Multiport Vector Network Analyzers

From the beginning to modern signal integrity applications

IEEE-MTT Distinguished Microwave Lectures
Summary

- Signal Integrity and Microwave Measurement
- S parameters basics
- VNA Hardware Evolution
- Error Models and Calibration Techniques
- Interconnections for accurate Measurements
- A complete example
- Conclusions
Signal Integrity and Microwave
Do we need Multiport?

ITRS (2006 Update) Package Pin Count

Package Pins

- 0
- 1,000
- 2,000
- 3,000
- 4,000
- 5,000
- 6,000
- 7,000
- 8,000

Years:
- 2005
- 2010
- 2015
- 2020
The old questions Microwave Measurements

- How can I generate and sample microwave signals?
- Where’s my reference plane?
- What’s my reference impedance?
Plus new problems...

- How do I keep reasonable microwave signals on non-microwave substrate?
- How can I make proper interconnections to measure these signals?
- How much accuracy can I accept?
Let’s start from scratch

- S-parameter concept
- Mixed Mode S parameters
- S-parameter measurements
Introduction

**Linear behavior:**
- input and output frequencies are the same (no additional frequencies created)
- output frequency only undergoes magnitude and phase change

**Nonlinear behavior:**
- output frequency may undergo frequency shift (e.g. with mixers)
- additional frequencies created (harmonics, intermodulation)
Linear Circuit

- Every Linear circuit can be described in **frequency domain** with a set linear equations which define the interaction of the circuit with the external world.

- Example: THE WELL KNOWN GENERATOR

  \[
  \text{eq. Thevenin Model} \quad V = -ZI + V_0
  \]

  \[
  \text{eq. Norton Model} \quad I = -YV + I_0
  \]
N-port Linear Circuit

Variables are grouped in vectors and the relationship become matrix equations

- Example: \( V = [Z] I + V_0 \)
- \( I = [Y]V + I_0 \) where \([Z]\), \([Y]\) are the impedance/admittance matrices

- THERE ARE INFINITIVIE POSSIBLE SET OF PARAMETERS THAT CAN BE USED TO SUCCESSFULL DESCRIBE A LINEAR NETWORK
- Every parameters can be linked with any others by means of a bi-linear matrix transform.
- THE PARAMETERS CHOICE DEPENDS ON THE USEFULLNESS
How do we measure them?

- If $V_0 = I_0 = 0$
- Each parameter can be identified by the measurement:

  $$Z_{ij} = \frac{V_i}{I_j \big|_{I_i=0}}, \quad Y_{ij} = \frac{I_i}{V_j \big|_{V_j=0}}$$

- With specific load and source conditions, as example:
  1. Open Circuits (for Z par) Short Circuits (for Y par)
  2. Single tone sinusoidal source at one port
  3. Measurement of $V, I$ exactly at DUT ports
  4. Change Frequency and repeat step 2-3

**NB:** VECTORIAL MEASUREMENT AT DIFFERENT FREQUENCY

DIFFERENT PARAMETERS MEAN DIFFERENT MEASUREMENT TECHNIQUES
What’s the best for the RF?

- At RF frequencies everything becomes POSITION/FREQUENCY dependance.

In general there are multiple modes and for every mode an equivalent transmission line can be used to describe the mode propagations.

\[ V(z) = V^+(z) + V^-(z) \]
\[ I(z) = I^+(z) + I^-(z) = \frac{V^+(z) - V^-(z)}{Z_\infty} \]

\[
\begin{align*}
V^+(z) &= V^+(0) e^{-jkz} \\
\end{align*}
\]

\[
\begin{align*}
V^+(z) &= \frac{V(z) + Z_\infty I(z)}{2} \\
V^-(z) &= \frac{V(z) - Z_\infty I(z)}{2} \\
\end{align*}
\]
Scattering Parameter

Each forward and reflected voltages/currents on the line moves as:

\[ V^+(z) = V^+(0)e^{-jkz} \]

\[ V^-(z) = V^-(0)e^{+jkz} \]

Thus the natural choice when transmission lines are involved are some new parameters link to forward and backward voltages:

S-PARAMETERS
Scattering Parameters

- \( V^2(z) = 0 \) if at every section \( V/I \) is constant and \( = Z_{\infty} \)
- At each port we define an arbitrary reference impedance and define new parameters such that:

\[
a_i = \frac{V_i^+}{2\sqrt{R_i}} \quad b_i = \frac{V_i^-}{\sqrt{R_i}} \quad \rightarrow \begin{bmatrix} b_1 \\ b_2 \\ S_{11} \\ S_{12} \\ S_{21} \\ S_{22} \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}
\]

- If \( R = Z_{\infty} \) many interesting properties occurs for the \( S \) parameters of a line I.e.:

\[
S(z) = \begin{bmatrix} 0 & e^{-jkz} \\ e^{-jkz} & 0 \end{bmatrix}
\]

But remember that it’s just a choice, a good choice but a choice!
Differential S-parameters

What if instead of single ended voltages and currents we wish to use differential ones?

\[
\begin{align*}
V_{djk} &= V_j - V_k \\
V_{ckj} &= \frac{(V_j + V_k)}{2} \\
I_{djk} &= \frac{(I_j - I_k)}{2} \\
I_{ckj} &= \frac{(I_j + I_k)}{2}
\end{align*}
\]

