ECEN720: High-Speed Links
Circuits and Systems
Spring 2017

Lecture 2: Channel Components, Wires, & Transmission Lines

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Announcements

• Lab
  • Lab begins on Jan 30 and is in CVLB 322
  • Prelab 1 due at beginning of lab on Jan 30
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    • Office Hours M 3PM-5PM, WEB 315A

• Reference Material Posted on Website
  • TDR theory application note
  • S-parameter notes
Agenda

- Channel Components
  - IC Packages, PCBs, connectors, vias, PCB Traces

- Wire Models
  - Resistance, capacitance, inductance

- Transmission Lines
  - Propagation constant
  - Characteristic impedance
  - Loss
  - Reflections
  - Termination examples
  - Differential transmission lines
Channel Components

[Meghelli (IBM) ISSCC 2006]
IC Packages

• Package style depends on application and pin count

• Packaging technology hasn’t been able to increase pin count at same rate as on-chip aggregate bandwidth
  • Leads to I/O constrained designs and higher data rate per pin

<table>
<thead>
<tr>
<th>Package Type</th>
<th>Pin Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Outline Package (SOP)</td>
<td>8 – 56</td>
</tr>
<tr>
<td>Quad Flat Package (QFP)</td>
<td>64 - 304</td>
</tr>
<tr>
<td>Plastic Ball Grid Array (PBGA)</td>
<td>256 - 420</td>
</tr>
<tr>
<td>Enhanced Ball Grid Array (EBGA)</td>
<td>352 - 896</td>
</tr>
<tr>
<td>Flip Chip Ball Grid Array (FC-BGA)</td>
<td>1089 - 2116</td>
</tr>
</tbody>
</table>

[Package Images - Fujitsu]
IC Package Examples

- Wirebonding is most common die attach method
- Flip-chip packaging allows for more efficient heat removal
- 2D solder ball array on chip allows for more signals and lower signal and supply impedance
IC Package Model

**Bondwires**
- \( L \sim 1 \text{nH/mm} \)
- Mutual L “K”
- \( C_{\text{couple}} \sim 20 \text{fF/mm} \)

**Package Trace**
- \( L \sim 0.7-1 \text{nH/mm} \)
- Mutual L “K”
- \( C_{\text{layer}} \sim 80-90 \text{fF/mm} \)
- \( C_{\text{couple}} \sim 40 \text{fF/mm} \)
Printed Circuit Boards

- Components soldered on top (and bottom)

- Typical boards have 4-8 signal layers and an equal number of power and ground planes

- Backplanes can have over 30 layers
PCB Stackup

- Signals typically on top and bottom layers

- GND/Power plane pairs and signal layer pairs alternate in board interior

- Typical copper trace thickness
  - “0.5oz” (17.5um) for signal layers
  - “1oz” (35um) for power planes
Connectors

- Connectors are used to transfer signals from board-to-board

- Typical differential pair density between 16-32 pairs/10mm

[Tyco]
Connectors

- Important to maintain proper differential impedance through connector
- Crosstalk can be an issue in the connectors
Vias

- Used to connect PCB layers

- Made by drilling a hole through the board which is plated with copper
  - Pads connect to signal layers/traces
  - Clearance holes avoid power planes

- Expensive in terms of signal density and integrity
  - Consume multiple trace tracks
  - Typically lower impedance and create “stubs”
Impact of Via Stubs at Connectors

- **Legacy BP** has default straight vias
  - Creates severe nulls which kills signal integrity
- **Refined BP** has expensive backdrilled vias
PCB Trace Configurations

- Microstrips are signal traces on PCB outer surfaces
  - Trace is not enclosed and susceptible to cross-talk
- Striplines are sandwiched between two parallel ground planes
  - Has increased isolation

[Johnson]
Wire Models

- Resistance
- Capacitance
- Inductance
- Transmission line theory
Wire Resistance

