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

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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
  - $R >> j\omega L$
  - typical of on-chip wires
    - $R = 150k\Omega/m$
    - $L = 600nH/m$
    - $\omega = 2.5 \times 10^{11}$ (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
  - \( \tau = RC = 30\mu s/m^2 = 30ps/mm^2 \)

\[
\begin{align*}
t_d &= 0.4d^2RC \\
t_r &= d^2RC
\end{align*}
\]

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

Simple Model of Resistive Attenuation

What is the voltage here?
Simple Model of Resistive Attenuation (2)

Source End Line Model

\[ V_s(x + dx) = \frac{V_s(x)}{2Z_0 + Rdx} = \frac{1}{1 + Rdx/2Z_0} \]

Attenuation Constant

\[ \alpha = \frac{R}{2Z_0} \]

See the text for an alternative derivation

Receiver End Line Model

\[ Z_0 \]

Zero-th Order Waveform

\[ \exp(-\alpha x) \]

Fast initial rise

Dispersive Tail

DC Attenuation

\[ Z_0/(Z_0 + Rx) \]
Q: So why worry about attenuation?
A: It closes the eye opening!

- 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

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 $\delta$-thick outer layer of conductor

\[
\delta = (\pi \mu \sigma)^{-1/2}
\]

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

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

Resistance and Attenuation of 5mil 0.5oz 50Ω Stripguide

![Graph showing the variation of resistance and attenuation with frequency.]
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*, $\tan(\delta)$

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

$$\alpha_D = \frac{G Z_0}{2}$$

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

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

<table>
<thead>
<tr>
<th>Material</th>
<th>$\tan \delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4</td>
<td>0.035</td>
</tr>
<tr>
<td>Polyimide</td>
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</tr>
<tr>
<td>GETEK</td>
<td>0.010</td>
</tr>
<tr>
<td>Teflon</td>
<td>0.001</td>
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</tbody>
</table>

Skin effect resistance and dielectric absorption

![Graph](Image)
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

\[
A(B_1) = A_i
\]
\[
A(B, d) = A_i d \left(\frac{B}{B_1}\right)^{1/2}
\]
\[
B d^2 = B_1
\]

Doubling distance cuts bandwidth by a factor of 4

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Multi-drop Buses

- Stubs
- Impedance Discontinuity
- Added load reduces effective $Z$ and $v$
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