Links are everywhere…
Basic Link Issues

• Signaling: getting bits from the TX to the RX

![Diagram showing signaling](image)

• Timing: determining which bit is which

![Timing diagram](image)

Speed of Light

• Why is a link (i.e., off-chip I/O) different than on-chip wires?
  • Both send info back and forth

• Usually model on-chip wires with capacitor
  • Sometimes with resistance too

• On-chip model works because dimensions $<< \lambda$
  • Not true for off-chip wires...
Transmission Lines

- Wire model when can’t ignore $c$:

- Properties:
  - Delay
  - Characteristic impedance
  - Energy stored in E, B fields

Termination and Reflection

- Two constraints at any junction:
  - Voltage are equal
  - Power is conserved
Loss

- Real T-lines have loss too:
  - Skin loss $\alpha \sqrt{f}$
  - Dielectric loss $\alpha f$

Not Just Material Issues...

- Energy splits at via
- Via stub looks like a capacitor – reflections
Example Channels

- 20-30dB loss at 3GHz
- How bad is that?
- Two related issues:
  - (1) Noise and min. signal amplitude
  - (2) Intersymbol interference

Noise and BER

- RX circuits always have noise
  - If noise is ever larger than the input signal (at sampling point), RX will decode the bit incorrectly
- BER = Bit Error Rate
  - I.e., average # of incorrectly received bits / total transmitted bits
Min. Signal Amplitude

- Min. signal set by noise $\sigma$ and residual offset:

$$BER = \frac{1}{2} \text{erfc} \left( \frac{V_{\text{in,ampl}} - V_{\text{off}}}{\sqrt{2} \sigma_{\text{noise}}} \right)$$

- BER = $10^{-12}$: $(V_{\text{in,ampl}} - V_{\text{off}}) = 7\sigma_n$
- BER = $10^{-20}$: $(V_{\text{in,ampl}} - V_{\text{off}}) = 9.25\sigma_n$

So What?

- Why not just hit the RX with a larger signal?
  - (Not a stupid question – this is often what people do)

- Simple (hand-wavy) answers:
  - Transmission line $Z$ usually low (~50$\Omega$)
    - 1V swing $\rightarrow$ 20mW
  - Larger swing doesn’t help with ISI...
    - More next lecture

- Bottom line:
  - If can use lower swing, can get lower power
  - Good application of EE240 material!
Link Circuits: “Current-Mode” TX

- Often use differential signaling/circuits to reject supply/CM noise:

Receiver Termination Options
Basic Receiver

Front-end Amp Gain
Front-end Amp Bandwidth