- Wire resistance is determined by material resistivity, $\rho$, and geometry
- Causes signal loss and propagation delay

\[ R = \frac{\rho l}{A} = \frac{\rho l}{wh} \]

\[ R = \frac{\rho l}{A} = \frac{\rho l}{\pi r^2} \]
Wire Capacitance

- Wire capacitance is determined by dielectric permittivity, $\varepsilon$, and geometry
- Best to use lowest $\varepsilon_r$
  - Lower capacitance
  - Higher propagation velocity

\[
C = \frac{w \varepsilon}{s}
\]
\[
C = \frac{2\pi \varepsilon}{\log\left(\frac{r_2}{r_1}\right)}
\]
\[
C = \frac{\pi \varepsilon}{\log(s/r)}
\]
\[
C = \frac{w \varepsilon}{s} + \frac{2\pi \varepsilon}{\log(4s/h)}
\]
Wire Inductance

- Wire inductance is determined by material permeability, $\mu$, and closed-loop geometry

- For wire in homogeneous medium

\[ CL = \varepsilon \mu \]

- Generally $\mu = \mu_0 = 4\pi \times 10^{-7} \text{ H/m}$
Wire Models

- **Model Types**
  - Ideal
  - Lumped C, R, L
  - RC transmission line
  - LC transmission line
  - RLGC transmission line

- **Condition for LC or RLGC model (vs RC)**
  \[ f_0 \geq \frac{R}{2\pi L} \]

<table>
<thead>
<tr>
<th>Wire</th>
<th>R</th>
<th>L</th>
<th>C</th>
<th>&gt;f (LC wire)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG24 Twisted Pair</td>
<td>0.08Ω/m</td>
<td>400nH/m</td>
<td>40pF/m</td>
<td>32kHz</td>
</tr>
<tr>
<td>PCB Trace</td>
<td>5Ω/m</td>
<td>300nH/m</td>
<td>100pF/m</td>
<td>2.7MHz</td>
</tr>
<tr>
<td>On-Chip Min. Width M6 (0.18µm CMOS node)</td>
<td>40kΩ/m</td>
<td>4µH/m</td>
<td>300pF/m</td>
<td>1.6GHz</td>
</tr>
</tbody>
</table>
RLGC Transmission Line Model

As \( dx \to 0 \)

1. \[
\frac{\partial V(x,t)}{\partial x} = -RI(x,t) - L \frac{\partial I(x,t)}{\partial t}
\]
2. \[
\frac{\partial I(x,t)}{\partial x} = -GV(x,t) - C \frac{\partial V(x,t)}{\partial t}
\]

General Transmission Line Equations
Time-Harmonic Transmission Line Eqs.

- Assuming a traveling sinusoidal wave with angular frequency, $\omega$

\[
\frac{dV(x)}{dx} = -(R + j\omega L)I(x) \quad (3)
\]

\[
\frac{dI(x)}{dx} = -(G + j\omega C)V(x) \quad (4)
\]

- Differentiating (3) and plugging in (4) (and vice versa)

\[
\frac{d^2V(x)}{dx^2} = \gamma^2 V(x) \quad (5)
\]

\[
\frac{d^2I(x)}{dx^2} = \gamma^2 I(x) \quad (6)
\]

- where $\gamma$ is the **propagation constant**

\[
\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (m^{-1})
\]
Transmission Line Propagation Constant

- Solutions to the Time-Harmonic Line Equations:

\[ V(x) = V_f(x) + V_r(x) = V_{f0}e^{-\gamma x} + V_{r0}e^{\gamma x} \]

\[ I(x) = I_f(x) + I_r(x) = I_{f0}e^{-\gamma x} + I_{r0}e^{\gamma x} \]

where \( \gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \) (m\(^{-1}\))

- What does the propagation constant tell us?
  - Real part (\( \alpha \)) determines attenuation/distance (Np/m)
  - Imaginary part (\( \beta \)) determines phase shift/distance (rad/m)
  - **Signal phase velocity**

\[ \nu = \frac{\omega}{\beta} \text{ (m/s)} \]
Transmission Line Impedance, $Z_0$

- For an infinitely long line, the voltage/current ratio is $Z_0$.
- From time-harmonic transmission line eqs. (3) and (4):

$$Z_0 = \frac{V(x)}{I(x)} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \ (\Omega)$$

- Driving a line terminated by $Z_0$ is the same as driving an infinitely long line.

