ECEN720: High-Speed Links
Circuits and Systems
Spring 2019

Lecture 2: Channel Components, Wires, & Transmission Lines

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Announcements

• Lab
  • Lab begins on Jan 30 and is in CVLB 324
  • Prelab 1 due at beginning of lab on Jan 30
  • Lab 1 report and Prelab 2 due on Feb 6
  • TA Ankur Kumar
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    • Office Hours M 11AM-1PM, WEB 160

• 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

[Image of a schematic diagram showing the components of a channel, including Line card trace, Edge connector, Backplane trace, and Via stub, with labels for Packaged SerDes, Tx IC, and Rx IC.]

[Text: 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 ~ 1nH/mm
- Mutual L “K”
- \( C_{\text{couple}} \sim 20\text{fF/mm} \)

**Package Trace**
- L ~ 0.7-1nH/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
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

\[
C_{\text{Parallel Plate}} = \frac{w \varepsilon}{s}
\]
\[
C_{\text{Coaxial}} = \frac{2\pi \varepsilon}{\log(r_2/r_1)}
\]
\[
C_{\text{Wire Pair}} = \frac{\pi \varepsilon}{\log(s/r)}
\]
\[
C_{\text{Rectangle over ground}} = \frac{w \varepsilon}{s} + \frac{2\pi \varepsilon}{\log(4s/h)}
\]

<table>
<thead>
<tr>
<th>Material</th>
<th>$\varepsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
</tr>
<tr>
<td>Teflon</td>
<td>2</td>
</tr>
<tr>
<td>Polyimide</td>
<td>3</td>
</tr>
<tr>
<td>Silicon dioxide</td>
<td>3.9</td>
</tr>
<tr>
<td>Glass-epoxy (PC board)</td>
<td>4</td>
</tr>
<tr>
<td>Alumina</td>
<td>10</td>
</tr>
<tr>
<td>Silicon</td>
<td>11.7</td>
</tr>
</tbody>
</table>
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 \( dx \to 0 \)

\[
\frac{\partial V(x, t)}{\partial x} = -RI(x, t) - L \frac{\partial I(x, t)}{\partial t} \quad (1)
\]

\[
\frac{\partial I(x, t)}{\partial x} = -GV(x, t) - C \frac{\partial V(x, t)}{\partial t} \quad (2)
\]

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

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

- 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**

\[ \nu = \omega/\beta \text{ (m/s)} \]
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)

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

- 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

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

[Johnson]
Low-Loss LRC Transmission Lines

- If $R/\omega L$ and $G/\omega C << 1$
- 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

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

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

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

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

- Resistive Loss
  \[
  \alpha_R \approx \frac{R}{2Z_0}
  \]

- Dielectric Loss
  \[
  \alpha_D \approx \frac{GZ_0}{2}
  \]

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

\[

\nu \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 $\sqrt{\text{frequency}}$

$$J = e^{-\frac{d}{\delta}}$$
$$\delta = (\pi \mu \sigma)^{-\frac{1}{2}}$$

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
\[ R_{DC} = 7 \Omega/m, \ f_s = 43MHz \]

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

\[ \alpha_R = \frac{R_{DC}}{2Z_0 \left( \frac{f}{f_s} \right)^{1/2}} \]
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_D )</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>

[Dally]
Total Wire Loss

---

**Graph:**

- **Graph Title:** Measured Attenuation vs. Frequency
- **Axes:**
  - Y-axis: Attenuation (0.2 to 1.0)
  - X-axis: Frequency (1 MHz to 6 GHz)
- **Lines:**
  - **Dielectric Loss**
  - **Conductor Loss**
  - **Calculated Attenuation**
- **Legend:**
  - Measured Attenuation

**Note:** [Dally]
Reflections & Telegrapher’s Eq.

- 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

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

Source termination

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

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

In (step begins at 1ns)
Termination Examples - Open

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

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

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

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

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

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

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

\[ R_S = 50\Omega \]
\[ Z_0 = 50\Omega, \quad t_d = 1ns \]
\[ R_T = 0\Omega \]
Arbitrary Termination Example

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

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

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

\[ R_S = 400 \Omega \]
\[ Z_0 = 50 \Omega, \quad t_d = 1ns \]
\[ R_T = 600 \Omega \]
Lattice Diagram

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

- Rings up to 0.6V (DC voltage division)
- in (step begins at 1ns)
Termination Reflection Patterns

- \( R_S = 25\Omega, RT = 25\Omega \)
  - \( kr_S & kr_T < 0 \)
  - Voltages Converge

- \( R_S = 25\Omega, RT = 100\Omega \)
  - \( kr_S < 0 & kr_T > 0 \)
  - Voltages Oscillate

- \( R_S = 100\Omega, RT = 25\Omega \)
  - \( kr_S > 0 & kr_T < 0 \)
  - Voltages Oscillate

- \( R_S = 100\Omega, RT = 100\Omega \)
  - \( kr_S > 0 & kr_T > 0 \)
  - 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

\[
\begin{align*}
t_r &> nT_{\text{round-trip}} = 2nl\sqrt{LC} \\
t_{\text{porch}} &\approx 2l\sqrt{LC}
\end{align*}
\]
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 $L = L - M$

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

$$Z_{even} = \left( \frac{L + M}{C_c} \right)^{\frac{1}{2}}$$

$$Z_{odd} = \left( \frac{L - M}{C_c + 2C_d} \right)^{\frac{1}{2}}$$
PI-Termination

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

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

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

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

\[
Z_{\text{odd}} = R_2
\]

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

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