Administrivia

Mailing list: make sure I have your email address

On-line documents:

- http://www.cs.berkeley.edu/~brewer/cs294.html
- Some papers, plus all slides and handouts

Projects:

- Worry about topics and partners
- Due next Wednesday: one sentence proposal and list of team members (groups of 2 or 3 preferred)
- Yes, I have a list of topics. No, you can't have it. If you are stuck come talk to me, but at least try first.
- Scope and deliverables will come later.

Physical Layer: Outline

Transmission basics

Electrical signalling

Optical signalling

Comparison

Future optical technologies

SONET

Summary

Goal

Goal: hide EE nastiness (motto: I don't want to know)

- Convert underlying analog medium to sequence of bits
- *virtual bit pipe*
- Hide representation, noise, and clock issues

Metrics:

- Speed in bits per second, bps
- Reliable: bit error rate (BER)
  - probability of an error
  - free-space: 10^{-4} (depends on environment, power)
  - wire: 10^{-8}
  - optical: 10^{-10}

Transmission Basics

"bandwidth" of n Hertz $\Rightarrow$ $2n$ samples per second

Example: standard phone lines

- Carrier typically 1700 Hz, bandwidth of 1200 Hz
- $\Rightarrow$ 2400 samples per second
- Creative encoding provides 1-12 bits per sample
- Bandwidth:
  - 1-bit samples $\Rightarrow$ 2400 bps (baud)
  - 6-bit samples $\Rightarrow$ 14,400 bps
- Sample size limited by signal-to-noise ratio

Long Wires

Problem: speed of light limitation

Example: copper wires transmits at 15 cm/ns

- 200 Mhz clock $\Rightarrow$ 5 ns clock period
- $\Rightarrow$ 75 cm per cycle
- $\Rightarrow$ < 40 cm wire for round trip
- $\Rightarrow$ must pipeline bits to maintain 200 Mbps

Solution 1: synchronous clock

- Wire length is an integral number of cycles
- CM-5: 40 Mhz, 25 ns $\Rightarrow$ 675 cm/cycle at Teflon's 27 cm/ns
- Longest cable is 27m, or 4 cycles

Solution 2: plesiochronous timing $\Rightarrow$ no limit on cables

Long Wires: Reflection Noise

Problem: signal reflects back down the line

Solution: impedance matching (absorbs signal)

Depends on wire, so make it adaptive

Depends on frequency, so limit rise time

Connectors also reflect, so connect chip to chip

Long Wires: Crosstalk

Problem: parallel wires induce currents in each other

Solution: coaxial cable or twisted pair

Generation depends on voltage, so use small voltage swings

Coupling for packaging depends on frequency, so minimize rise time

Long Wires: Power

Problem: long wires eat power

Solution: minimize voltage swing

- $Power = VI = \frac{V^2}{R}$
- At 25Ω, 3V swings $\Rightarrow$ 360mW, while 250mV swing $\Rightarrow$ 2.5mW

New problem: too much noise for small swings

- Eliminate internal noise by avoiding on/off switching
- Add pins to absorb internal noise
- Ignore power-supply noise; no reference voltage
- Switch slowly to reduce ringing

Bidirectional VLSI Pad

Beautiful design

Bidirectional: reduces pin count

Tiny voltage swings: 250 mV

- very low power
- generates no noise for neighboring wires

Ideal rise time: 

- Minimizes frequency
- Reduces reflections due to packaging/connectors
- Reduces power consumption
- Reduces internal noise

What about Optical?

Given 200+ Mbps electrical, why use optical?

Answers:

- Bandwidth is huge
- Much better for longer distances (> 10m)
- No crosstalk or reflections
- Lighter, smaller, and more durable than wire

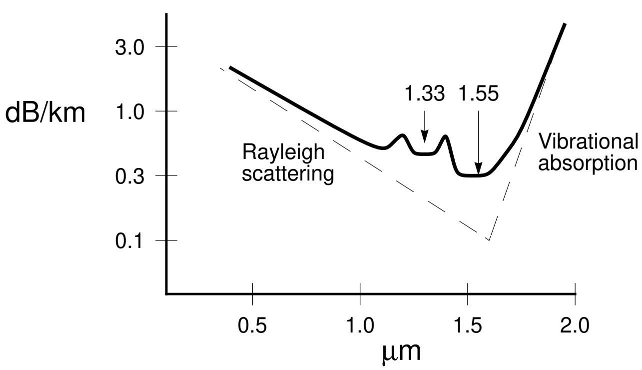
Problems:

