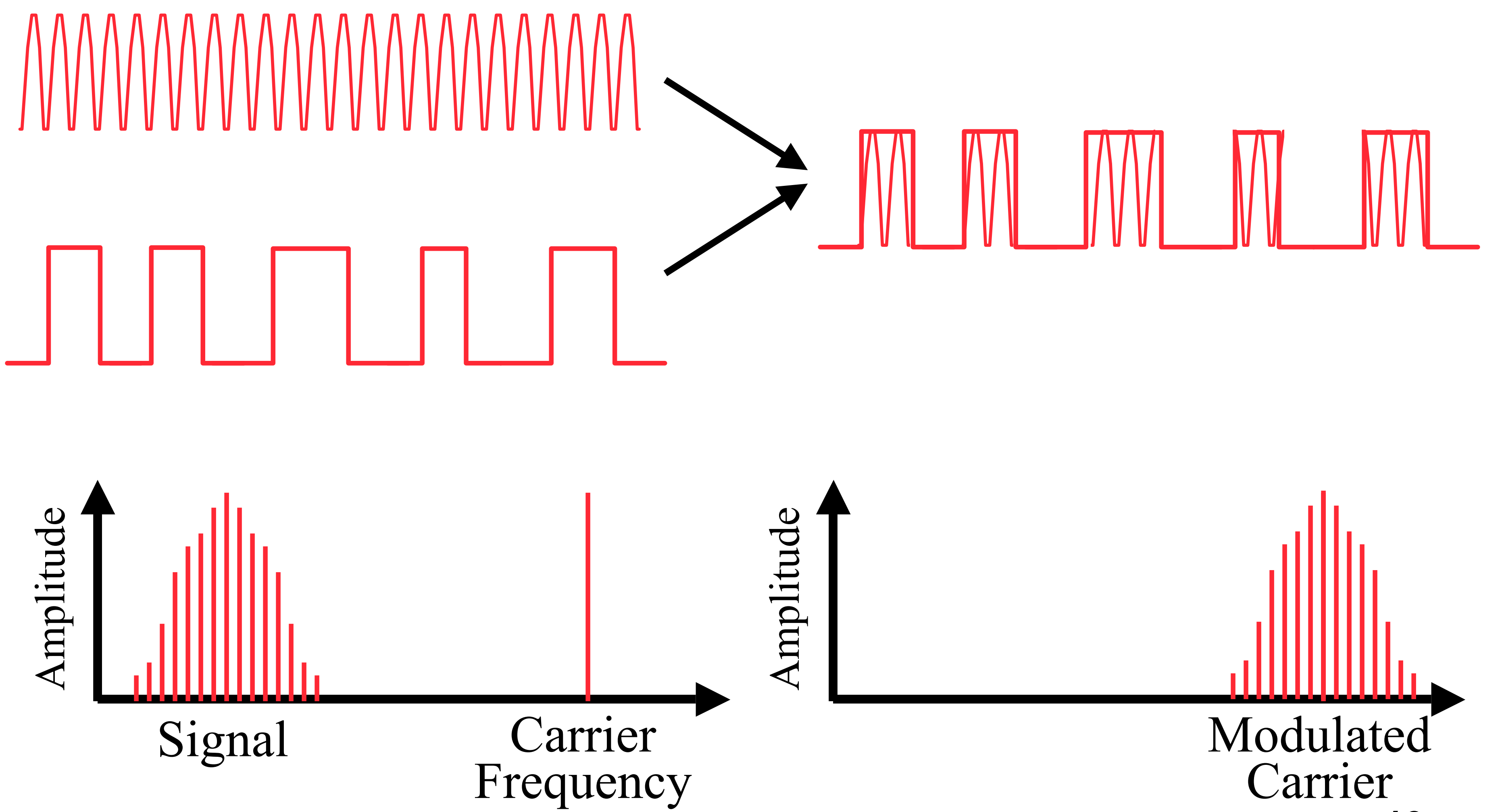




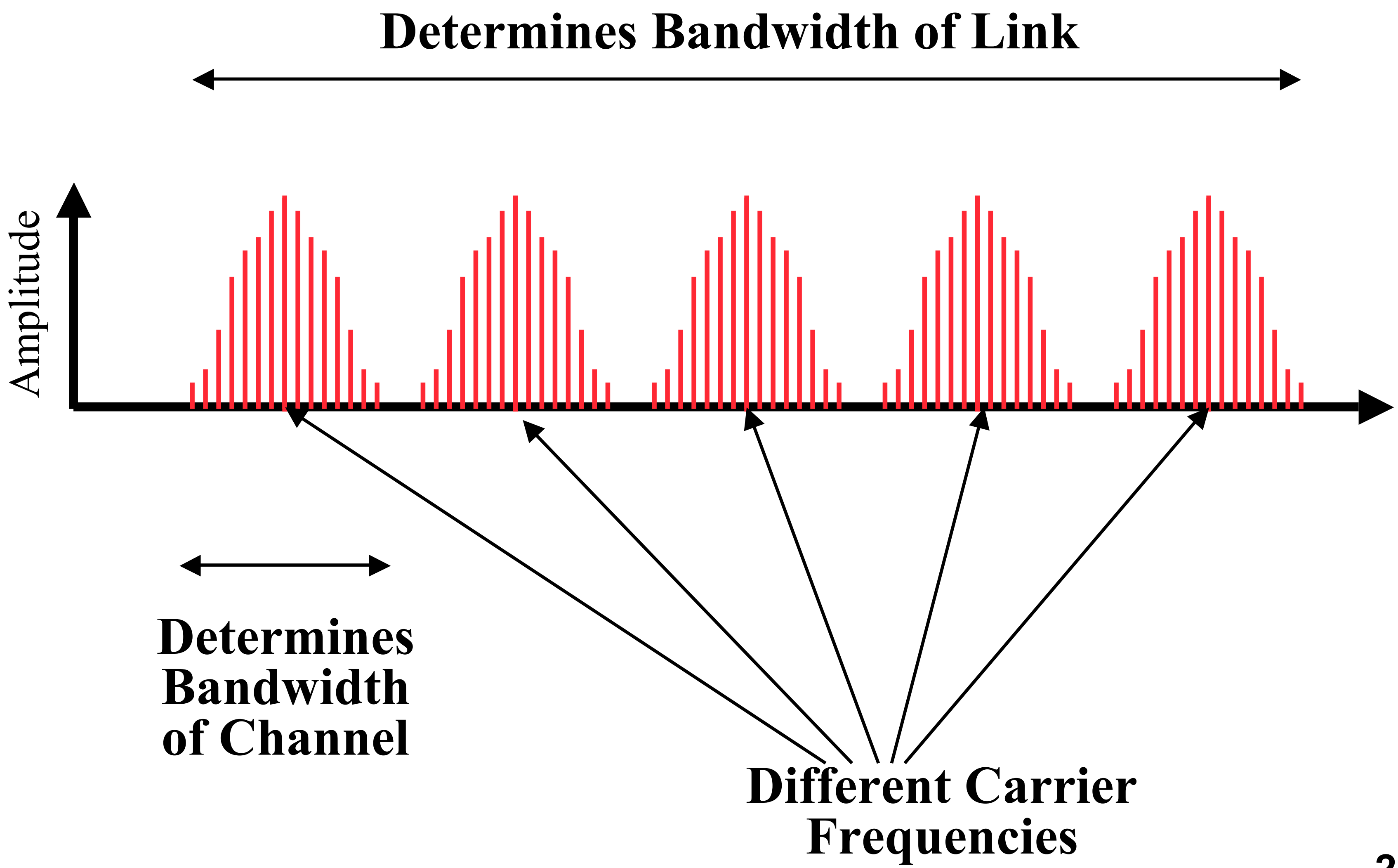
Baseband versus Carrier Modulation

- Baseband modulation: send the “bare” signal.
- Carrier modulation: use the signal to modulate a higher frequency signal (carrier).
  - Can be viewed as the product of the two signals
  - Corresponds to a shift in the frequency domain
- Same idea applies to frequency and phase modulation.
  - E.g. change frequency of the carrier instead of its amplitude