For Each Couple
Differential S-parameters

- What are the propagation properties and is it useful to have an “S-parameter equivalent”?
- Use a linear combination of V and I; it’s just another convention but to link it to propagation became more tricky:
  - Which Reference impedance we need to take?
  - What if we wish to have some port left single ended, i.e. an Operational Amplifier?
  - Which are the properties of the new parameters?
Mixed Mode S-parameter

- Traditional definitions are:

\[
\begin{align*}
        a_{\delta jk} &= \frac{1}{\sqrt{2}} (a_j - a_k) \\
        b_{\delta jk} &= \frac{1}{\sqrt{2}} (b_j - b_k) \\
        a_{\epsilon jk} &= \frac{1}{\sqrt{2}} (a_j + a_k) \\
        b_{\epsilon jk} &= \frac{1}{\sqrt{2}} (b_j + b_k)
\end{align*}
\]

BUT THESE ARE VALID ONLY IF

\[
Z_{\epsilon jk} = \frac{R}{2} \quad \text{Real Only}
\]

\[
Z_{\delta jk} = 2R \quad \text{Real Only}
\]

\[
S = \text{MSM}^{-1}
\]
Generalized Mixed Mode

- In general we may have

\[
\begin{align*}
    a_{djk} &\equiv \sqrt{R_{djk}} \frac{V_{djk} + I_{djk} Z_{djk}}{2|Z_{djk}|} \\
    b_{djk} &\equiv \sqrt{R_{djk}} \frac{V_{djk} - I_{djk} Z_{djk}}{2|Z_{djk}|} \\
    a_{cjk} &\equiv \sqrt{R_{cjk}} \frac{V_{cjk} + I_{cjk} Z_{cjk}}{2|Z_{cjk}|} \\
    b_{cjk} &\equiv \sqrt{R_{cjk}} \frac{V_{cjk} - I_{cjk} Z_{cjk}}{2|Z_{cjk}|}
\end{align*}
\]

\[
\mathbf{S} = (\Xi_{21} + \Xi_{22} \mathbf{S})(\Xi_{11} + \Xi_{12} \mathbf{S})^{-1}
\]

**BILINEAR MATRIX TRANSFORM**
S-parameter Measurement

From the definition in a 2 port case:

\[
\begin{bmatrix}
  b_1 \\
  b_2 
\end{bmatrix} =
\begin{bmatrix}
  S_{11} & S_{12} \\
  S_{21} & S_{22} 
\end{bmatrix}
\begin{bmatrix}
  a_1 \\
  a_2 
\end{bmatrix} =
\begin{bmatrix}
  b_1 \\
  b_2 
\end{bmatrix} = S_{11}a_1 + S_{12}a_2
\]

\[
S_{ij} = \frac{b_i}{a_j} \quad a_j a_i \neq j = 0
\]

Which Means

Measurements of incident and reflected signal while terminating the other port on their reference impedance
VNA BASIC SCHEME

Vector IF Voltmeter

FOUR-CHANNEL MICROWAVE RECEIVER

DUT

SIGNAL SEPARATION

REFLECTOMETER

MICROWAVE SOURCE

BIAS 1

BIAS 2

PORT 1

PORT 2

a_{m1} b_{m1} b_{m2} a_{m2}
3-Sampler VNA

SOURCE

Incident

DUT

Transmitted

Reflected

INCIDENT (R)

REFLECTED (A)

TRANSMITTED (B)

RECEIVER / DETECTOR

PROCESSOR / DISPLAY
VNA Source

- Synthesised Source (PLL + DDS)
- Very Broadband
- Very Fast Sweeping
- Power Leveled
- Low Phase Noise Not really Necessary
- High Repeatability

Agilent PNA Source block
Signal Separation

- Provides a and b waves separation
- Provides signal excitation at DUT ports
- It may have also bias tee and attenuators
Receiver Block

- Typically two or three downconversion
- Digital vectorial measurement of mag and phase
- Phase lock of the internal source through receiver signals
Phase Lock through its receiver

Unlike the old VNA where the source was autonomuos locked and the receiver could be lock to any microwave signal, modern VNAs cannot work unless their internal source is used. As example: You cannot use a VNA to measure the signal coming out from a chip where it’s clock cannot be lock to an external reference.
Going More than 2 ports

2-ports
2 Ref
2 Rec

4 Ports
4 Ref
4 Rec
Are 4 ports VNA enough?

Differential pairs are used so:

1. 12-port data is required for channel modeling.
2. Data for a fully characterized 12-port DUT results in a completely filled 12x12 matrix.

**Example:** Package/Socket footprint

- Port 1 & Port 7
- Port 3 & Port 9
- Port 5 & Port 11
- Port 2 & Port 8
- Port 4 & Port 10
- Port 6 & Port 12

Ports 1-6 are on the socket bottom.

Ports 7-12 are on the socket top.

