ECEN689: Special Topics in High-Speed Links Circuits and Systems
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Lecture 5: S-Parameter Channel Models

Sam Palermo
Analog & Mixed-Signal Center
Texas A&M University
Announcements

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

• Network analyzer
• S-parameters
• Cascading S-parameter models
• Full S-parameter channel model
• Transient simulations
  • Impulse response generation
  • Eye diagrams
  • Inter-symbol interference
• Majority of today’s material from Hall “Advanced Signal Integrity for High-Speed Digital Designs “ Chapter 9
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)
Network Analyzer

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

[Dally]
Transfer Function & Impedance Measurements

- Test Set for Transfer Function
- Test Set for Impedance Measurements

[Dally]
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

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

[Dally]
Formal S-Parameter Definitions

\[
\begin{align*}
S_{11} &= \left. \frac{b_1}{a_1} \right|_{a_2=0} = \text{Input reflection coefficient with the output port terminated by a matched load (} Z_L=Z_0 \text{ sets} \ a_2=0) \\
S_{22} &= \left. \frac{b_2}{a_2} \right|_{a_1=0} = \text{Output reflection coefficient with the input terminated by a matched load (} Z_S=Z_0 \text{ sets} \ V_s=0) \\
S_{21} &= \left. \frac{b_2}{a_1} \right|_{a_2=0} = \text{Forward transmission (insertion) gain with the output port terminated in a matched load.} \\
S_{12} &= \left. \frac{b_1}{a_2} \right|_{a_1=0} = \text{Reverse transmission (insertion) gain with the input port terminated in a matched load.}
\end{align*}
\]
Cascading S-Parameters

• Network analysis allows cascading of independently characterized structures

• However, can’t directly cascade s-parameter matrices and multiply

• Must first convert to an ABCD matrix (or T matrix)
**ABCD Parameters**

![Two Port Network Diagram]

\[
A = \frac{v_1}{v_2} \bigg|_{i_2=0} \quad B = \frac{v_1}{i_2} \bigg|_{v_2=0} \quad C = \frac{i_1}{v_2} \bigg|_{i_2=0} \quad D = \frac{i_1}{i_2} \bigg|_{v_2=0}
\]

\[
\begin{vmatrix} v_1 \\ i_i \end{vmatrix} = \begin{vmatrix} A & B \\ C & D \end{vmatrix} \cdot \begin{vmatrix} v_2 \\ i_2 \end{vmatrix}
\]
TABLE 9-3. Relationships Between Two-Port $S$ and $ABCD$ Parameters$^a$

\[
\begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix}
\begin{bmatrix}
\frac{B - Z_n(D - A + CZ_n)}{B + Z_n(D + A + CZ_n)} & \frac{2Z_n(AD - BC)}{B + Z_n(D + A + CZ_n)} \\
\frac{2Z_n}{B + Z_n(D + A + CZ_n)} & \frac{B - Z_n(A - D + CZ_n)}{B + Z_n(D + A + CZ_n)}
\end{bmatrix}
\]

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\begin{bmatrix}
\frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{21}}{2S_{21}} & \frac{Z_n(1 + S_{11})(1 + S_{22}) - S_{12}S_{21}}{2S_{21}} \\
\frac{1}{Z_n} \frac{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}}{2S_{21}} & \frac{(1 - S_{11})(1 + S_{22}) + S_{12}S_{21}}{2S_{21}}
\end{bmatrix}
\]

$^aZ_n$ is the termination impedance at the ports.

[Hall]
Example: Cascaded Via & Transmission Line

\[
\begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix}_{\text{via}} = \begin{bmatrix}
-0.1235 - j0.1516 & 0.7597 - j0.6190 \\
0.7597 - j0.6190 & -0.1235 - j0.1516
\end{bmatrix}
\]

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}_{\text{via}} = \begin{bmatrix}
0.790 & j22.22 \\
j0.01686 & 0.790
\end{bmatrix}
\]

\[
\begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix}_{\text{t-line}} = \begin{bmatrix}
0.00325 - j0.00323 & -1.00 - j0.003 \\
-1.00 - j0.003 & 0.00325 - j0.00323
\end{bmatrix}
\]

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}_{\text{t-line}} = \begin{bmatrix}
-1 & j0.3228 \\
j0.000129 & -1
\end{bmatrix}
\]

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}_{\text{cascade}} = \begin{bmatrix}
A & B \\
C & D
\end{bmatrix}_{\text{via}} \begin{bmatrix}
A & B \\
C & D
\end{bmatrix}_{\text{t-line}}
\]

- Taken from “Advanced Signal Integrity for High-Speed Digital Designs” by Hall
Example: Cascaded Via & Transmission Line

\[
\begin{bmatrix}
A & B \\
C & D \\
\end{bmatrix}_{\text{cascade}} = \begin{bmatrix}
A & B \\
C & D \\
\end{bmatrix}_{\text{via}} \begin{bmatrix}
A & B \\
C & D \\
\end{bmatrix}_{\text{t-line}}
\]

\[
= \begin{bmatrix}
0.790 & j22.22 \\
0.01686 & 0.790 \\
\end{bmatrix} \cdot \begin{bmatrix}
-1 & j0.3228 \\
0.000129 & -1 \\
\end{bmatrix}
\]

\[
= \begin{bmatrix}
-0.790 & -j21.965 \\
-0.790 & -0.795 \\
\end{bmatrix}
\]