Amplitude Carrier Modulation

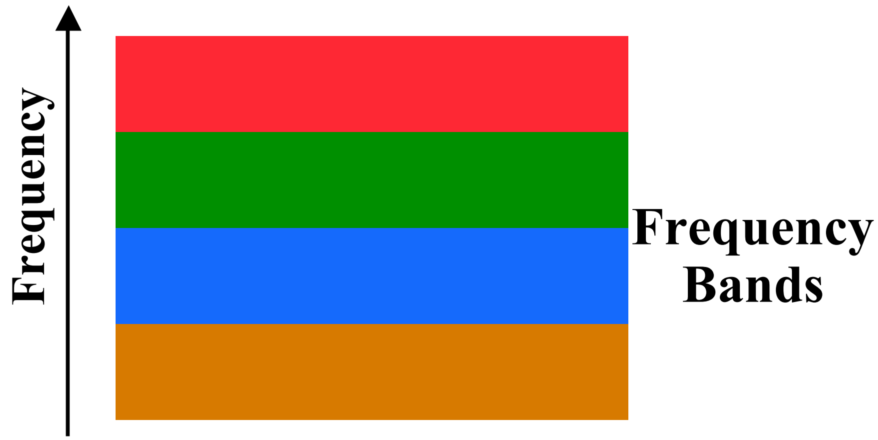


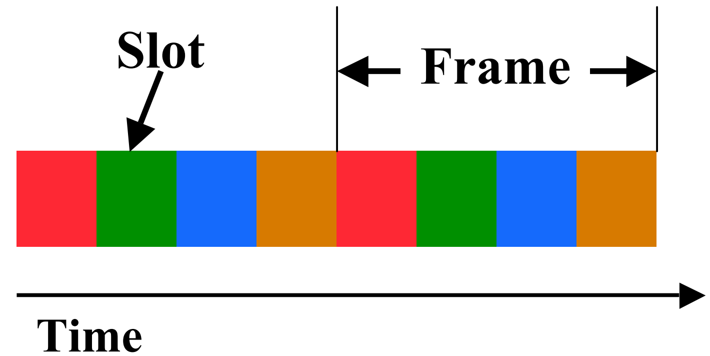
Frequency Division Multiplexing: Multiple Channels



Frequency versus Time-division Multiplexing

- With frequency-division multiplexing different users use different parts of the frequency spectrum.
  - I.e. each user can send all the time at reduced rate
  - Example: roommates
- With time-division multiplexing different users send at different times.
  - I.e. each user can sent at full speed some of the time
  - Example: a time-share condo
- The two solutions can be combined.