[Dally]
Lossless LC Transmission Lines

- If \( R_{dx} = G_{dx} = 0 \)
  \[
  \gamma = \alpha + j\beta = j\omega\sqrt{LC} \\
  \alpha = 0 \quad \text{No Loss!} \\
  \beta = \omega\sqrt{LC}
  \]

- Waves propagate w/o distortion
  - Velocity and impedance independent of frequency
  - Impedance is purely real

\[
\nu = \frac{\omega}{\beta} = \frac{1}{\sqrt{LC}} \\
Z_0 = \sqrt{\frac{L}{C}}
\]  

\[\text{Distance } (Y - X)\]

\[\text{At point } X, \text{ step is still of size } V, \text{ but delayed}\]

\[\text{At point } Y, \text{ step is delayed even more}\]

\[\text{A step of } V \text{ volts propagates down the transmission line}\]

\[\text{Time delay } t_1 - t_0 = (Y - X)\sqrt{\frac{L}{C}}\]

[Johnson]
Low-Loss LRC Transmission Lines

- If $\frac{R}{\omega L}$ and $\frac{G}{\omega C} << 1$
- Behave similar to ideal LC transmission line, but ...
  - Experience resistive and dielectric loss
  - Frequency dependent propagation velocity results in dispersion
    - Fast step, followed by slow DC tail

\[
\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}
\]

\[
\approx j\omega \sqrt{LC} \left(1 - j \frac{RC + GL}{\omega LC}\right)^{\frac{1}{2}}
\]

\[
\approx \frac{R}{2Z_0} + \frac{GZ_0}{2} + j\omega \sqrt{LC} \left[1 + \frac{1}{8} \left(\frac{R}{\omega L}\right)^2 + \frac{1}{8} \left(\frac{G}{\omega C}\right)^2\right]
\]

\[
= \alpha_R + \alpha_D + j\beta
\]

\[
\alpha_R \approx \frac{R}{2Z_0}
\]

\[
\alpha_D \approx \frac{GZ_0}{2}
\]

Resistive Loss

Dielectric Loss

\[
\beta \approx \omega \sqrt{LC} \left[1 + \frac{1}{8} \left(\frac{R}{\omega L}\right)^2 + \frac{1}{8} \left(\frac{G}{\omega C}\right)^2\right]
\]

\[
v \approx \left(\sqrt{LC} \left[1 + \frac{1}{8} \left(\frac{R}{\omega L}\right)^2 + \frac{1}{8} \left(\frac{G}{\omega C}\right)^2\right]\right)^{-1}
\]
Skin Effect (Resistive Loss)

- High-frequency current density falls off exponentially from conductor surface.
- Skin depth, $\delta$, is where current falls by $e^{-1}$ relative to full conductor:
  - Decreases proportional to $\sqrt{\text{frequency}}$.
- Relevant at critical frequency $f_s$ where skin depth equals half conductor height (or radius):
  - Above $f_s$, resistance/loss increases proportional to $\sqrt{\text{frequency}}$.

\[
J = e^{-\frac{d}{\delta}} \\
\delta = \left(\frac{2\pi \mu \sigma}{\rho}\right)^{\frac{1}{2}}
\]

For rectangular conductor:

\[
f_s = \frac{\rho}{\pi \mu \left(\frac{h}{2}\right)^2} \\
R(f) = R_{DC} \left(\frac{f}{f_s}\right)^{\frac{1}{2}} \\
\alpha_R = \frac{R_{DC}}{2Z_0} \left(\frac{f}{f_s}\right)^{\frac{1}{2}}
\]
Skin Effect (Resistive Loss)

5-mil Stripguide
\[ R_{DC} = 7\, \Omega/m, \quad f_s = 43\, MHz \]