- Big power requirements
- If reasonable power, then too slow

Optical Fiber: Attenuation

Attenuation: signal loss is measured in dB/km

- 10^x times fainter = $10x$ dB, e.g. 1000 times = 30 dB
- Coaxial cable: 30 dB/km at 100 Mhz



Optical Fiber: Bandwidth

Literal bandwidth: 100nm

Range: $\frac{c}{\lambda + 100}$ to $\frac{c}{\lambda}$, λ = 1.33, 1.55 μm

$\Rightarrow 2.10 \times 10^{14}$ Hz to 2.26×10^{14} Hz

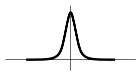
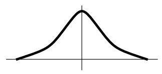
$\Rightarrow$ bandwidth of 1.6×10^{13} Hz

$\Rightarrow$ > 10^{13} bps, or 10 Tbps, or one billion phone calls

Range today: 30nm (3 Tbps per fiber)

Optical Fiber: Dispersion

Spreading of pulses during transmission:

Input:  Output: 

Implications:

- ◆ Limits distance without repeaters
- ◆ Limits frequency (rate), dispersion should be < 1/4 period
- ◆ Can trade distance for rate

The Electro-Optic Bottleneck

Bandwidth of fiber is 4 orders of magnitude more than electrical connections

Real limiting factor is the power required to switch the light source (LED or laser diode):

- ◆ Typical VLSI power $\Rightarrow$ 30ns switching time, or 33 Mhz
- ◆ Higher power can get up to 200 Mhz
- ◆ Adds latency, requires multiple channels to get bandwidth

Attenuation $\Rightarrow$ fiber wins as distance increases

- ◆ Crossover distance at VLSI power is several meters
- ◆ Electrical attenuation proportional to $\sqrt{freq}$

Electrical vs. Optical

Metric	Electrical	Optical
Bandwidth, Gbps	< 1	> 1000
Speed of light, cm/ns c = 30 cm/ns	Copper: 15 Teflon: 27	19
Latency in cycles 3m at 200 Mhz	Copper: 4 Teflon: 2	6+3 (6 channels)
Attenuation, dB/km	30	0.4
Noise	Crosstalk, reflections	none
Power, mW	2.5	>100
Practical issues	Cheap	Light, durable

All Optical?

Idea: remove electrical switches

Optical amplifiers:

- ◆ Recently invented, (see Wil93)
- ◆ Maintains 30nm bandwidth (3 Tbps)
- ◆ Dispersion becomes limit, use solitons?

Optical buffering doesn't exist:

- ◆ Option 1: buffer via loops of cable (LOTS of cable)
- ◆ Option 2: connection-based, true circuit-switched routing
- ◆ Option 3: misroute instead (keep packets moving)

Wavelength Division Multiplexing

Can be done completely optically

Each connection gets small portion of bandwidth

Switches optically route each channel independently

- Filters selectively pass or reflect various bands
- Apply recursively to demultiplex
- Multiplex by simply joining signals
- Controlled electrically, but transport is optical

Key advantage: tremendous bandwidth

Key problems: very expensive, high power

Sonet

Not a physical layer, but a data-link control layer

Assumes mostly reliable optical bit stream

What does it add:

- Framing: converts bit stream into sequence of frames
- Byte interleaving of n streams to get n times the bandwidth
- Support for many existing carrier rates
- Support for plesiochronous interconnect

Basic rate: STS-1= 51.84 Mb/s

- STS-3: 155 Mbps, current ATM
- STS-12: 622 Mbps, next generation ATM

Summary

Physical layer hides many problems:

- Electrical: reflections, crosstalk, internal noise
- Optical: dispersion, power/speed trade-off
- Representation of 1's and 0's
- Clocking problems

The output is a nearly reliable bit stream: BER=10^{-9}

Optical only works well for medium to long distances:

- Requires too much power for short distances
- Low attenuation overcomes this problem eventually
- Only a tiny fraction of bandwidth actually used
- All-optical networks could provide terabytes per second