EE273 Lecture 3
More about Wires
Lossy Wires, Multi-Drop Buses, and Balanced Lines

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William J. Dally
Computer Systems Laboratory
Stanford University
billd@csl.stanford.edu

Today's Assignment

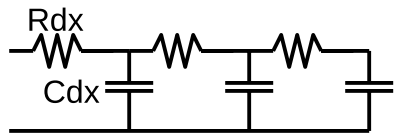
- Reading
  - Sections 3.6 and 3.7
  - Complete before class on Monday
- Problem Set 2
  - do exercises 3-2, 3-6, 3-7, and 3-16
  - run SPICE to verify your answer for all four problems
  - due at start of class on Wednesday 10/7

A Quick Overview

- Real transmission lines have loss
  - resistance of conductors
  - conductance of insulators
- RC lines are an extreme case
  - propagation governed by heat equation
  - delay and rise time are quadratic with length
- This loss distorts the waveform
  - rapid rise to AC signal level
  - long tail to DC signal level
- This distortion reduces the eye opening and hence the noise immunity
- Loss is frequency dependent
  - skin effect $R \sim f^{1/2}$
  - dielectric absorption $G \sim f$
- Multidrop buses have stubs and lumped loads
  - clean signal propagation is possible only when rise time is long compared to length of
    - stubs
    - space between loads
  - distributed capacitance reduces impedance significantly

RC Transmission Lines

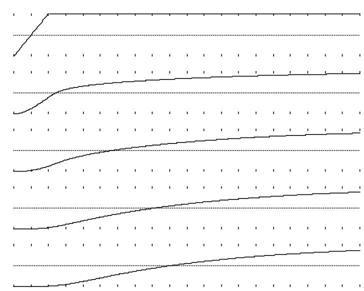
- Most real lines dissipate power
  - resistance of conductors
  - conductance of insulator
- RC lines are an extreme case
  - $R \gg j\omega L$
  - typical of on-chip wires
    - $R = 150\text{k}\Omega/\text{m}$
    - $L = 600\text{nH/m}$
    - $\omega_1 = 2.5 \times 10^{11}$ (40GHz)
  - propagation is governed by the heat equation



$$\frac{\partial^2 V}{\partial x^2} = RC\frac{\partial V}{\partial t}$$

Propagation in RC Transmission Lines

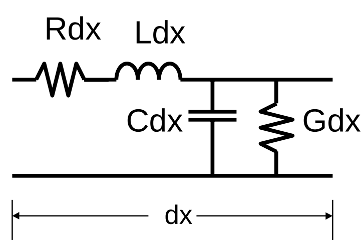
- Signal is dispersed as it propagates down a line
  - R increases with length, d
  - C increases with d
  - delay and rise time increase with RC and thus with d^2
  - for a typical wire
    - R = 150KΩ/m, C=200pF/m
    - $\tau = RC = 30\mu s/m^2 = 30ps/mm^2$

