Lecture 5: Interconnect Measurement Techniques
Announcements

• HW1 due NOW

• HW2 posted on website and due 2/5

• Current Reading
  • Chapter 3.4, 3.6 – 3.7

• For next time
  • TBD
Agenda

• Differential transmission lines
• Interconnect measurement techniques
  • Time-domain reflectometry (TDR)
  • Network analyzer
    • S-parameters
• Majority of today’s material from Dally Chapter 3.4, 3.6 - 3.7
• Some s-parameter material from Sackinger “Broadband Circuits” text
Differential Transmission Lines

- 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)
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 $L = L - M$

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

\[ Z_{even} = R_1 \]

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

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

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

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

\[ R_1 = \frac{1}{2} \left( Z_{\text{even}} - Z_{\text{odd}} \right) \]
Interconnect Modeling

- Why do we need interconnect models?
  - Perform hand calculations and simulations (Spice, Matlab, etc…)
  - Locate performance bottlenecks and make design trade-offs

- Model generation methods
  - Electromagnetic CAD tools
  - Actual system measurements

- Measurement techniques
  - Time-Domain Reflectometer (TDR)
  - Network analyzer (frequency domain)
Time-Domain Reflectometer (TDR)

- TDR consists of a fast step generator and a high-speed oscilloscope
- TDR operation
  - Outputs fast voltage step onto channel
  - Observe voltage at source, which includes reflections
  - Voltage magnitude can be converted to impedance
  - Impedance discontinuity location can be determined by delay
- Only input port access to characterize channel
TDR Impedance Calculation

\[ k_r(t) = \frac{V_r(t)}{V_i} = \frac{Z_T(t) - Z_0}{Z_T(t) + Z_0} \]

\[ Z_T(t) = Z_0 \left( \frac{1 + k_r(t)}{1 - k_r(t)} \right) = Z_0 \left( \frac{V_i + V_r(t)}{V_i - V_r(t)} \right) = Z_0 \left( \frac{V(t)}{2V_i - V(t)} \right) \]

If \( V_{\text{STEP}} = 1V \Rightarrow V_i = 0.5V \)

\[ Z_T(t) = Z_0 \left( \frac{V(t)}{1V - V(t)} \right) \quad Z_T(x) = Z_T \left( t = \frac{2x}{v} \right) \]
TDR Waveforms (Open & Short)

• Open termination

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

• Short termination

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

Input step at 1ns

\[ 2t_d \]
TDR Waveforms (Matched & Mismatched)

- Matched termination

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

\[ Z_T = Z_0 \]

- Mismatched termination

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

\[ Z_T > Z_0 \]
\[ Z_T < Z_0 \]
TDR Waveforms (C & L Discontinuity)

- Shunt C discontinuity

- Series L discontinuity

Peak voltage spike magnitude:

$$\frac{\Delta V}{V} = \left( \frac{\tau}{t_r} \right) \left[ 1 - e\left( -\frac{t_r}{\tau} \right) \right]$$

$$\tau_C = \frac{Z_0 C}{2}$$

$$\tau_L = \frac{L}{2Z_0}$$
TDR Rise Time and Resolution

- TDR spatial resolution is set by step risetime: \( \Delta x > t_r \nu \)
- Step risetime degrades with propagation through channel
  - Dispersion from skin-effect
  - Lump discontinuities low-pass filter the step
- Causes difficulty in estimating L & C values
- Channel filtering can actually compensate for lump discontinuity spikes 😊
TDR Multiple Reflections
TDR Waveforms (Multiple Discontinuities)

Note: Step comes at 1ns
Time-Domain Transmission (TDT)

- Can measure channel transfer function
- Hard to isolate impedance discontinuities, as they are superimposed on a single rising edge

\[ H(j\omega) = \frac{V_2(j\omega)}{V_1(j\omega)} \]
Network Analyzer

- Stimulates network with swept-frequency source
- Measures network response amplitude and phase
- Can measure transfer function, scattering matrices, impedance, ...
Transfer Function & Impedance Measurements

Test Set for Transfer Function

Test Set for Impedance Measurements
Scattering (S) Parameters

• Why S Parameters?
  • Easy to measure
  • Y, Z parameters need open and short conditions
  • S parameters are obtained with nominal termination
  • S parameters based on incident and reflected wave ratio

\[
\begin{bmatrix}
  B_1 \\
  B_2
\end{bmatrix} = \begin{bmatrix}
  S_{11} & S_{12} \\
  S_{21} & S_{22}
\end{bmatrix} \cdot \begin{bmatrix}
  A_1 \\
  A_2
\end{bmatrix}
\]

[S-matrix] [Dally]
S-Parameter Test Circuits & Meaning

- $S_{11} =$ Input reflection coefficient
- $S_{21} =$ Forward transmission coefficient
  - Gain w/ input matching dependency
- $S_{22} =$ Output reflection coefficient
  - $1/S_{22} =$ Output return loss
- $S_{12} =$ Reverse transmission coefficient (isolation)

\[
S_{11}(s) = \frac{V_{i,\text{reflected}}}{V_{i,\text{incident}}} = \frac{V_i - R_0 I_i}{V_i + R_0 I_i} = \frac{V_i - V_s}{V_s}
\]

\[
S_{21}(s) = \frac{V_{o,\text{transmitted}}}{V_{i,\text{incident}}} = \frac{V_o - R_0 I_o}{V_i + R_0 I_i} = \frac{V_o}{V_s}
\]

\[
S_{22}(s) = \frac{V_{o,\text{reflected}}}{V_{o,\text{incident}}} = \frac{V_o - R_0 I_o}{V_o + R_0 I_o} = \frac{V_o - V_s}{V_s}
\]

\[
S_{12}(s) = \frac{V_{i,\text{transmitted}}}{V_{o,\text{incident}}} = \frac{V_i - R_0 I_i}{V_o + R_0 I_o} = \frac{V_i}{V_s}
\]

\[
S_{21}(s) = (1 + S_{11}(s))A(s)
\]

where $A(s)$ is voltage gain
Next Time

• S-parameter examples

• Impulse response generation

• Communication techniques
  • Eye Diagram
  • Intersymbol interference
  • Modulation techniques