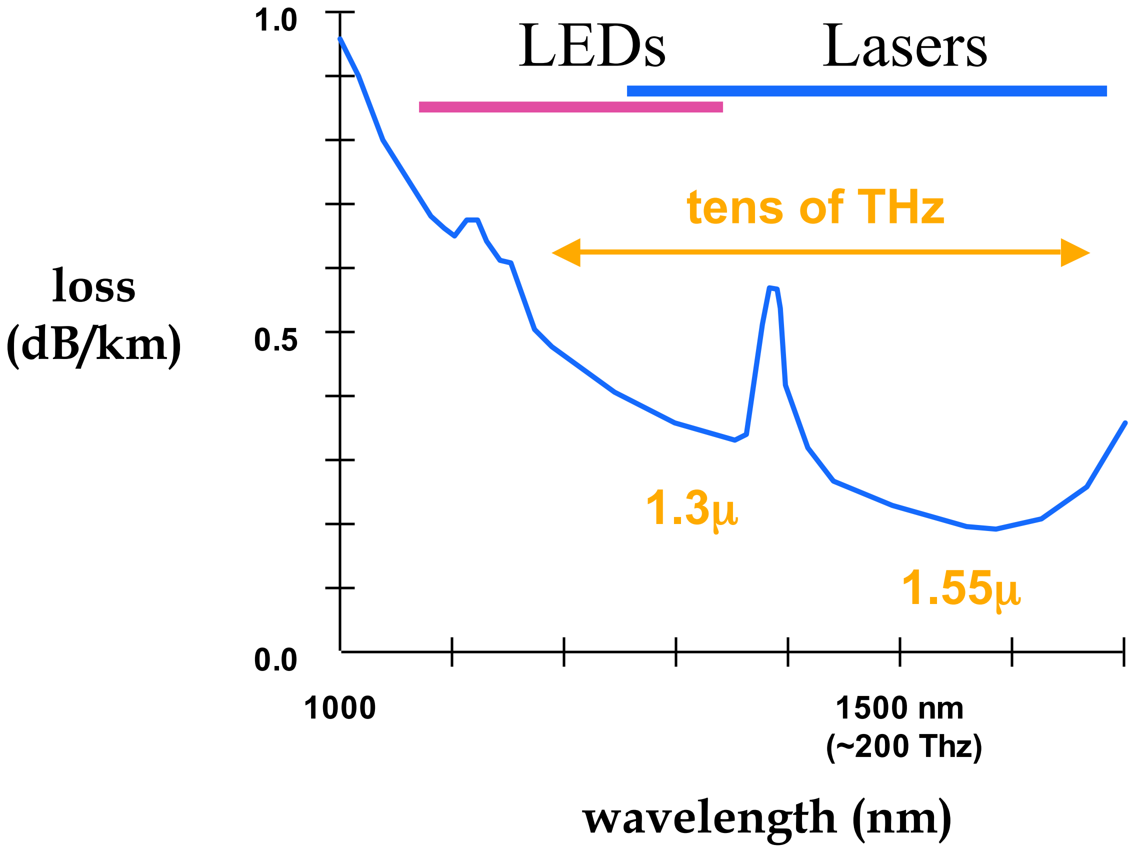




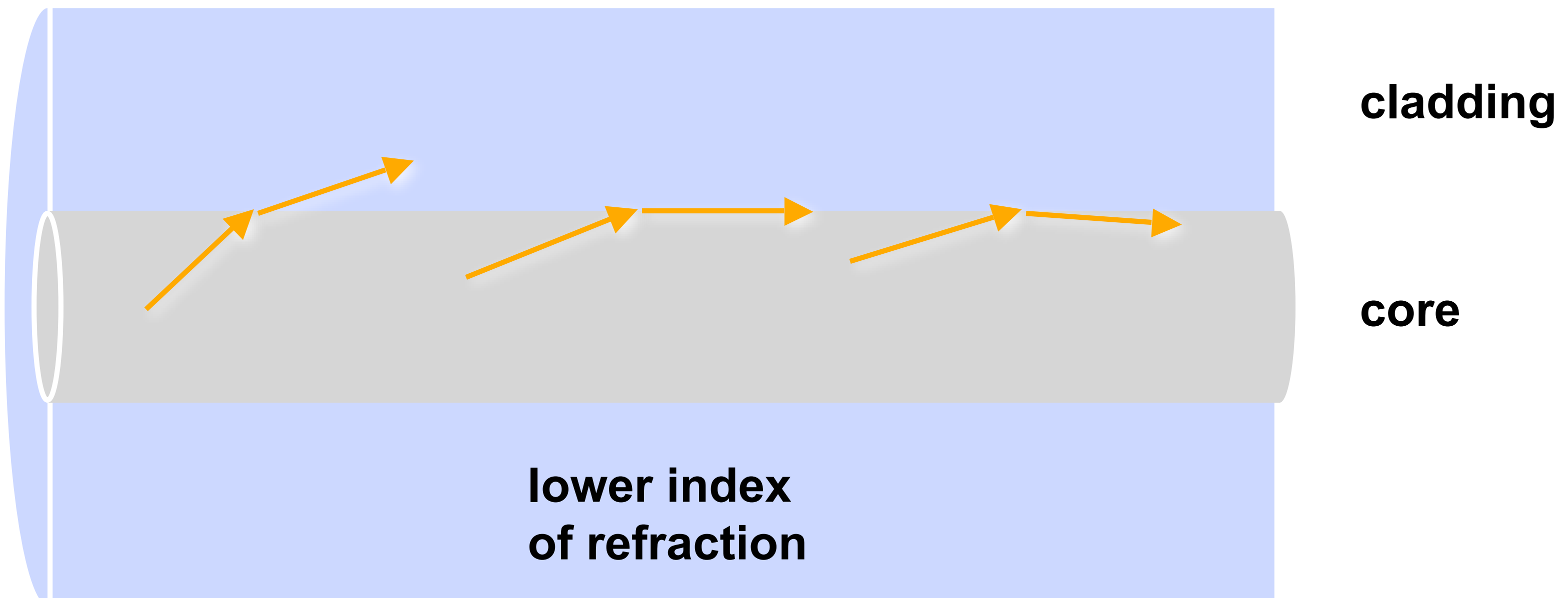
Copper Wire

- **Unshielded twisted pair**
  - » Two copper wires twisted - avoid antenna effect
  - » Grouped into cables: multiple pairs with common sheath
  - » Category 3 (voice grade) versus category 5
  - » 100 Mbit/s up to 100 m, 1 Mbit/s up to a few km
  - » Cost: ~ 10cents/foot
- **Coax cables.**
  - » One connector is placed inside the other connector
  - » Holds the signal in place and keeps out noise
  - » Gigabit up to a km
- **Signaling processing research pushes the capabilities of a specific technology.**
  - » E.g. modems, use of cat 5

Light Transmission in Fiber



Ray Propagation



(note: minimum bend radius of a few cm)