GNDs
4-port Measurements w/symmetry

Coupling within pairs:
Measured, as long as symmetry is assumed

Coupling between pairs:
Unknown

<table>
<thead>
<tr>
<th>Coupling within pairs</th>
<th>Measurement Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9 1 0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
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<tr>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>1 0 1 1 2</td>
<td></td>
</tr>
</tbody>
</table>

= data collected via measurement
8-port Measurements w/symmetry

Crosstalk Measurements

Coupling within pairs:
Measured, as long as symmetry is assumed

Coupling between pairs:
Nearest neighbor measured, as long as symmetry is assumed

Measurement Matrix

Coupling within pairs

Coupling between pairs

= data collected via measurement
12-port Measurements

Crosstalk Measurements

Coupling within pairs:
Measured

Coupling between pairs:
Measured

Measurement Matrix

= data collected via measurement
12 ports

2 Ref
2 Switched Rec
65GHz

LEFT PORTS

RIGHT PORTS
12 ports

2 Ref
2 Switched Rec
50GHz
Interfacing

- Custom Fixtures
Let’s summarize up to now

1. Directional Couplers have finite directivity and frequency depend behaviour
2. Switches are not ideal and frequency dependent
3. Reference Plane position depends on cable, adapter interconnections and so on
4. DownConversion and Digitizing problems like:
   1. Source Phase Noise
   2. Frequency accuracy and repeatability
   3. Non linearity of mixer/sampler
   4. ADC Dynamic Range & Speed
5. Interfacing effect
QUESTIONS UP TO NOW
Cause of Uncertainty

- **Systematic Errors (85%)**
  - Microwave Components
  - Interconnections
  - Incorrect Standard Modeling
  - Calibration Algorithm

- **Random Error (10%)**
  - Connection Repeatibility
  - Frequency Stability
  - Noise

- Drift (5%)

**Calibration**

**Lab Care**
Today 2-ports Calibrations

Example TRL Thru Reflect Line

An error model

Standard sequence
Error Model Definition I

- **Hypothesis**
  1. sampler (mixer), and all the other system components are **linear** and **invariant parts**
  2. The two half are independent 4-port network such that we can isolate each of them and the “talk” only through the DUT

- Let the half
- 8 unknowns: $a_0, b_0, a_1, b_1, a_3, b_3, a_4, b_4$
- The two acquire data are proportional to $b_3, b_4$:
  - $V_{m_1} = k_1 b_3$, $V_{m_2} = k_2 b_4$
Error Model Definition II

\[
\begin{bmatrix}
    b_0 \\
    b_1 \\
    b_3 \\
    b_4
\end{bmatrix} = \begin{bmatrix}
    S_{11} & S_{12} & S_{13} & S_{14} \\
    S_{21} & S_{22} & S_{23} & S_{24} \\
    S_{31} & S_{32} & S_{33} & S_{34} \\
    S_{41} & S_{42} & S_{43} & S_{44}
\end{bmatrix} \begin{bmatrix}
    a_0 \\
    a_1 \\
    a_3 \\
    a_4
\end{bmatrix}
\]

4 port equation

\[
a_3 = \Gamma_3 b_3 \quad V_{m1} = k_3 b_3
\]

\[
a_4 = \Gamma_4 b_4 \quad V_{m2} = k_4 b_4
\]

Reflection Coefficients of the downconversion part and reading vs. wave

8 eq. with 10 unknowns. \((a_0, b_0, a_1, b_1, a_3, b_3, a_4, b_4, V_{m1}, V_{m2})\):

Let use \(V_{m1}\) e \(V_{m2}\) as independent variables and called them:

\[
a_{m1} = V_{m1}, \quad b_{m1} = V_{m2}, \quad a_1 = a_{1\text{DUT}} \quad e \quad b_1 = b_{1\text{DUT}}
\]

we find the following model
Error Model Definition III

\[
\begin{bmatrix}
  b_0 \\
  b_1 \\
  b_3 \\
  b_4 \\
\end{bmatrix} = \begin{bmatrix}
  S_{11} & S_{12} & S_{13} & S_{14} \\
  S_{21} & S_{22} & S_{23} & S_{24} \\
  S_{31} & S_{32} & S_{33} & S_{34} \\
  S_{41} & S_{42} & S_{43} & S_{44} \\
\end{bmatrix} \begin{bmatrix}
  a_0 \\
  a_1 \\
  a_3 \\
  a_4 \\
\end{bmatrix}
\]

\[
b_0 = S_{11}a_0 + S_{12}a_1 + S_{13}a_3 + S_{14}a_4 \\
b_1 = S_{21}a_0 + \ldots \\
b_3 = S_{31}a_0 + \ldots \\
b_4 = S_{41}a_0 + \ldots + S_{44}a_4
\]

\[
a_3 = \Gamma_3 b_3 \\
a_4 = \Gamma_4 b_4
\]
Error Model Definition IV

\[-S_{11}a_0 + b_0 - S_{12}a_1 = S_{13}\Gamma_3 b_3 + S_{14}\Gamma_4 b_4\]
\[-S_{21}a_0 - S_{12}a_1 + b_1 = S_{23}\Gamma_3 b_3 + S_{24}\Gamma_4 b_4\]
\[-S_{31}a_0 - S_{32}a_1 = (S_{33}\Gamma_3 - 1)b_3 + S_{34}\Gamma_4 b_4\]
\[-S_{41}a_0 - S_{42}a_1 = S_{43}\Gamma_3 b_3 + (S_{44}\Gamma_4 - 1)b_4\]