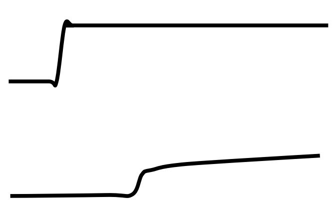


$$t_d \approx 0.4 d^2 RC$$
$$t_r \approx d^2 RC$$

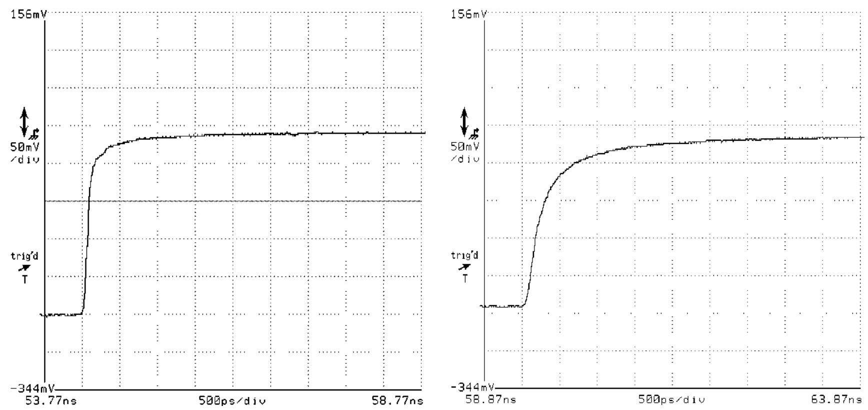
Lossy Transmission Lines

- LC lines with resistance and conductance
  - propagation mostly by wave
  - some by diffusion
- R and G dissipation
  - reduces the amplitude of the signal
  - disperses the signal
    - fast rise to AC attenuation
    - slow tail to DC attenuation
- Resistance and conductance depend on frequency
  - we will ignore this for now





Step Response of 1m 8mil Stripguide



0.2m 1m

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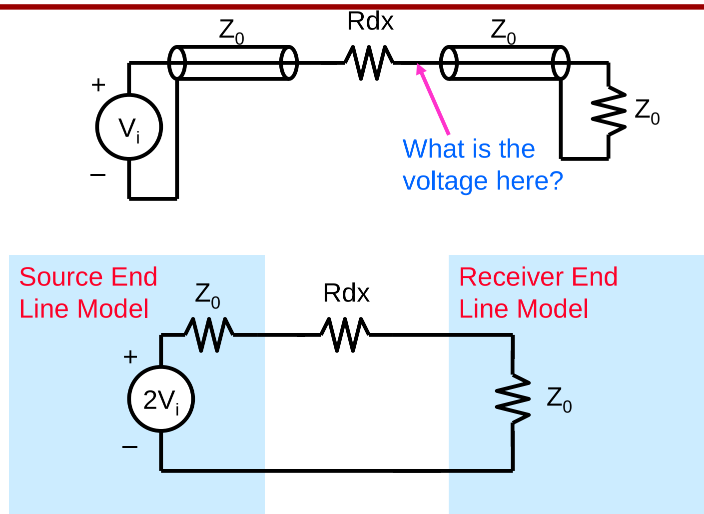
Simple Model of Resistive Attenuation



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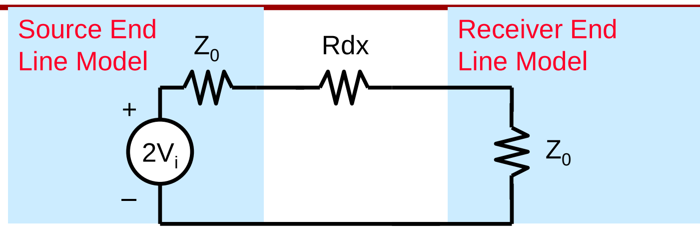
Simple Model of Resistive Attenuation (2)



$$\frac{V_i(x+dx)}{V_i(x)} = \frac{Z_0}{2Z_0 + Rdx} = \frac{1}{1 + Rdx/2Z_0}$$

$$\frac{V_i(x+ndx)}{V_i(x)} = \left(\frac{1}{1 + Rdx/2Z_0}\right)^n$$

$$\frac{V_i(x)}{V_i(0)} \approx \exp\left(-x\left(R/2Z_0\right)\right)$$

Attenuation Constant

$$\alpha = \frac{R}{2Z_0}$$

See the text for an alternative derivation

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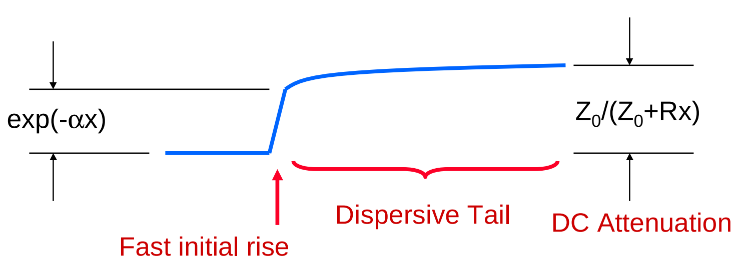
Zero-th Order Waveform



