How to Read S-Parameters
Like a Book

or

Tapping Into Some Of The Information Buried Inside S-
Parameter Black Box Models

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Overview

• S-parameters as a “black box” behavioral model
• Root cause analysis: a powerful methodology
• Four common patterns and their possible root cause
• A Pop Quiz
For More Information

www.beTheSignal.com

- Recent Publications
- My Blog: What I learned this month
- Class schedule

Boston: Sept 28-29
Hyderabad: Oct 10-11
Bangalore: Oct 13-14
Singapore: Oct 18
Penang: Oct 20
Shah Alam: Oct 21
San Jose: Nov 8-10

Hands on Labs in All Bogatin Enterprises Classes
(simulation software and lab exercises provided)

- Quite Universal Circuit Simulator (QUCS)
  - Circuit Simulator: transient, frequency domain, S-parameter
- LeCroy’s SI Studio
  - S-parameter viewer
  - Simulate eye diagrams from channel S-parameters
  - Serial data analysis
A Special Thank you for all Webinar Attendees

- 10% discount to any Boston or San Jose, Bogatin Enterprises class:
  - SPSI, Sept 28, 2011, Boston
  - DPD, Sept 29, 2011, Boston
  - EPSI, Nov 8-9, 2011, San Jose
  - SPSI, Nov 10, 2011, San Jose

- Use discount code NMA1109A when registering online at [www.beTheSignal.com](http://www.beTheSignal.com)

The Real World: Interconnects are Not Transparent

1. We use S-parameters to describe the behavior of the interconnects
2. We can answer some “why” questions from the S-parameters
Characterize an Interconnect by How “Precision” Reference Signals Scatter Off a DUT

**Time Domain t**

**Frequency Domain t**

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**TDR**

**S11**

**Incident Wave**

**Reflected Wave**

**Transmitted wave**

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What are S-Parameters?

- A collection of scattered responses (at every frequency):
  - Reflected sine waves
    \[ S_{11} = \frac{\text{sine wave out from port 1}}{\text{sine wave into port 1}} \]
  - Transmitted sine waves
    \[ S_{21} = \frac{\text{sine wave out from port 2}}{\text{sine wave into port 1}} \]

- Stored in a special format: Touchstone file
  - .s1p: scattered data from 1 port
  - .s2p: scattered data from 2 ports

- Freq units are MHz
- S-parameters dB and degrees
- Reference Z 50 ohm
System Simulation with S-Parameter
Behavioral “Black Box” Models

Turn S-parameter Behavioral Model into a SPICE compatible model using pole-zero model of S-parameters which any SPICE can use:

“broad band SPICE”: Simbeor, HyperLynx, ADS, Sigirity, SiSoft ...

Opening the Lid to the Black Box

What treats lay within?
Fastest Way to Solve a Problem is to Identify its Root Cause

If you have the wrong root cause, you will only fix the problem by luck.

Don’t Think Frequency or Time Domain, Think Frequency AND Time Domain

Single ended S-parameters  Frequency Domain  Differential S-parameters

Measurement

Circuit simulation

Electromagnetic simulation

Single ended T-parameters  Time Domain  Differential T-parameters
2 Port S-Parameters

Applies to single-ended and differential S-parameters

- **S11**: Return loss
  - It is the reflected signal
  - Impedance mismatch from 50 ohms throughout the interconnect
  - A little about losses
- **S21**: Insertion loss
  - It is the transmitted signal
  - Impedance mismatches throughout the interconnect
  - Losses

**Transparent interconnect:**
- **S11**: large, negative dB
- **S21**: small, negative dB

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Four Important Patterns in S11, S21

- Ripples in S11, sometimes in S21: reflections
- Monotonic drop in S21: losses
- Broad dips: ¼ wave stub resonances
- Sharp dips (hi Q), coupling to resonances
How Reflections Result in Return, Insertion Loss Ripples

- When $\text{Len} \ll \frac{1}{4} \lambda$
  - Reflections from front and back, 180 deg out of phase
  - No net reflection, all transmitted waves in phase and add
  - $S11$ large negative dB, $S21$ nearly 0 db

When $\text{Len} = \frac{1}{4} \lambda$, $S21$ Lowest, $S11$ Highest

- When $\text{Len} = \left(\frac{1}{2} \times n + \frac{1}{4}\right) \lambda$
  - Max $S11$, min $S21$
When \( Z_0 \neq 50 \) Ohms, Multiple Reflections From The Terminations Cause Ripples

- When \( \text{Len} = n \times \frac{1}{2} \lambda \):
  - Reflected waves from front and back subtract
  - Minimum reflected signal
  - Transmitted waves all in phase, \( S_{21} \) max