\[
\begin{bmatrix}
-S_{11} & -S_{12} & 0 \\
-S_{21} & 0 & -S_{22} \\
-S_{31} & 0 & -S_{32} \\
-S_{41} & 0 & -S_{42}
\end{bmatrix}
\begin{bmatrix}
a_0 \\
b_0 \\
a_1 \\
b_1
\end{bmatrix}
=
\begin{bmatrix}
S_{13}\Gamma_3 & S_{14}\Gamma_4 \\
S_{23}\Gamma_3 & S_{24}\Gamma_4 \\
(S_{33}\Gamma_3 - 1) & S_{34}\Gamma_4 \\
S_{43}\Gamma_3 & (S_{44}\Gamma_4 - 1)
\end{bmatrix}
\begin{bmatrix}
b_3 \\
b_4
\end{bmatrix}
\]

If we call \(a_{m1}\) and \(b_{m1}\)

\(V_{m1} = a_{m1} = k_3 b_3\)
\(V_{m2} = b_{m1} = k_4 b_4\)

\[
\begin{bmatrix}
a_{m1} \\
b_{m1}
\end{bmatrix}
=
\begin{bmatrix}
k_1 & 0 \\
0 & k_2
\end{bmatrix}
\begin{bmatrix}
b_3 \\
b_4
\end{bmatrix}
\]
The famous error box

\[
\begin{bmatrix}
  a_0 \\
  b_0 \\
  a_1 \\
  b_1 \\
\end{bmatrix} = W \begin{bmatrix}
  b_3 \\
  b_4 \\
\end{bmatrix} = Q \begin{bmatrix}
  a_{m1} \\
  b_{m1} \\
\end{bmatrix} = k_1 \begin{bmatrix}
  b_3 \\
  b_4 \\
\end{bmatrix} = K \begin{bmatrix}
  b_3 \\
  b_4 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
  a_0 \\
  b_0 \\
  a_1 \\
  b_1 \\
\end{bmatrix} = W^{-1}QK^{-1} \begin{bmatrix}
  a_{m1} \\
  b_{m1} \\
\end{bmatrix} = D \begin{bmatrix}
  a_{m1} \\
  b_{m1} \\
\end{bmatrix}
\]

\[
\begin{align*}
  a_0 &= D_{11}a_{m1} + D_{12}b_{m1} \\
  b_0 &= D_{21}a_{m1} + D_{22}b_{m1} \\
  a_1 &= D_{31}a_{m1} + D_{32}b_{m1} \\
  b_1 &= D_{41}a_{m1} + D_{42}b_{m1}
\end{align*}
\]

Ideal VNA

Error Box E

DUT

Shuffle the last 2 Equations and rename as

\[
\begin{align*}
  b_{m1} &= e_{11}a_{m1} + e_{12}b_1 \\
  a_1 &= e_{21}a_{m1} + e_{22}b_1
\end{align*}
\]
Error Box Property

- It’s not an actual network but only a linear system model
- Every parameter is frequency dependent but time invariant
- Since the $E$ parameters are more or less link with some specifications of the coupler they are also called:

\[
\begin{align*}
e_{11} & = E_D & \cong & \text{Directivity} \\
e_{22} & = E_S & \cong & \text{SourceMatch} \\
e_{21}e_{12} & = E_R & \cong & \text{Tracking}
\end{align*}
\]
Two Port Error Model

Two error boxes on the right and left

\[
\begin{bmatrix}
b_{m1} \\
b_{m2}
\end{bmatrix} = \mathbf{S}_m \begin{bmatrix}
a_{m1} \\
a_{m2}
\end{bmatrix}
\]

2-ports Measured S-matrix

\( Sm_{ij} = \frac{b_{mi}}{a_{mj}} \quad a_{mi} \neq 0 \)

\[
\begin{bmatrix}
b'_{1m} \\
b'_{2m}
\end{bmatrix} = \begin{pmatrix} S_{11m} & S_{12m} \end{pmatrix} \begin{bmatrix}
a'_{1m} \\
a'_{2m}
\end{bmatrix},
\begin{bmatrix}
b''_{1m} \\
b''_{2m}
\end{bmatrix} = \begin{pmatrix} S_{11m} & S_{12m} \end{pmatrix} \begin{bmatrix}
a''_{1m} \\
a''_{2m}
\end{bmatrix}
\]

\[
\begin{pmatrix} S_{11m} & S_{12m} \\
S_{21m} & S_{22m} \end{pmatrix} = \begin{pmatrix} b'_{1m} & b'_{1m} \\
b'_{2m} & b'_{2m} \end{pmatrix} \begin{pmatrix} a_{1m} & a''_{1m} \\
a''_{2m} & a''_{2m} \end{pmatrix}^{-1}
\]

To apply this model, 4 independent readings on each source position are required.
FULL 2-Ports Error Model

\[
\begin{bmatrix}
    b_{1DUT} \\
    a_{1DUT}
\end{bmatrix} = \begin{bmatrix}
    T_{A11} & T_{A12} \\
    T_{A21} & T_{A22}
\end{bmatrix}^{-1} \begin{bmatrix}
    b_{1m} \\
    a_{1m}
\end{bmatrix} = T_A^{-1} \begin{bmatrix}
    b_{1m} \\
    a_{1m}
\end{bmatrix}
\]