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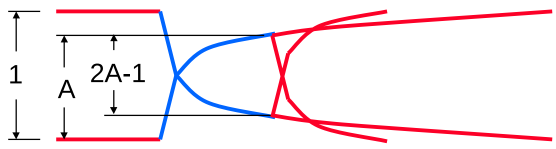
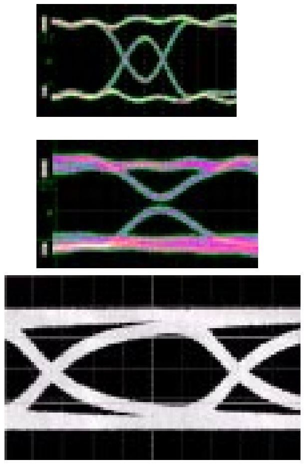
Q: So why worry about attenuation?
A: It closes the eye opeing!

- Critical parameter is what fraction of swing, A is achieved in one bit time
- Eye opening is reduced to B = 2A-1
- No eye opening at 50% attenuation
- Significant degradation of margins at lower levels of attenuation





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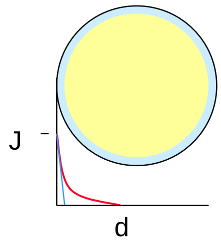
Skin Effect Resistance

- Beauty is only skin deep - so is current
  - current density drops off exponentially with depth
- Skin depth decreases with frequency, $f^{-1/2}$
- Model as if all current flowed in δ-thick outer layer of conductor

$$\delta = (\pi f \mu \sigma)^{-1/2}$$



$$J = \exp\left(-\frac{d}{\delta}\right)$$

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Skin-Effect Resistance

- Effect does not occur until frequency, f_s, at which skin depth equals conductor radius
- Above f_s, R and A increase as the square-root of frequency

$$R(f) = \frac{R_{DC}}{2}\left(\frac{f}{f_s}\right)$$

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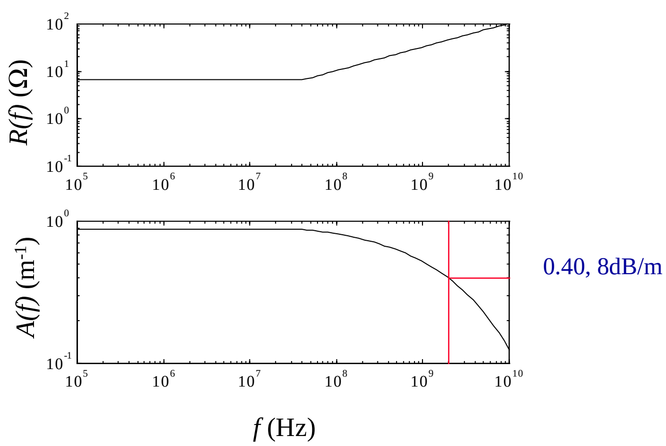
Resistance and Attenuation of 5mil 0.5oz 50Ω Stripguide



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Dielectric Absorption

- High frequency signals *jiggle* molecules in the insulator
  - insulator *absorbs* signal energy
- This effect is approximately linear with frequency and is modeled as a conductance
- Dielectric loss is often specified in terms of a *loss tangent*, tan(δ)