- Using conversion table:

\[
\begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22} \\
\end{bmatrix}_{\text{cascade}} = \begin{bmatrix}
-0.1259 - j0.1553 & -0.7635 + j0.6186 \\
-0.7645 + j0.6182 & -0.1200 - j0.1565 \\
\end{bmatrix}
\]

- Can also use T matrixes to cascade

- Taken from “Advanced Signal Integrity for High-Speed Digital Designs” by Hall
S-Parameter Channel Example

- Advanced TCA backplane test system
- Vector Network Analyzer
- Surface mount SMA launch
- Settings
  - 50 MHz – 15 GHz, 10 MHz step
  - IF BW 300 Hz
  - Leveled output power –5 dB
  - 4 averages

[Peters, IEEE Backplane Ethernet Task Force]
S-Parameter Channel Example
(4-port differential)

Data from 50MHz to 15GHz in 10MHz steps

\[
\begin{align*}
\begin{bmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{bmatrix}
= \begin{bmatrix}
\begin{bmatrix}
b_1 \\
b_2 \\
b_3 \\
b_4
\end{bmatrix}
& \begin{bmatrix}
a_1 \\
a_2 \\
a_3 \\
a_4
\end{bmatrix}
\end{bmatrix}
= \begin{bmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{bmatrix}
\begin{bmatrix}
v \\
0 \\
0 \\
-\nu
\end{bmatrix}
\end{align*}
\]

Hall

\[
S_{dd11} = \frac{b_{d1}}{a_{d1}} \bigg|_{a_2 = a_4 = 0} = \frac{1}{2} \left( S_{11} + S_{33} - S_{13} - S_{31} \right)
\]

\[
S_{dd21} = \frac{b_{d2}}{a_{d1}} \bigg|_{a_2 = a_4 = 0} = \frac{1}{2} \left( S_{21} + S_{43} - S_{23} - S_{41} \right)
\]
S-Parameter Channel Example

T20 Backplane Channel

Frequency (GHz)

$S_{21}$, $S_{11}$ (dB)
Impulse Response

• Channel impulse responses are used in
  • Time domain simulations
  • Link analysis tools

\[ Y(\omega) = H(\omega)X(\omega) \]

\[ y(t) = h(t) * x(t) = \int_{-\infty}^{\infty} h(t - \tau)x(\tau) \]

\[ h(t) = F^{-1}\{H(w)\} \]
Generating an Impulse Response from S-Parameters

- Perform the inverse Fourier transform on the s-parameter of interest

- Step 1: For ifft, produce negative frequency values and append to s-parameter data in the following manner

\[ h(t) = F^{-1} \{ S(\omega) \} \]

\[ S(-f) = S(f)^* \]
Increasing Impulse Response Resolution

- Could perform ifft now, but will get an impulse response with time resolution of
  \[
  \frac{1}{2f_{\text{max}}} = \frac{1}{2(15\text{GHz})} = 33.3\text{ps}
  \]

- To improve impulse response resolution, expand frequency axis and “zero pad”

For 1ps resolution: zero pad to +/-500GHz

T20 Backplane Channel
Channel Impulse Response

- Now perform ifft to produce impulse response
- Can sanity check by doing an fft on impulse response and comparing to measured data
Impulse Response of Different Channels

Channel Responses

Channel Impulse Responses

- Frequency (GHz)
- Time (ns)
Channel Transient Response

[Graphs showing Channel Transient Response, including Input Data, Channel Impulse Response, and Channel Output, with respective time and voltage scales.]
Eye Diagrams

Use a precise clock to chop the data into equal periods.
Overlay each period onto one plot.

[Walker]
Eye Diagrams vs Data Rate

Channel Frequency Response

Channel Response (dB)

Frequency (GHz)

1Gb/s Eye

2Gb/s Eye

5Gb/s Eye

Voltage (V)

Time (ps)

Voltage (V)

Time (ps)

Voltage (V)

Time (ps)
Eye Diagrams vs Channel

Channel Responses

Channel Response (dB)

Frequency (GHz)

Desktop 5Gb/s Eye

Refined BP 5Gb/s Eye

Legacy BP 5Gb/s Eye
Inter-Symbol Interference (ISI)

- Previous bits residual state can distort the current bit, resulting in inter-symbol interference (ISI).
- ISI is caused by:
  - Reflections, Channel resonances, Channel loss (dispersion)

![Legacy BP 5Gb/s Pulse Response]
ISI Impact

- At channel input (TX output), eye diagram is wide open
- As data pulses propagate through channel, they experience dispersion and have significant ISI
  - Result is a closed eye at channel output (RX input)

[Meghelli (IBM) ISSCC 2006]
Next Time

• Channel pulse response model

• Modulation schemes