8 error terms, but

\[
\begin{bmatrix}
    a_{2DUT} \\
    b_{2DUT}
\end{bmatrix} = \begin{bmatrix}
    T_{B11} & T_{B12} \\
    T_{B21} & T_{B22}
\end{bmatrix}^{-1} \begin{bmatrix}
    a_{2m} \\
    b_{2m}
\end{bmatrix} = T_B^{-1} \begin{bmatrix}
    a_{2m} \\
    b_{2m}
\end{bmatrix}
\]

\(T_A, T_B\) are the transmission matrix equivalent of the two E matrices of left and right side while \(T_m\) is the transmission matrix equivalent of \(S_m\)

\[
\begin{bmatrix}
    b_{m1} \\
    a_{m1}
\end{bmatrix} = T_m \begin{bmatrix}
    a_{m2} \\
    b_{m2}
\end{bmatrix}
\]

\[
\begin{bmatrix}
    b_{1m} \\
    a_{1m}
\end{bmatrix} = T_A T_{DUT} T_B^{-1} \begin{bmatrix}
    a_{2m} \\
    b_{2m}
\end{bmatrix}
\]
Most USED 2-port Calibrations

- TSD-TRL (Thru, Short, Delay or Thru, Reflect, Line)
- LRM (Line, Reflect, Match)
- SOLR (Short, Open, Load, Reciprocal)
- SOLT (Short, Open, Load, Thru)

MANDATORY FOR 3 samplers VNAs
SOLT

- The old good cal: **S**hort, **O**pen, **L**oad and **T**hru
- It measures 3 standards at port 1, 3 at port 2 and the THRU.
- It obviously overdetermined with the 8 port model (10 equations for 8 unknowns) but it’s the proper choice for the 3-sampler architecture
Thru Reflect Line

- The Thru and Line must have the same geometry
  I.e. REFERENCE IMPEDANCE
- Normally the Reference plane it’s placed in the middle of the THRU
- The system Reference impedance IS THE Characteristic impedance of the LINE
- Known 1 port Standard TSD
- Unknown 1 port standard -> TRL
The length difference from the THRU and the LINE should avoid $\lambda/2$ and its multiple.

To have broadband TRL, more line are useful (different line length).

Side Result: The propagation constant of the line comes from free.
Transmission matrix of the Line with $Z_{\text{ref}} = Z_\gamma$

$$T_L = \begin{pmatrix} e^{\gamma L_L} & 0 \\ 0 & e^{-\gamma L_L} \end{pmatrix}$$

Transmission matrix of Thru with $Z_{\text{ref}} = Z_\gamma$, which imply that the LINE and THRU have the same geometry

$$T_T = \begin{pmatrix} e^{\gamma L_T} & 0 \\ 0 & e^{-\gamma L_T} \end{pmatrix}$$

$$T_{Lm} = T_A T_L T_B^{-1}$$

$$T_{Tm} = T_A T_T T_B^{-1}$$

$$T_L = T_A^{-1} T_{Lm} T_B$$

$$T_T = T_A^{-1} T_{Tm} T_B$$

$T_{Lm}$ e $T_{Tm}$ Measure Transmission Line of Line and Thru
\[ R_m = T_{Lm} T_{Tm}^{-1} = T_A T_L T_T^{-1} T_A^{-1} = T_A \Lambda T_A^{-1} \]

\[ R_n = T_{Tm}^{-1} T_{Lm} = T_B T_T^{-1} T_L T_B^{-1} = T_B \Lambda T_B^{-1} \]

\[ \Lambda = \begin{pmatrix} e^{\gamma (L_L - L_T)} & 0 \\ 0 & e^{-\gamma (L_L - L_T)} \end{pmatrix} \]

\[ L \text{ Diagonal Matrix} \]

\[ T_A \text{ Eigenvector matrix of } R_m, T_B \text{ Eigenvector matrix of } R_n \]
$T_A = p \begin{pmatrix} k \\ \frac{a}{p} \\ k \\ \frac{1}{p} \end{pmatrix} = pX_A$, $T_B = w \begin{pmatrix} 1 \\ \frac{u}{w} \\ f \\ \frac{u}{w} \end{pmatrix} = wX_B$

- $a, b + f, g$ from eingenvector

Deembedding:

$T_{DUT} = \frac{p}{w} X_A T_m X_B^{-1} = \alpha X_A T_m X_B^{-1}$
TSD I

1. The one port standard $G_S$ is known
2. $G_S$ is measured at port 1 ($G_{Sm1}$) and 2 ($G_{Sm2}$)

$$
\Gamma_{Sm1} = \frac{b + \frac{k}{p} a \Gamma_S}{1 + \frac{k}{p}} \Rightarrow \frac{k}{p} = \frac{b - \Gamma_{Sm1}}{(\Gamma_S - a) \Gamma_{Sm1}}
$$

$$
\Gamma_{Sm2} = \frac{f + \frac{u}{w} g \Gamma_S}{1 + \frac{u}{w}} \Rightarrow \frac{u}{w} = \frac{f - \Gamma_{Sm2}}{(\Gamma_S - g) \Gamma_{Sm2}}
$$
TSD II