30 AWG Pair
\[ R_{DC} = 0.08\, \Omega/m, \quad f_s = 67\, kHz \]

\[ \alpha_R = \frac{R_{DC}}{2Z_0} \left( \frac{f}{f_s} \right)^{\frac{1}{2}} \]
Dielectric Absorption (Loss)

- An alternating electric field causes dielectric atoms to rotate and absorb signal energy in the form of heat
- Dielectric loss is expressed in terms of the loss tangent
- Loss increases directly proportional to frequency

\[
\tan \delta_D = \frac{G}{\omega C}
\]

### Table 3-4 Electrical Properties of PC Board Dielectrics

<table>
<thead>
<tr>
<th>Material</th>
<th>(\varepsilon_r)</th>
<th>(\tan \delta_p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woven glass, epoxy resin (&quot;FR-4&quot;)</td>
<td>4.7</td>
<td>0.035</td>
</tr>
<tr>
<td>Woven glass, polyimide resin</td>
<td>4.4</td>
<td>0.025</td>
</tr>
<tr>
<td>Woven glass, polyphenylene oxide resin (GETEK)</td>
<td>3.9</td>
<td>0.010</td>
</tr>
<tr>
<td>Woven glass, PTFE resin (Teflon)</td>
<td>2.55</td>
<td>0.005</td>
</tr>
<tr>
<td>Nonwoven glass, PTFE resin</td>
<td>2.25</td>
<td>0.001</td>
</tr>
</tbody>
</table>

\[
\alpha_D = \frac{GZ_0}{2} = \frac{2\pi f C \tan \delta_D \sqrt{L/C}}{2} = \pi f \tan \delta_D \sqrt{LC}
\]

[Dally]
Total Wire Loss

[Graph showing attenuation vs. frequency from 1 MHz to 6 GHz, with labels for Measured Attenuation, Calculated Attenuation, Dielectric Loss, and Conductor Loss.]

[Dally]
• With a Thevenin-equivalent model of the line:

Termination Current: \[ I_T = \frac{2V_i}{Z_0 + Z_T} \]

• KCL at Termination:

\[ I_f = \frac{V_i}{Z_0}, \quad I_r = I_f - I_T \]

\[ I_r = \frac{V_i}{Z_0} - \frac{2V_i}{Z_T + Z_0} \]

\[ I_r = \frac{V_i}{Z_0} \left( \frac{Z_T - Z_0}{Z_T + Z_0} \right) \]

Telegrapher’s Equation or Reflection Coefficient:

\[ k_r = \frac{I_r}{I_f} = \frac{V_r}{V_i} = \frac{Z_T - Z_0}{Z_T + Z_0} \]
Termination Examples - Ideal

\[ V_i = 1 \times \left( \frac{50}{50 + 50} \right) = 0.5V \]

\[ k_{rT} = \frac{50 - 50}{50 + 50} = 0 \]

\[ k_{rS} = \frac{50 - 50}{50 + 50} = 0 \]

\[ R_S = 50\Omega \]
\[ Z_0 = 50\Omega, \ t_d = 1\text{ns} \]
\[ R_T = 50\Omega \]
Termination Examples - Open

\[ V_i = 1V \left( \frac{50}{50 + 50} \right) = 0.5V \]

\[ k_{rT} = \frac{\infty - 50}{\infty + 50} = +1 \]

\[ k_{rS} = \frac{50 - 50}{50 + 50} = 0 \]

\[ R_S = 50\Omega \]
\[ Z_0 = 50\Omega, \quad t_d = 1\text{ns} \]
\[ R_T \sim \infty \ (1\text{M}\Omega) \]

in (step begins at 1ns)
Termination Examples - Short

\[ R_S = 50\Omega \]

\[ Z_0 = 50\Omega, \ t_d = 1\text{ns} \]

\[ R_T = 0\Omega \]

\[
V_i = 1V \left( \frac{50}{50 + 50} \right) = 0.5V
\]

\[
k_{rT} = \frac{0 - 50}{0 + 50} = -1
\]