Fiber Types

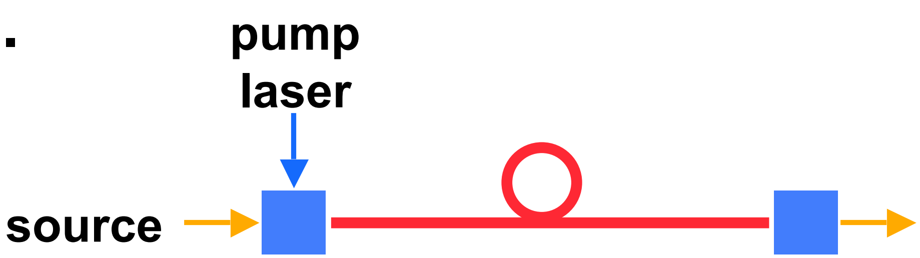
- **Multimode fiber.**
  - » 62.5 or 50 micron core carries multiple “modes”
  - » used at 1.3 microns, usually LED source
  - » subject to mode dispersion: different propagation modes travel at different speeds
  - » typical limit: 1 Gbps at 100m
- **Single mode**
  - » 8 micron core carries a single mode
  - » used at 1.3 or 1.55 microns, usually laser diode source
  - » typical limit: 1 Gbps at 10 km or more
  - » still subject to chromatic dispersion

Gigabit Ethernet: Physical Layer Comparison

Medium	Transmit/receive	Distance	Comment
Copper	1000BASE-CX	25 m	machine room use
Twisted pair	1000BASE-T	100 m	not yet defined; cost? Goal:4 pairs of UTP5
MM fiber 62 μm	1000BASE-SX	260 m	
	1000BASE-LX	500 m	
MM fiber 50 μm	1000BASE-SX	525 m	
	1000BASE-LX	550 m	
SM fiber	1000BASE-LX	5000 m	
Twisted pair	100BASE-T	100 m	2p of UTP5/2-4p of UTP3
MM fiber	100BASE-SX	2000m	

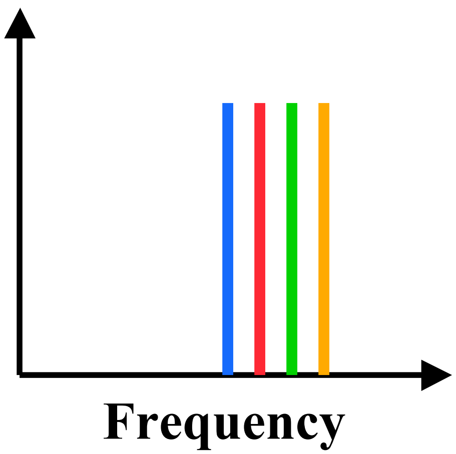
Regeneration and Amplification

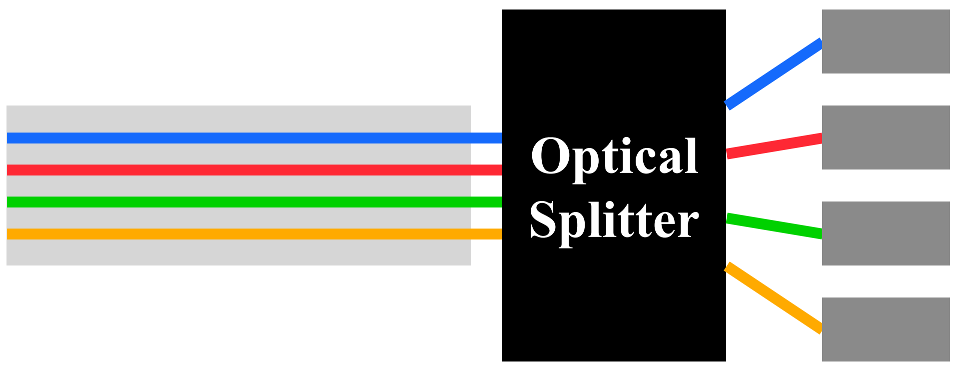
- At end of span, either regenerate electronically or amplify.
- Electronic repeaters are potentially slow, but can eliminate noise.
- Amplification over long distances made practical by erbium doped fiber amplifiers offering up to 40 dB gain, linear response over a broad spectrum. Ex: 10 Gbps at 500 km.