3. Once \( k/p e u/w \) are known, from the measurement of Thru \( S_{21m} \) we finally find \( \alpha \):

\[
\alpha = \frac{(g - f) \frac{u}{w}}{S_{21m}(1 - \frac{k \cdot u}{p \cdot w})}
\]
1. The one port standard is unknown $\Gamma_S$
2. And measured at port 1 ($\Gamma_{Sm1}$) and 2 ($\Gamma_{Sm2}$)
3. There are 3 unknowns: $\Gamma$, $u/p$, $w$

And 3 equations:

\[
\begin{align*}
\Gamma_{sm1} &= \frac{b + \frac{k}{a} a \Gamma_s}{1 + \frac{p}{k}}, \\
\Gamma_{sm2} &= \frac{f + \frac{u}{g} g \Gamma_s}{1 + \frac{w}{u}}, \\
\frac{T_{Tm12}}{T_{Tm22}} &= S_{Tm11} = \frac{-\frac{k}{a} \frac{u}{w} + b}{\frac{p}{k} \frac{w}{u} + 1}
\end{align*}
\]

\[
\Gamma_S^2 = \frac{(b - \Gamma_{Sm1})(f - \Gamma_{Sm2})(S_{11m} - a)}{(a - \Gamma_{Sm1})(g - \Gamma_{Sm2})(S_{11m} - a)}
\]
Summary of TRL-TSD

- Thru and Line have the same $Z_{ref}=Z_{\infty}$ and this becomes the reference impedance of the system and must be known in advance.
- AVOID FREQUENCY WHICH BRING THRU and the LINE length = $\lambda/2$ and its multiple
- Multiple lines to cover broadband with at least 10° of phase difference
- IT REQUIRES TO MOVE THE PROBE LATERALLY
Wrong TRL LINE

Here the test set were used below it's spec frequency limits (0.5GHz), the Dynamic Range decrease so much that the results become completely out.
Different Algorithms

$S_{11}$ (dB)

$S_{17}$ (dB)

ESOLT

TRL
Coax TRL On-Board Calibration/Verification Structures

Thru and Line Structures

Reflect and Match Structures
On-wafer Standard
SOLR

- Short, Open, Load and Reciprocal
- NO MORE THRU OR LINE REQUIRED BUT

- 3 fully known standards and one fully unknown but reciprocal 2-port device (a cable for example)
- Free from port position problem
Let’s take again $X_a \ e X_b$ and $\Gamma_{sm1,2}$

$$T_A = p \begin{pmatrix} \frac{k}{a} & b \\ \frac{k}{p} & 1 \\ \frac{k}{p} & 1 \end{pmatrix} = pX_A, \quad T_B = w \begin{pmatrix} 1 & u \\ f & g \\ w & w \end{pmatrix} = wX_B$$

$$\Gamma_{sm1} = \frac{k}{p} a \Gamma_s + b, \quad \Gamma_{sm2} = \frac{u}{w} g \Gamma_s + f$$
With 3 fully known loads at port 1 we get:

\[
\begin{align*}
\alpha &= \frac{p}{w} \\
\end{align*}
\]

Thus \(X_a\) is now known.

• Than with 3 fully known standard on port 2 we get:

\[
\begin{align*}
\alpha &= \frac{u}{w} \\
\end{align*}
\]

Thus even \(X_b\) is now fully know what is left is
The sign of $a$ is given by a rough estimate of the delay introduced by the reciprocal.
SOLR Features

- A Thru is no more needed but just a way to connect the ports
- It’s more to perform a calibration with the same port gender
- It’s enough accurate when good one port standard and their models are available
- The Reference impedance is the one of the load standard
Multiport Calibration

**What if:**
Calibration cannot be based on a fixed sequence
A general formulation must be found!
Classical multiport error model

Complete reflectometer multiport architecture: two directional couplers @ each port
Error box extension as

\[ a_i = l_i b_{mi} - h_i c_{mi} \]
\[ b_i = k_i b_{mi} - m_i c_{mi} \]

with \( 4n - 1 \) unknowns:

\[
\begin{bmatrix}
1 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & 0 \\
\end{bmatrix}
\begin{bmatrix}
a_1 \\
0 \\
\vdots \\
0 \\
\end{bmatrix}
= 
\begin{bmatrix}
l_{m1} & \cdots & l_{mn} \\
0 & \cdots & 0 \\
\vdots & \ddots & \vdots \\
0 & \cdots & 0 \\
\end{bmatrix}
\begin{bmatrix}
b_{m1} \\
0 \\
\vdots \\
0 \\
\end{bmatrix}
- 
\begin{bmatrix}
h_{m1} & \cdots & h_{mn} \\
0 & \cdots & 0 \\
\vdots & \ddots & \vdots \\
0 & \cdots & 0 \\
\end{bmatrix}
\begin{bmatrix}
c_{m1} \\
0 \\
\vdots \\
0 \\
\end{bmatrix}.
\]
**Partial Reflectometer error model**

- Partial reflectometer multiport architecture: two directional couplers @ each port are not always available.
- This architecture has the advantages of costs (n-2 couplers are saved) and speed.