$$\tan\delta = \frac{G}{\omega C}$$

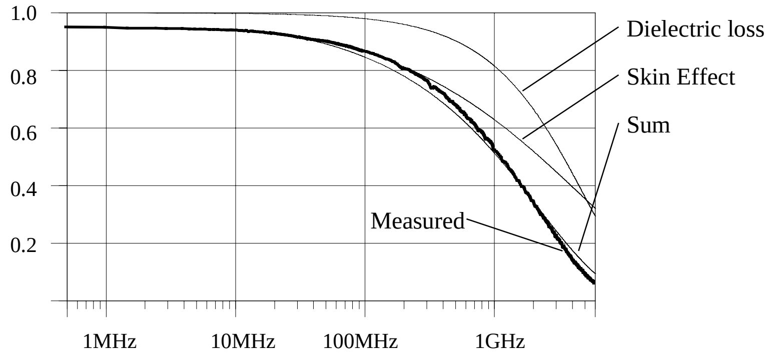
$$\alpha_D = \frac{GZ_0}{2}$$

$$= \pi f \tan\delta\sqrt{LC}$$

$$= \frac{\pi\sqrt{\varepsilon_r}\, f \tan\delta}{c}$$

material	tan δ
FR4	0.035
Polyimide	0.025
GETEK	0.010
Teflon	0.001

Skin effect resistance and dielectric absorption



1m 8mil 50Ω stripguide with GETEK dielectric

The Bd^2 Constant

- Suppose you can tolerate a certain attenuation, A
  - eye opening is 2A-1
- At a certain bandwidth, B_1, attenuation A is achieved with a distance of 1m
- As bandwidth is increased, resistance, and hence attenuation, increases as $B^{1/2}$
- So distance must be decreased by a proportional amount

$$A(B_1) = A_1$$

$$A(B,d) = A_1 d \left(\frac{B}{B_1}\right)^{1/2}$$

$$Bd^2 = B_1$$

Doubling distance cuts bandwidth by a factor of 4

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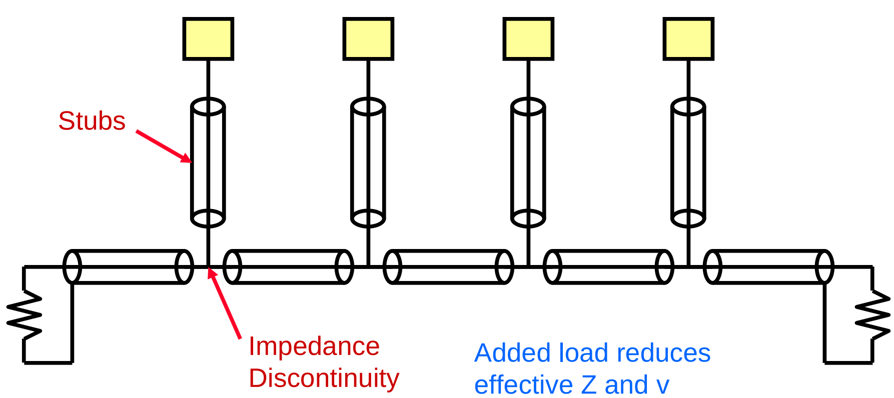
Multi-drop Buses



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Multi-Drop Buses

- Consider a typical bus
  - 50Ω PC board traces
    - C = 100pF/m, L=300nH/m
  - Stubs are 10cm long (0.7ns)
    - 20pF load at end
  - Spacing between modules is 3cm
- Constraints:
  - rise time must be *long* compared to stub length (>3ns) and spacing (>1ns)
  - 30pF each 3cm brings C to 1100pF/m
    - Z = 16.5Ω, v=5.5 x 10^7 m/s
    - driver sees 8.25Ω
- Bus speed is limited by geometry of the bus
  - stub length
  - stub spacing
- Leaving a module 'unplugged' causes a discontinuity
- Point-to-point signaling
  - is electrically much cleaner
  - allows concurrent transfers
- 'Just say no' to buses

Next Time

- Balanced lines
  - return current induces voltage across signal return inductance
  - if return and signal have identical L and C line is balanced
    - even and odd modes of propagation
- Modeling Wires
  - given a *real* wire, make a SPICE model
- Measurement Techniques
  - time-domain reflectometry
  - time-domain transmission measurements
  - network analysis