Wavelength Division Multiplexing

- Send multiple wavelengths through the same fiber.
  - Multiplex and demultiplex the optical signal on the fiber
- Each wavelength represents an optical carrier that can carry a separate signal.
  - E.g., 16 colors of 2.4 Gbit/second
- Like radio, but optical and much faster





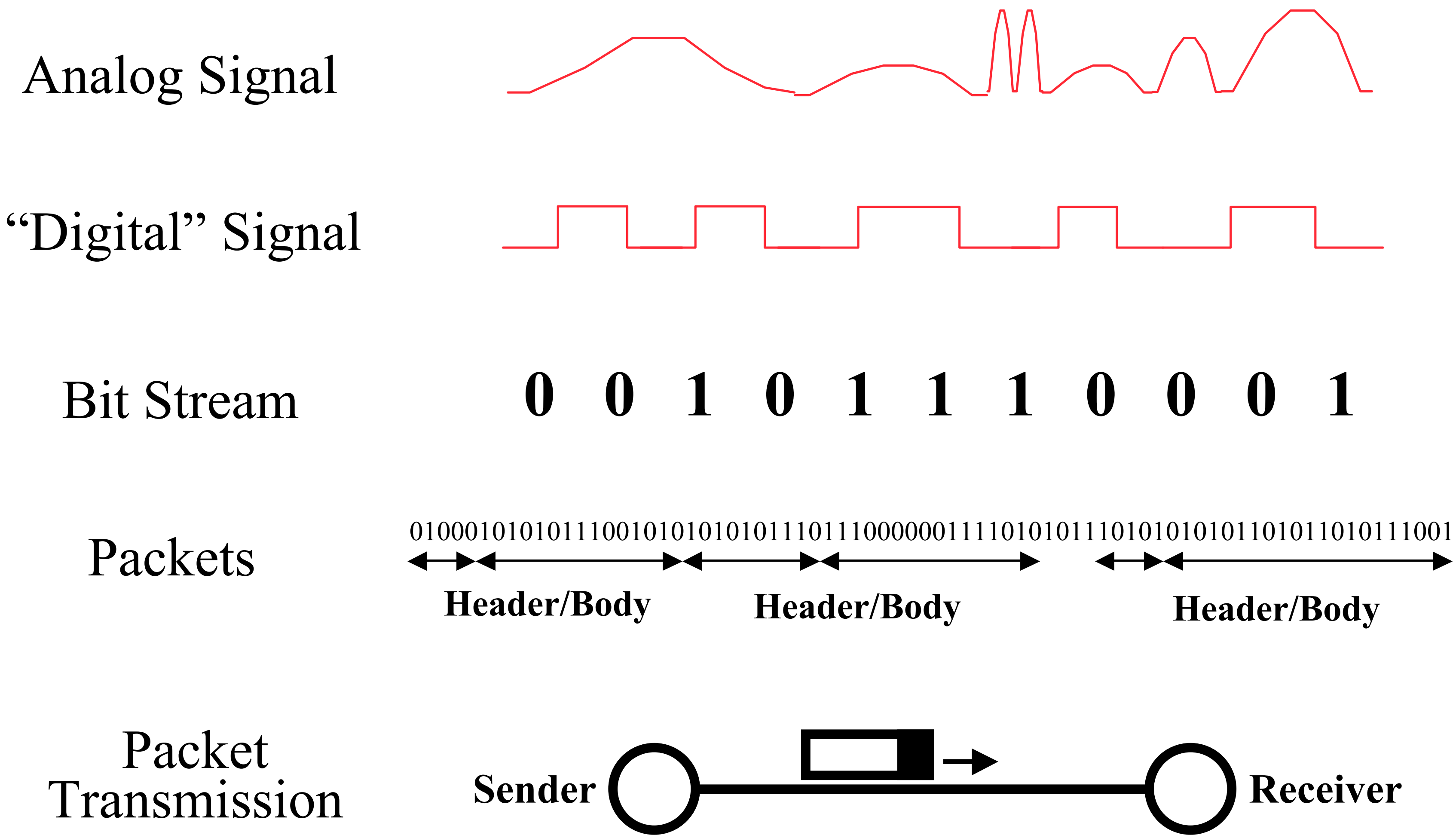
Wireless Technologies

- Great technology: no wires to install, convenient mobility, ..
- High attenuation limits distances.
  - Wave propagates out as a sphere
  - Signal strength reduces quickly $(1/distance)^3$
- High noise due to interference from other transmitters.
  - Use MAC and other rules to limit interference
  - Aggressive encoding techniques to make signal less sensitive to noise
- Other effects: multipath fading, security, ..
- Ether has limited bandwidth.
  - Try to maximize its use
  - Government oversight to control use

Things to Remember

- **Bandwidth and distance of networks is limited by physical properties of media.**
  - » **Attenuation, noise, …**
- **Network properties are determined by transmission medium and transmit/receive hardware.**
  - » **Nyquist gives a rough idea of idealized throughput**
  - » **Can do much better with better encoding**
    - – **Low b/w channels: Sophisticated encoding, multiple bits per wavelength.**
    - – **High b/w channels: Simpler encoding (FM, PCM, etc.), many wavelengths per bit.**
- **Multiple users can be supported using space, time, or frequency division multiplexing.**
- **Properties of different transmission media.**

From Signals to Packets



Analog versus Digital Encoding

- Digital transmissions.
  - » Interpret the signal as a series of 1's and 0's
  - » E.g. data transmission over the Internet
- Analog transmission
  - » Do not interpret the contents
  - » E.g broadcast radio
- Why digital transmission?