- The model for these cases must be:
  - of general validity (i.e. not valid for only one calibration algorithm and scalable)
  - compatible with the complete reflectometer one
  - easy to be calibrated
The new formulation

The partial reflectometer multiport system has two states, for each i port:

STATE A

\[ a = \begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{pmatrix}, \quad a_i = b_i^l, \quad i = k_i^l \]

STATE B

\[ a_m = \begin{pmatrix} a_{m1} \\ a_{m2} \\ \vdots \end{pmatrix} \]

\[ \hat{a}_{mi}, \hat{b}_{mi} \]

\[ \hat{b}_{mi} \]

\[ \Gamma_i \]

\[ b_i \rightarrow a_i \]

\[ a = L \]

\[ b = K \]
In any measurement condition, $a_i$ and $b_i$ are defined quantities, with a certain value, VALUE THAT DOES NOT DEPEND on which error model we adopt, i.e.:

\[
\begin{align*}
    a_i &= l_i b_{mi} - h_i a_{mi} \\
    b_i &= k_i b_{mi} - m_i a_{mi}
\end{align*}
\]

$\begin{align*}
    a_i &= g_i \hat{b}_{mi} \\
    b_i &= f_i \hat{b}_{mi}
\end{align*}$

- All these equations can be written for each source position, and stacked together in matrix form:

$$
\begin{pmatrix}
    a_1' \\
    a_2' \\
    \vdots \\
    a_n'
\end{pmatrix} =
\begin{pmatrix}
    a_1 \\
    a_2 \\
    \vdots \\
    a_n
\end{pmatrix}, \quad
\begin{pmatrix}
    b_1 \\
    b_2 \\
    \vdots \\
    b_n
\end{pmatrix}, \quad
\begin{pmatrix}
    b_1 b_2 \ldots b_n
\end{pmatrix}
$$

$$
\begin{pmatrix}
    a_{m1} a_{m2} \ldots a_{mn}
\end{pmatrix}, \quad
\begin{pmatrix}
    b_{m1} b_{m2} \ldots b_{mn}
\end{pmatrix}
$$
Let:

\[
\begin{align*}
\tilde{A}_m & \equiv \begin{bmatrix}
a_{m11} & 0 & \cdots & 0 \\
0 & a_{m22} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & a_{mnn}
\end{bmatrix} & & \tilde{B}_m & \equiv \begin{bmatrix}
b_{m11} & 0 & \cdots & 0 \\
0 & b_{m22} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & b_{mnn}
\end{bmatrix} & & \hat{B}_m & \equiv \begin{bmatrix}
0 & \hat{b}_{m12} & \hat{b}_{m13} & \cdots & \hat{b}_{m1n} \\
\hat{b}_{m21} & 0 & \hat{b}_{m23} & \cdots & \hat{b}_{m2n} \\
\hat{b}_{m31} & \hat{b}_{m32} & 0 & \cdots & \hat{b}_{m3n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\hat{b}_{mn1} & \hat{b}_{mn2} & \cdots & \hat{b}_{mn(n-1)} & 0
\end{bmatrix}
\end{align*}
\]

As well as:

\[
\begin{align*}
A & = \tilde{A} + \hat{A} & B & = \tilde{B} + \hat{B}
\end{align*}
\]

\[
\begin{align*}
\tilde{A} & \equiv \begin{bmatrix}
a_{11} & 0 & \cdots & 0 \\
0 & a_{22} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & a_{nn}
\end{bmatrix} & & \hat{A} & \equiv \begin{bmatrix}
a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\
a_{21} & 0 & a_{23} & \cdots & a_{2n} \\
a_{31} & a_{32} & 0 & \cdots & a_{3n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & \cdots & a_{nn-1} & 0
\end{bmatrix}
\end{align*}
\]
Since for each source position at each port we may have:

\[ a_i = l_i b_{mi} - h_i a_{mi} \]
\[ b_i = k_i b_{mi} - m_i a_{mi} \]

or

\[ a_i = g_i \hat{b}_{mi} \]
\[ b_i = f_i \hat{b}_{mi} \]

\[ \tilde{A} = L \tilde{B}_m - H \tilde{A}_m \]
\[ \tilde{B} = K \tilde{B}_m - M \tilde{A}_m \]

\[ A = \tilde{A} + \hat{A} \]
\[ B = \tilde{B} + \hat{B} \]

and

\[ A = \tilde{A} + \hat{A} = L \tilde{B}_m - H \tilde{A}_m + G \hat{B}_m \]
\[ B = \tilde{B} + \hat{B} = K \tilde{B}_m - M \tilde{A}_m + F \hat{B}_m \]
\[ B = K \hat{B}_m - M \hat{A}_m + F \hat{B}_m \quad A = L \hat{B}_m - H \hat{A}_m + G \hat{B}_m \]

\[ B = SA \]

\[-SG\hat{B}_m + F\hat{B}_m - SL\hat{B}_m + K\hat{B}_m + SH\hat{A}_m - M\hat{A}_m = 0\]

- And the de-embedding is:

\[ S = \left[ K\hat{B}_m - M\hat{A}_m + F\hat{B}_m \right] \left[ L\hat{B}_m - H\hat{A}_m + G\hat{B}_m \right]^{-1} \]

