Probes and Setup for Measuring Power-Plane Impedances with Vector Network Analyzer
Outline

• Introduction
• Z, Y, and S parameters
• Self and transfer impedances
• VNA
• One-port impedance measurement
• Two-port impedance measurement
• DUTs
• Measured self and transfer impedances
• Correlation to simulations
• Resources
• References
Requirements in Power Distribution

In digital and mixed analog/digital systems:
• Core and signaling voltages drop
• Noise margin goes down
• Core and total I/O current go up
• Bandwidth goes up

Requirement:
Few milliohms over hundreds of MHz bandwidth.

Solution:
In multilayer boards, power and ground are distributed over (solid) planes.
Z, Y, and S Parameters

\[ v = Z i \]
\[ v_1 = Z_{11} i_1 + Z_{12} i_2 \]
\[ v_2 = Z_{21} i_1 + Z_{22} i_2 \]
\[ i = Y v \]
\[ i_1 = Y_{11} v_1 + Y_{12} v_2 \]
\[ v_2 = Y_{21} v_1 + Y_{22} v_2 \]

\[ b = S a \]
\[ b_1 = S_{11} a_1 + S_{12} a_2 \]
\[ b_2 = S_{21} a_1 + S_{22} a_2 \]

- Zero wave is easier to set
- Calibration plane is not critical

- Zero volt/current is hard to set
- Calibration plane is critical
Which Parameters Do We Need

At high frequencies, S parameters are easier to measure, but

- Digital designers deal with voltages and currents
- Good power-distribution network is a voltage source >>> Z parameters needed

\[ Z_{ii} = \frac{v_i}{i_i} \bigg|_{i_j=0} \]
\[ Z_{ji} = \frac{v_j}{i_i} \bigg|_{i_j=0} \]
Measuring Power-Distribution Network

- TDR
- LCR Bridge
- VNA $\Gamma$ or S11, and S21
What is a VNA

- Tuned sinewave generator
- Directional couplers
- Tracking receiver(s)

\[
S_{11} = \frac{b_1}{a_1} \bigg|_{a_2=0}
\]

\[
S_{21} = \frac{b_2}{a_1} \bigg|_{a_2=0}
\]
One-Port Self-Impedance Measurement

The impedance is measured between the ground and power planes at the selected point.

\[ S_{11} = \frac{Z_{in} - 50}{Z_{in} + 50} \]

\[ Z_{11} = Z_{in} = 50 \frac{1 + S_{11}}{1 - S_{11}} \]
Errors of One-Port Self-Impedance Measurement

- VNA accuracy is lower at high reflections
- Connecting discontinuity is in series of low-Z DUT
VNA Error in S11 Measurement

- $|S11|$ uncertainty of HP8720D is 1.5% at $|\Gamma| \sim 1$ in the 50-2000MHz range
- Impedance uncertainty is 0.375 ohms
- For low measurement errors, $Z_{DUT}$ must be in the ohms range

**But we want to measure fractions of an ohm**
Errors Due to Discontinuities

- 50 mils of pigtail connector/cable discontinuity is \( L_p \approx 0.4 \text{nH} \)
- 0.4 nH is \( Z_p \approx 2.4 \text{ ohms at 1GHz} \)
- Problem: \( Z_p \) is in series to \( Z_{\text{DUT}} \)

![Diagram](attachment:image.png)
Two-Port Self-Impedance Measurement

- $S_{21}$ instead of $S_{11}$ is measured
- $S_{21}$ uncertainty is less
- $Z_p$ is in series to 50 ohms instead of $Z_{DUT}$
Two-Port Self-Impedance Reading

First-order calculation:
Assume that
- $L_p \sim 0$
- $Z_{DUT} \ll Z_0$

Port 1 and Port 2 of VNA: 25 ohm

$$Z_{DUT} = Z_{11} = S_{21} \times 25 \text{ [ohm]}$$
Transfer Impedance Measurement

Cable and Port1 of VNA: 50 ohm

Cable and Port2 of VNA: 50 ohm
Transfer Impedance Reading

First-order calculation:
Assume that
- $L_p \sim 0$
- $Z_{11} \ll Z_0$
- $Z_{22} \ll Z_0$
- $Z_{21} \ll Z_0$

\[ Z_{21} = Z_{12} = S_{21} \times 25 \text{ [ohm]} \]
S21 Uncertainty

- $|S_{21}|$ uncertainty of HP8720D:
  - <1dB in the $|S_{21}| > -60$dB range
  - <3dB in the $|S_{21}| > -70$dB range

- Impedance uncertainty:
  - 1dB (10%) for $Z_{DUT} > 25$milliohms
  - 3dB (40%) for $Z_{DUT} > 8$milliohms
Measurement Setup

Vector Network Analyzer: HP 4396 or HP 8720C VNA
Probe: 2 pieces of 12-inch long semirigid coax
Dual Semirigid Probe

Cross-sectional view of the Dual Semirigid Probe
NOT TO SCALE

Semirigid coax 1
Semirigid coax 2
Coax sleeve soldered all around to upper plane
31 mils
Parallel Cu planes
Coax pigtail: $L_p$
80 mils: 1.5% of $\lambda$ at 1GHz

80 mils: 1.5% of $\lambda$ at 1GHz
Device Under Test (1)

