Wires Etc. Part I

\[ R = \frac{\rho L}{A} \]
Some Transmission Lines

Coaxial Cable
- Insulating jacket
- Outer shield
- Inner dielectric
- Inner conductor

Twisted Pair
- Dielectric
- Conductor

Microstrip
- Conductor
- Dielectric
- Ground (Gnd)

Stripline
- Conductor
- Dielectric
- Ground (Gnd)
Cross Section of PCB Board

- FR4 Dielectric
- M1 (signal layer)
- M2 (Ground plane)
- M3 (Power plane)
- M4 (signal layer)
- M5 (Power plane)
- M6 (signal layer)
LRCG, LC and RC Models I

\[ Z_0 = \left( \frac{R + j\omega L}{G + j\omega C} \right)^{1/2} \]

“Low” Freq
\[ R >> j\omega L \]

“High” Freq
\[ R << j\omega L \]

find \( f_0 \) where
\[ R = j\omega L \]

- Transmission lines have characteristic frequency \( f_0 \)
- Below \( f_0 \) \( \sim \) RC model, Above \( f_0 \) \( \sim \) LC model
Propagation Constant

\[ s = j\omega \]

\[
\frac{\partial V(s)}{\partial x} = - (R + Ls) I(s) = - (R + Ls) \frac{V(s)}{Z_0} = - \left( (R + Ls)(G + Cs) \right)^{\frac{1}{2}} V(s)
\]

\[
V(s,x) = V(s,0) e^{-Ax} \quad A = \left( (R + Ls)(G + Cs) \right)^{\frac{1}{2}}
\]
The Payoff

\[ V(s,0) \]

\[ V(s,x) = V(s,0) e^{-Ax} \]

\[ A = ((R + Ls)(G + Cs))^{\frac{1}{2}} \]

\[ A = A' + A''j \]

\[ V(s,x) = V(s,0) e^{-A'x} e^{-A''x} \]

real component: attenuation

imaginary: phase shift
LRCG, LC and RC Models II

\[ Z_0 = \left( \frac{L}{C} \right)^{\frac{1}{2}} = \left( \frac{0.5 \text{ nH}}{0.1 \text{ pF}} \right)^{\frac{1}{2}} \approx 70 \Omega \]

Example from Poulton 1999 ISSCC Tutorial

\begin{align*}
L &= 0.6 \text{ nH/mm} \\
C &= 73 \text{ nF/mm} \\
R_{dc} &= 120\Omega /\text{mm} \\
f_0 &= 32 \text{ GHz} \\

L &= 0.5 \text{ nH/mm} \\
C &= 104 \text{ fF/mm} \\
R_{dc} &= 0.008\Omega /\text{mm} \\
f_0 &= 2.5 \text{ MHz}
\end{align*}
Lossless LC Line

wave velocity
\[ v = (LC)^{-1/2} \]

- Wave propagation velocity is a function of inductance and capacitance
- Waves propagate down in both directions without distortion
- Waveform on line is superposition of forward and reverse waves
Transmission Line Reflection

![Diagram](attachment:image.png)

Reflection Coefficient = \( \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \frac{Z_L - Z_S}{Z_L + Z_S} \)
**Special Cases**

![Diagram showing reflection coefficient]

**Reflection Coefficient**

\[
\rho = \frac{Z_L - Z_S}{Z_L + Z_S}
\]

- \(Z_L = 0\); Short Circuit
  \[
  \rho = \frac{0 - Z_S}{0 + Z_S} \quad \rho = -1
  \]

- \(Z_L = \text{inf}\); Open Circuit
  \[
  \rho = \frac{Z_L}{Z_L} \quad \rho = 1
  \]

- \(Z_L = Z_S\); Matched Load
  \[
  \rho = \frac{Z_L - Z_L}{Z_L + Z_S} = 0
  \]
Example Part I

V_s = V_i \frac{Z_s}{Z_s + Z_0} = 2 \frac{50}{25 + 50} = 1.3333 V

ρ_{(load)} = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{\text{inf} - 50}{\text{inf} + 50} = 1

ρ_{(source)} = \frac{Z_s - Z_0}{Z_s + Z_0} = \frac{25 - 50}{25 + 50} = -0.3333
Example Part II

\[\rho_{\text{load}} = 1\]
\[\rho_{\text{source}} = -0.3333\]

\[\text{TD} = 250 \text{ ps}\]

\[V_S \quad Z_0 \quad V_L\]

\[V_I \quad Z_S\]

\[\rho_{\text{load}} = 1\]
\[\rho_{\text{source}} = -0.3333\]

Time (ps)

0 1.33 v 1.33 v 0 v
250 1.33 v -0.443 v 2.66 v
500 2.22 v -0.443 v 1.77 v
750 2.66 v 0.148 v
1000 1.92 v

\[V_S \quad V_I \quad V_L\]

\[Z_0 \quad Z_L\]
Example Part III

```
<table>
<thead>
<tr>
<th>Time (ps)</th>
<th>Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-250</td>
<td>0.5v</td>
</tr>
<tr>
<td>250-500</td>
<td>1.0v</td>
</tr>
<tr>
<td>500-750</td>
<td>1.5v</td>
</tr>
<tr>
<td>750-1000</td>
<td>2.0v</td>
</tr>
<tr>
<td>1000-1250</td>
<td>2.5v</td>
</tr>
<tr>
<td>1250-1500</td>
<td>V_load</td>
</tr>
<tr>
<td>1500-1750</td>
<td>V_source</td>
</tr>
</tbody>
</table>
```

- **Time (ps)**: 0 to 1750
- **Volts**:
  - 0.5v to 2.5v
- **V_load**: load voltage
- **V_source**: source voltage
Revisiting Multidrop Bus

Transmission line quality depends on system board

Each impedance discontinuity is a reflective interface
Rambus Channel - 16 bit

- RIMM #3 dropped from spec to solve signalling problems
- Need Continuity RIMM
Rambus Channel - 32/64 bit

- Termination brought onto RIMM
- Connector interface count reduced from 4 to 3
- No need for special terminated RIMM and non-terminated RIMM
Skin Effect

- Current flow depth is a function of frequency
- Higher frequency == Smaller depth
- Smaller depth == Higher resistivity
- Characteristic impedance isn’t much affected
  (R grows wrt $\omega^{1/2}$, L grows wrt $\omega$)
Dielectric Loss

100 Ω differential PCB loss, as function of data rate, PCB lengths from 10” to 50” (8 mil line width)

- Graph taken from North East Systems Associates Inc. presentation slides. Copyright 2001