- As frequency increases, insertion, return loss increase, decrease
  - Longer distance between reflections, shorter the frequency between high and low
  - Larger the impedance difference, the larger the modulation

\[ Z_0 < 50 \text{ Ohms} \]

\[ \text{min } S_{11} \quad \text{max } S_{21} \]

Attenuation and Insertion Loss

In real interconnects, amplitude drops off exponentially with distance

\[ V_{\text{out}}(d) = V_{\text{in}} e^{-\alpha \text{nepers/len} d} = V_{\text{in}} 10^{-\frac{\alpha \text{dB/len} d}{20}} \]

\[ S_{21} = \frac{V_{\text{out}}}{V_{\text{in}}} \]

\[ S_{21}[\text{in dB}] = 20 \times \log \left( \frac{V_{\text{out}}}{V_{\text{in}}} \right) = -\alpha [\text{dB/in}] \times d = \text{attenuation} \]

\( S_{21} \) is attenuation when terminations are matched and there is no coupling out of the transmission line
**Estimating Attenuation per Length in 50 Ohm Interconnects**

\[
\text{atten}_\text{Len} = - \left( \frac{1}{w} \sqrt{f + 2.3 \times f \times Df \times \sqrt{Dk}} \right) \text{ dB/inch}
\]

- \(w\) = line width in mils
- \(f\) in GHz
- \(Dk\) = dielectric constant
- \(Df\) = dissipation factor

Simple estimate matches measured behavior ok

Never sign off on a design based on a rough estimate

**The \(\frac{1}{4}\) Wave Stub Resonance**

\[
\text{TD} = \frac{\text{Len}}{6 \text{ nsec/}}
\]

When \(2 \times \text{TD} = \frac{1}{2}\) cycle, minimum received signal

\(\text{TD} = \frac{1}{4}\) cycle: the quarter wave resonance

\[
\text{TD} = \frac{1}{4} \frac{1}{f_{\text{res}}}
\]

\[
f_{\text{res}} = \frac{1}{4} \frac{1}{\text{TD}} \times \frac{1}{\text{Len}} = 1.5
\]

f in GHz Len in inches

Example: Len = 0.5 inch, \(f_{\text{res}} = 3\) GHz
\[ f_{res} = \frac{1}{4} \frac{1}{TD} = \frac{1.5}{Len} \]

Stub 0.5 inches long
\[ f_{res} = 3 \text{ GHz} \]

Where does the energy go?

Measured Insertion Loss with and without Via Stub in a ¼ inch Thick Backplane

No via stub in the channel

0.2 inch via stub
\[ f_{res} = \frac{1.5}{Len} = \frac{1.5}{0.20} = 7.5 \text{ GHz} \]
**Coupling to Hi-Q Resonances**

- What are hi-Q resonators?
  - Any floating metal (copper fill)
  - Plane cavities

**Via to Cavity Coupling in a 4 Layer Board**

Plane resonances expected:
- \( f_{res} = \frac{12 \text{ GHz}}{\sqrt{\text{Dk} \times 2 \times \text{Len}}} = \frac{3 \text{ GHz}}{\text{Len}} \)

<table>
<thead>
<tr>
<th>Length (inches)</th>
<th>( f_{res} ) (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.25</td>
<td>0.92</td>
</tr>
<tr>
<td>1.187</td>
<td>2.5</td>
</tr>
<tr>
<td>0.8</td>
<td>3.75</td>
</tr>
</tbody>
</table>

S21 wo return vias

Frequency (Hz)

**Insertion Loss (dB)**

-8 -6 -4 -2 0 2 4 6 8

1e09 2e09 3e09 4e09 5e09 6e09
**Four Important Patterns in S11, S21**

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**Pop Quiz:**

*What Causes the Higher Loss?*

- Measured SDD21 for 2 differential pairs, up to 10 GHz
  - Looks like bottom (blue) line has more SDD21 than top (red) line.
  - What causes the higher attenuation?
    - Conductor loss from surface roughness?
    - Poor copper plating
    - High Df in one layer
    - ???

- Data courtesy of Bob Haller, Enterasys

- Same measurement, but up to 20 GHz
  - Dip at 14 GHz
  - What causes the large dip?
    - Stub resonance?
    - Mode conversion?
    - Resonant coupling to other structures?
    - Bloch waves and glass weave?
    - Dielectric absorption resonance?

Which S-parameters might have the answers?
Could it Be Mode Conversion?

Mode conversion terms:
- SCD11, SCD21
- SDD11 shows reflected energy
- SCD11 shows mode conversion reflected
- SCD21 shows mode conversion transmitted

Summary

• Get in the habit of looking inside S-parameters
  ✓ “You can observe a lot by watching”, Yogi Berra

• Look for the four patterns
  ✓ Ripples
  ✓ Monotonic drop
  ✓ Broad dips
  ✓ Sharp dips

• This has been just a “tip of the iceberg” look at data mining S-parameters
Data Mining S-Parameters

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