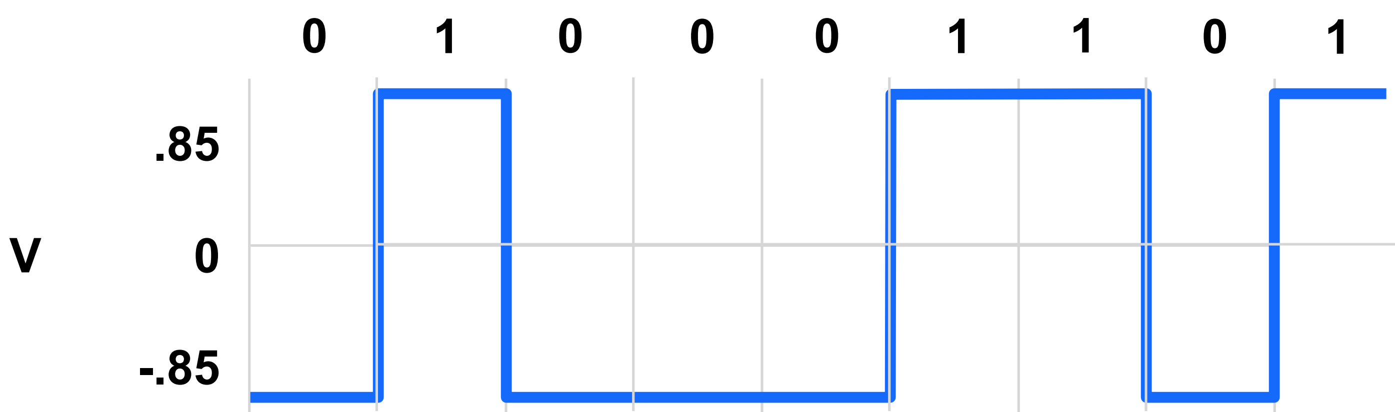
Why Do We Need Encoding?

- Meet certain electrical constraints.
  - Receiver needs enough “transitions” to keep track of the transmit clock
  - Avoid receiver saturation
- Create control symbols, besides regular data symbols.
  - E.g. start or end of frame, escape, ...
- Error detection or error corrections.
  - Some codes are illegal so receiver can detect certain classes of errors
  - Minor errors can be corrected by having multiple adjacent signals mapped to the same data symbol
- Encoding can be very complex, e.g. wireless.

Encoding

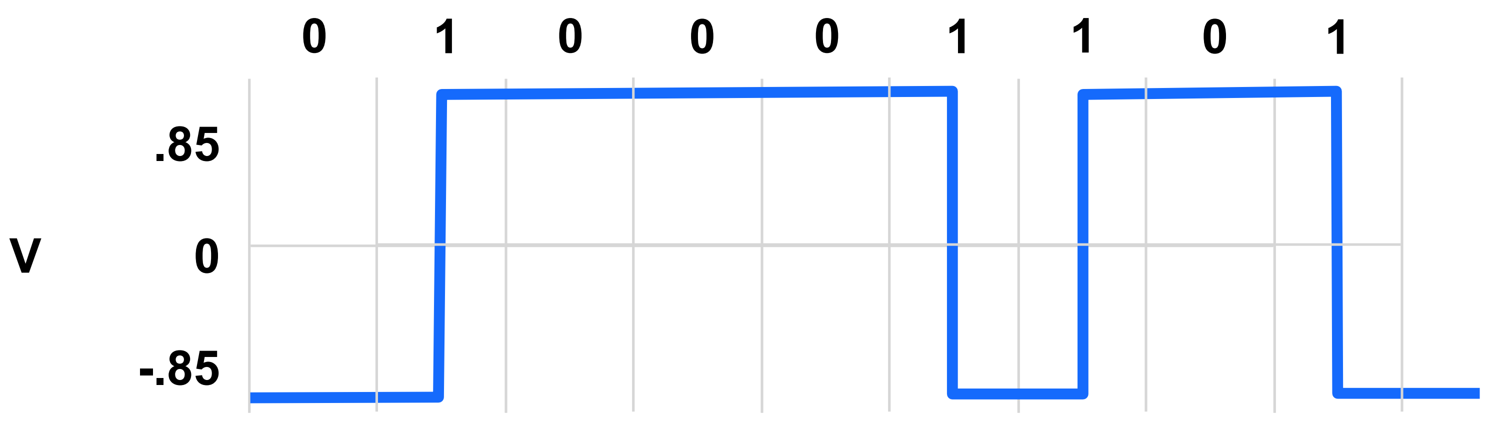
- Use two discrete signals, high and low, to encode 0 and 1.
- Transmission is synchronous, i.e., a clock is used to sample the signal.
  - » In general, the duration of one bit is equal to one or two clock ticks
  - » Receiver's clock must be synchronized with the sender's clock
- Encoding can be done one bit at a time or in blocks of, e.g., 4 or 8 bits.