\[
k_{rS} = \frac{50 - 50}{50 + 50} = 0
\]
Arbitrary Termination Example

\[ R_S = 400 \Omega \]
\[ Z_0 = 50 \Omega, \ t_d = 1 \text{ns} \]
\[ R_T = 600 \Omega \]

\[ V_i = 1V \left( \frac{50}{400 + 50} \right) = 0.111V \]

\[ k_{rT} = \frac{600 - 50}{600 + 50} = 0.846 \]

\[ k_{rS} = \frac{400 - 50}{400 + 50} = 0.778 \]
$R_S = 400 \Omega$

$Z_0 = 50 \Omega$, $t_d = 1$ns

$R_T = 600 \Omega$

in (step begins at 1ns)

Rings up to 0.6V

(DC voltage division)
Termination Reflection Patterns

- **RS = 25Ω, RT = 25Ω**
  - $kr_S < 0$ & $kr_T < 0$
  - Voltages Converge

- **RS = 25Ω, RT = 100Ω**
  - $kr_S < 0$ & $kr_T > 0$
  - Voltages Oscillate

- **RS = 100Ω, RT = 25Ω**
  - $kr_S > 0$ & $kr_T < 0$
  - Voltages Oscillate

- **RS = 100Ω, RT = 100Ω**
  - $kr_S > 0$ & $kr_T > 0$
  - Voltages Ring Up
Termination Schemes

• **No Termination**
  - Little to absorb line energy
  - Can generate oscillating waveform
  - Line must be **very short** relative to signal transition time
    - $n = 4 - 6$
  - Limited off-chip use

• **Source Termination**
  - Source output takes 2 steps up
  - Used in moderate speed point-to-point connections

\[
t_r > nT_{\text{round-trip}} = 2nl\sqrt{LC}
\]

\[
t_{\text{porch}} \approx 2l\sqrt{LC}
\]
Termination Schemes

- **Receiver Termination**
  - No reflection from receiver
  - Watch out for intermediate impedance discontinuities
    - Little to absorb reflections at driver

- **Double Termination**
  - Best configuration for min reflections
    - Reflections absorbed at both driver and receiver
  - Get half the swing relative to single termination
  - Most common termination scheme for high performance serial links
Differential Signaling

- Differential signaling advantages
  - Self-referenced
  - Common-mode noise rejection
  - Increased signal swing
  - Reduced self-induced power-supply noise

- Requires 2x the number of signaling pins relative to single-ended signaling
  - But, smaller ratio of supply/signal (return) pins
  - Total pin overhead is typically 1.3-1.8x (vs 2x)
Odd & Even Modes

• Even mode
  • When equal voltages drive both lines, only one mode propagates called even mode

• Odd mode
  • When equal in magnitude, but out of phase, voltages drive both lines, only one mode propagates called odd mode

• For a differential pair (odd mode), a virtual reference plane exists between the conductors that provides a continuous return current path
  • Electric field is perpendicular to the virtual plane
  • Magnetic field is tangent to the virtual plane
Balanced Transmission Lines

- Even (common) mode excitation
  - Effective $C = C_C$
  - Effective $L = L + M$

- Odd (differential) mode excitation
  - Effective $C = C_C + 2C_d$
  - Effective $L = L - M$

\[
Z_{DIFF} = 2Z_{odd}, \quad Z_{CM} = \frac{Z_{even}}{2}
\]

[Dally]
PI-Termination

Even Mode Equivalent

Odd Mode Equivalent

\[ Z_{\text{even}} = R_1 \]

\[ Z_{\text{odd}} = R_1 \parallel R_2/2 = Z_{\text{even}} \parallel R_2/2 \]

\[ R_2 = 2 \left( \frac{Z_{\text{odd}} Z_{\text{even}}}{Z_{\text{even}} - Z_{\text{odd}}} \right) \]
T-Termination

\[ Z_{even} = R_2 + 2R_1 \]

\[ Z_{odd} = R_2 \]

\[ R_1 = \frac{1}{2} \left( Z_{even} - Z_{odd} \right) \]
Next Time

- Channel modeling
  - Time domain reflectometer (TDR)
  - Network analysis