31 mil plane separation
10-inch by 10-inch FR4 two-sided PCB
Bare PCB or 5.1 ohm/inch DET
Signal input and output: 12” Dual Semirigid Probe
Test points: on a 1-inch by 1-inch grid

Top view:

Side view without and with DET:

805 SMD
5.1 ohm per inch
Device Under Test (2)

- 2 mil plane separation
- 10-inch by 10-inch FR4 PCB
- Bare PCB or 1 ohm/half-inch DET
- Probes: 12” Dual Semirigid Probe
- Test points: on a 1-inch by 1-inch grid

Top view:

Side view with DET:

805 SMD
1 ohm / half inches
Residual Probe Response (1)

- DUT is not in place
- Dual Semirigid Probe, 50-mil pigtails, disconnected
Residual Probe Response (2)

- Probe sleeves are soldered to 31-mil DUT
- 50-mil probe tails in place, but not connected

- Probe sleeves are soldered to 31-mil DUT
- 50-mil probe tails in place, but not connected

Z_L of 2-mil planes
Z_L of 0.2-mil planes

Log impedance magnitude [ohm]
Log frequency [Hz]

- Probe sleeves are soldered to 31-mil DUT
- 50-mil probe tails in place, but not connected

Residual Probe Response (2)
Measured Self Impedance of Bare Board at Center

- 31-mil DUT, edge open
- Dual Semirigid Probe at center of planes

Log impedance magnitude [ohm]

Log frequency [Hz]

0.1G 0.5G 1G 5G

• 31-mil DUT, edge open
• Dual Semirigid Probe at center of planes
Measured Self Impedance of Board with DET at Center

- 31-mil DUT, edge terminated with 40x5.1 ohms
- Dual Semirigid Probe, at center of planes
Measured vs. Simulated Self-Impedance of DUT

- 10" x 10" x 31mil FR4 with DET
- Measured with HP8720C VNA
- Simulated with 1-inch grid at center node:

<table>
<thead>
<tr>
<th>Freq [Hz]</th>
<th>Zmagn[ohm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00E+08</td>
<td>0.3143</td>
</tr>
<tr>
<td>1.58E+08</td>
<td>0.4413</td>
</tr>
<tr>
<td>2.51E+08</td>
<td>0.6574</td>
</tr>
<tr>
<td>3.98E+08</td>
<td>1.233</td>
</tr>
<tr>
<td>6.31E+08</td>
<td>1.744</td>
</tr>
<tr>
<td>1.00E+09</td>
<td>2.645</td>
</tr>
</tbody>
</table>
Measured Transfer Impedance

- 31-mil DUT, edge terminated with 40x5.1 ohms
- Two separate semirigid probes, at middle of side and at corner
Measured vs. Simulated Transfer Impedance of DUT

Zoomed responses:

S21 [dB]

Log frequency [Hz]

Measured Simulated
Self Impedance, 2-mil DUT

- 2-mil DUT, edge terminated with 80x(1ohm + 100nF)
- Dual Semirigid Probe, at center of planes
Equivalent Circuit of Probes Connection

Self impedance:
- Coax and Port1 of VNA: 50 ohm
- \(L_{p1}\)
- \(L_{p2}\)
- \(V_S\)
- \(V_1\)
- \(V_2\)
- \(Z_{11} = Z_{DUT}\)

Transfer impedance:
- Cable and Port1 of VNA: 50 ohm
- \(L_{p1}\)
- \(L_{p2}\)
- \(V_S\)
- \(V_1\)
- \(V_2\)
- Cable and Port2 of VNA: 50 ohm
**S\_21 Conversion to Self Impedance**

\[
Z_{ii} = S_{21} \frac{Z_1}{2} \left( \frac{1}{1 - S_{21}} \frac{1}{Z_1 + Z_2} \right) \approx S_{21} \ast 25 \ast \frac{1 + j\omega \tau_p}{1 - S_{21}}
\]

Where

- \( Z_1 = 50 + j\omega L_{p1} \)
- \( Z_2 = 50 + j\omega L_{p2} \)
- \( \tau_p = L_p / 50 \)
**S₂₁ Conversion to Transfer Impedance**

\[
Z_{ji} = S_{21} \frac{Z_1}{2} \left( \frac{1 + \frac{Z_{11}}{Z_1}}{1 + S_{21} \frac{Z_{21}}{Z_1}} \right) \left( \frac{1 + \frac{Z_{22}}{Z_2}}{1 + \frac{S_{21} Z_{21}}{Z_2}} \right) \approx
\]

\[
S_{21} * 25 * \frac{1 + j \omega \tau_p}{1 + 50 * \left( \frac{S_{21}}{2} \right)^2} \left( \frac{Z_{11}}{Z_1} \right) \left( 1 + \frac{Z_{22}}{Z_2} \right)
\]

Where

\[ Z_1 = 50 + j \omega L_{p1} \]
\[ Z_2 = 50 + j \omega L_{p2} \]
\[ \tau_p = \frac{L_p}{50} \]
Recommended Resources

Hewlett Packard Vector Network Analyzers:
• HP 8720 VNA
• HP4396 VNA

Circuit simulator software:
• Avant! HSPICE
Conclusions

- Power-distribution network is characterized by self and transfer impedances
- One-port measurements cannot handle low impedances
- 2-port VNA measurement introduced
- Probes: Dual semirigid coax with soldered pigtail
- Transmission-line grid is used to simulate parallel planes
- Good agreement between measured and simulated self and transfer impedances was found
References