Non-Return to Zero (NRZ)



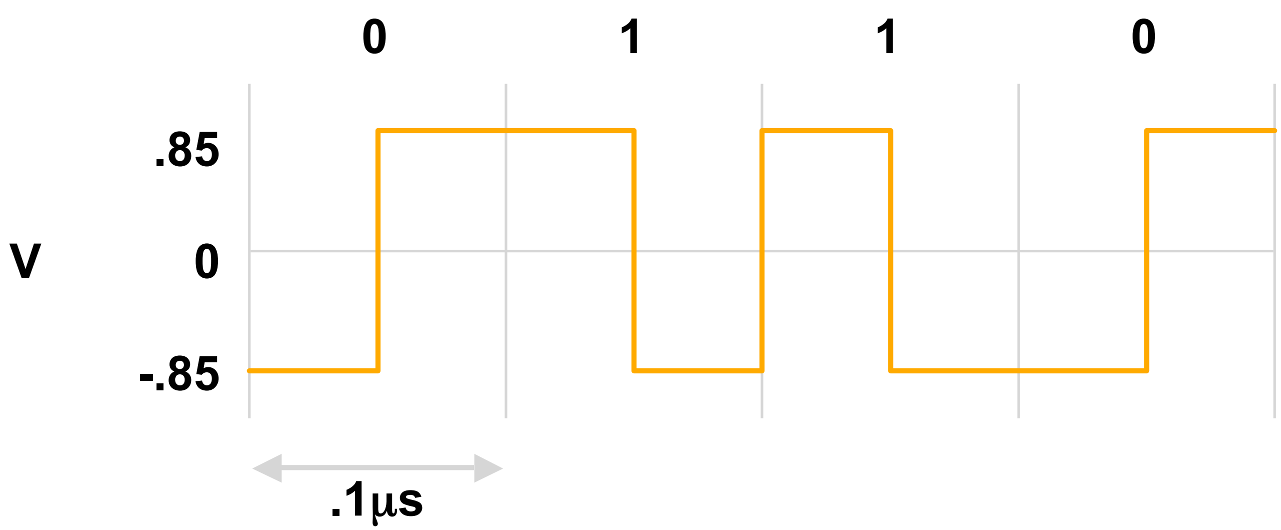
- 1 -> high signal; 0 -> low signal
- Long sequences of 1's or 0's can cause problems:
  - » Sensitive to clock skew, i.e. hard to recover clock
  - » Difficult to interpret 0's and 1's

Non-Return to Zero Inverted (NRZI)



- 1 -> make transition; 0 -> signal stays the same
- Solves the problem for long sequences of 1's, but not for 0's.

Ethernet Manchester Encoding



- Positive transition for 0, negative for 1
- Transition every cycle communicates clock (but need 2 transition times per bit)
- DC balance has good electrical properties

4B/5B Encoding

- Data coded as *symbols* of 5 line bits => 4 data bits, so 100 Mbps uses 125 MHz.
  - Uses less frequency space than Manchester encoding
- Uses NRI to encode the 5 code bits
- Each valid symbol has at least two 1s: get dense transitions.
- 16 data symbols, 8 control symbols
  - Data symbols: 4 data bits
  - Control symbols: idle, begin frame, etc.
- Example: FDDI.

4B/5B Encoding

Data	Code
0000	11110
0001	01001
0010	10100
0011	10101
0100	01010
0101	01011
0110	01110
0111	01111

Data	Code
1000	10010
1001	10011
1010	10110
1011	10111
1100	11010
1101	11011
1110	11100
1111	11101

Other Encodings

- 8B/10B: Fiber Channel and Gigabit Ethernet
  - » DC balance
- 64B/66B: 10 Gbit Ethernet
- B8ZS: T1 signaling (bit stuffing)