VNA & Calibration

Fall 2007

 RF/Microwave Circuits I

VNA Calibration

- Vector Network Analyzer → Measures amplitude and phase of
  - Reference, reflected, and transmitted signal to find $S$
- Basic Components of VNA
  - Synthesized swept signal RF source
  - Test set (signal routing from/to source, DUT, and internal IF circuitry)
  - IF circuitry (down convert RF to IF, e.g., 100KHz) (page 183, 3rd edition)
  - Digital processors (A/D conversion, amp & phase measurements, etc)
From Anritsu
In reality, there is much hardware within VNA that affects $a_1$, $b_1$, etc.

Measurements are determined after IF and digital processing.

To determine $[S]$ of the DUT, we need information about signals at DUT ports → have to calibrate/remove all VNA effects.

First step: Determine how to represent these complex VNA effects. This is “error modeling”

- $[S] \rightarrow$ scattering matrix
- $[T] \rightarrow$ transmission matrix (e.g., $[ABCD]$)
- Error box – networks that include internal VNA effects (couplers, switches, IF and DSP circuits, etc) and possibly external cables etc
  - different “error models” have different “error boxes”
Second Step: Determine values for error box parameters (i.e., \([S_{e1}], [S_{e2}]\) or \([T_{e1}], [T_{e2}]\)).

- Determining the error box parameters is called “calibration”

\[
[T_m] = [T_{e1}] [T'] [T_{e2}]
\]

This is what we measure (or raw-measured data)

Error corrected or “calibrated data”

\[
[T'] = [T_{e1}]^{-1} [T_m] [T_{e2}]^{-1}
\]

Determined when calibration is performed

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A SIMPLE 1-PORT MEASUREMENT

\[
S_{11}' = S_{11,e1} + \frac{S_{21,e1} \Gamma_L S_{12,e1}}{1 - S_{22,e1} \Gamma_L}
\]
Goal: Find $[S_{el}]$ (i.e., “calibrate” the system)

- You can select different $\Gamma_L$ (cal stds) and measure $S_{11}$
- How?

(i) choose $\Gamma_L = 0$ (use match load)

\[
\text{then } S_{11}' = S_{e1,11} \quad S_{11} = S_{11,e1} + \frac{S_{21,e1}\Gamma_L S_{12,e1}}{1 - S_{22,e1}\Gamma_L}
\]

(ii)

\[
\left(1 - \Gamma_L S_{e1,22}\right)\left(S_{11}' - S_{e1,11}\right) = \left(S_{e1,21}\right)\left(\Gamma_L\right)\left(S_{e1,12}\right)
\]

\[
U_1 \cdot K = U_2 \quad U = \text{unknown} \quad K = \text{known}
\]

1-port calibration (cont’d)

(iii)

choose 2 more known $\Gamma_L'$ (e.g., $\Gamma_1 = 1$ (open) and -1 (short))

$\Rightarrow$ find $U_1$ and $U_2$ (2 equations and 2 unknowns)

(iv)

once $U_1$ is known, find $S_{e1,22}$

(v)

also know $\left(S_{e1,21}, S_{e1,12}\right)$ $\Rightarrow$ you only need to know the product

Now that you know $[S_{e1}]$

\[
\Gamma_L = \frac{(S_{11}' - S_{11,e1})}{(S_{e1,21} - S_{e1,12}) + S_{e1,22} (S_{11}' - S_{11,e1})}
\]
### Commonly Used Calibration Methods

1. OSL (can be used only for 1-port calibration)
   - Open, Short, Load
2. OSLT (2-port calibration)
   - Open, Short, Load, Thru
     - Thru is a section of matched transmission line
3. LRM
   - Thru Line, Reflect, Matched load
     - Reflect can be open or short
4. TRL
   - Thru line, Reflect, delay Line

For many calibration methods, precise knowledge of the standards (e.g., the $\Gamma$ for the short) must be known
- It won’t be exactly $-1$!
**TRL Calibration**

- Used for planar circuits (e.g., microstrip) this is the most accurate approach, especially at mm-wave frequencies
- Does not require perfect (or well known) matched loads, opens, or sorts (other methods do require) ⇒ TRL is known as “self-calibrating”
- **How to construct TRL calibration lines for measuring a DUT…**

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**Diagram:**
- Assumed to be identical in all measurements
- T.L (coax, microstrip, CPW, etc.)
- Reference plane in the center of thru
- DELAY
- REFLECT
- THRU
**TO MEASURE DUT**

![Diagram of DUT measurement setup]

**DESIGN RULES**
- $Z_0$ must be identical for all standards and DUT
- Theoretically, any $L > 0$ is acceptable
- Ideally, $\Delta L = 90^\circ$ at center frequency
  - Calibration is typically valid from $f_1$ to $f_2$, when
  - $f_1$ when $\Delta L = 20^\circ$
  - $f_2$ when $\Delta L = 160^\circ$
- Reflect standards do not have to be perfect opens or shorts, but $\Gamma_1$ has to be identical to $\Gamma_2$
- $Z_0$ does not have to be 50Ω, but its value does serve as the reference impedance for the calculated [S] matrix

**DESIGN TRL STD’s FROM 1-6GHz AND MEASURE A CHIP CAPACITOR**
- We need to know the following:
  - Capacitor size, substrate properties on which capacitor will be mounted/measured, what kind of TL (microstrip, CPW, etc)
  - Frequency range
- Capacitor dimensions from the manufacturer data sheet is
  - 2mm × 1.2mm
  - Given that the substrate is 31-mil FR-4 ($\varepsilon_r=4.27$)
- Choose a value of “L”, this is the length of “thru”. There is no equation for choosing $L$
  - Let’s say $L=5$mm
CALCULATIONS

THRU (Top View)

Use equation 3.197 to calculate W that will give $Z_0=50\Omega$

$W$ from 3.197 is 1.49mm

We want the length $\Delta L = 90^\circ$ at 3GHz (center frequency)

$\lambda = \frac{V_{in}}{f} = \frac{c}{\sqrt{\varepsilon_r}} f$

Use 3.195 for calculating $\varepsilon_{\text{eff}}$

$\Delta L = 13.89\text{mm}$

DELAY

REFLECT

CAPACITOR

DUT
TRL Standards and Test Fixtures

LineCalc
De-Embedding Example

Hypothetical Error Box

Coax cable  Connector  Microstrip on circuit board

De-Embedding Example

S-parameters for the Error Box

Use with S-Parameter Simulations

Revers Transmission, dB

Forward Transmission, dB

Input Reflection Coefficient

Output Reflection Coefficient
De-Embedding Example

What is measured

“Deembed Network”

S-Parameters

1

2

Term

Term

Z=50 Ohm

Num=3

21

BPF_Chebyshev

As top=20 dB

BWpass=1.0 GHz

Fcenter=3.5 GHz

BPF1

W=1.2 GHz

Ripple=1 dB

calibration_port1

X2

X1

X4

X3

Term

Term

Z=50 Ohm

Num=2

1

2

Term

Term

Z=50 Ohm

Num=1

21

SNP2

File="calibration_port1.ds"

1

2

SNP1

File="calibration_port1.ds"

“Deembed Networks” reference the dataset for the Error Box

De-Embedding Example

BLUE – Measured Data

RED – Deembedded Data