Let’s look at the cal equation

$$-S\hat{G}\hat{B}_m + F\hat{B}_m - S\hat{L}\hat{B}_m + K\hat{B}_m + S\hat{H}\hat{A}_m - M\hat{A}_m = 0$$

- Based on S parameters
- Always defined for any standards
- Can be used to find $H, L, M, K, F, G$ during the cal
- As well as to find $S$ during the measurement
Even a more careful look at the model reveals that:

- For the calibration the matrix equation can be written in iterative form, i.e. for an “all state A” measurement:
  \[ \sum_{p=1}^{n} S_{ip} l_{p} b_{mpj} - \sum_{p=1}^{n} (1 - \delta_{ip}) b_{mpj} \]

- and for a “state A-B” measurement:

- during calibration, each standard measurement will give type A equations, or type B equations, accordingly to the measurement configuration used (AA or AB)
Since no constraints are given on the standard type and the math can combine whatever sequence, the calibration becomes dynamic i.e. the software can generate the standard sequence which gives a set of enough linear independent equations as well as it accomplished for:

- Connectors at each ports
- Available standards USE ONLY 1 or 2 ports ONES !!
- User interconnection description
- Use of particular two port pairs self calibration
Partially Known Standards

- If two ports can go in state A contemporarily, classical SOLT, LRM, TRL, SOLR etc. algorithms can be applied to these ports because the new error model is compatible with the classical one!

Let’s combine everything and design a cal that fits the DUT
Example: Design CAL for the DUT

![Image of a device with labels P_1, P_2, P_3, P_4]

### Connection Property

<table>
<thead>
<tr>
<th></th>
<th>P_1</th>
<th>P_2</th>
<th>P_3</th>
<th>P_4</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_1</td>
<td>×</td>
<td>TRL</td>
<td>×</td>
<td>Recip</td>
</tr>
<tr>
<td>P_2</td>
<td>TRL</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>P_3</td>
<td>×</td>
<td>×</td>
<td>SOL</td>
<td>Recip</td>
</tr>
<tr>
<td>P_4</td>
<td>Recip</td>
<td>×</td>
<td>Recip</td>
<td>SOL</td>
</tr>
</tbody>
</table>

### Standard Sequence

<table>
<thead>
<tr>
<th>Standard</th>
<th>Port</th>
<th>Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>APC7THRU</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>APC7-AirLine</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>APC7REFLECT</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3.5mm BroadBand Load-F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3.5mm Female Open</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>5mm Coaxial Female Short</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3.5mm Female Open</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>5mm Coaxial Female Short</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3.5mm BroadBand Load-F</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3.5mm Female Open</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>APC7-3.5mmF</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>3.5mm F-F Adapter</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>
Cause of Uncertainty

- **Systematic Errors (85%)**
  - Microwave Components
  - Interconnections
  - Incorrect Standard Modeling
  - Calibration Algorithm

- **Random Error (10%)**
  - Connection Repeatability
  - Frequency Stability
  - Noise

- **Drift (5%)**

**Calibration**

**Lab Care**
VNA Noise

THE GOOD OLD 8510: RAW DATA NOISE
Repeatability an example: APC7mm

A close look to the connector

Table 2-3 Electrical Specifications for 85050D 7 mm Devices

<table>
<thead>
<tr>
<th>Device</th>
<th>Specification</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadband loads</td>
<td>≥ 38 dB Return loss</td>
<td>≤ 18 GHz</td>
</tr>
<tr>
<td>Short* collet style</td>
<td>± 0.2° from nominal</td>
<td>≤ 2 GHz</td>
</tr>
<tr>
<td></td>
<td>± 0.3° from nominal</td>
<td>2 to 8 GHz</td>
</tr>
<tr>
<td></td>
<td>± 0.5° from nominal</td>
<td>8 to 18 GHz</td>
</tr>
<tr>
<td>Open* with collet pusher</td>
<td>± 0.3° from nominal</td>
<td>≤ 2 GHz</td>
</tr>
<tr>
<td></td>
<td>± 0.4° from nominal</td>
<td>2 to 18 GHz</td>
</tr>
<tr>
<td></td>
<td>± 0.6° from nominal</td>
<td>8 to 18 GHz</td>
</tr>
</tbody>
</table>

a. The specifications for the opens and shorts are given as allowed deviation from the nominal model as defined in the standard definitions (see "Nominal Standard Definitions" on page A-9).
b. Nominal, in this case, means the electrical characteristics as defined by the calibration constants supplied on the calibration constants disk.
Multifinger On wafer probes

- Probe landing repeatability
- Probe Coupling

Graph 1: $S_{11}$ (dB), x-axis variation

Graph 2: $S_{11}$ (dB), y-axis variation
1. The scattering matrix is reciprocal ($R_{12} = R_{21}$, this implies $\delta_{12} = \delta_{21} = \delta_T$)
2. The scattering matrix is physically symmetrical ($R_{11} = R_{22}$, this implies $\delta_{11} = \delta_{22} = \delta_R$)

$$
R = \begin{bmatrix}
\delta_R & 1 + \delta_T \\
1 + \delta_T & \delta_R
\end{bmatrix}
$$
Standard Accuracy

- Standard Model
- Model Identification
- Parameter Accuracy
Standard Model

\[ C = C_0 + C_1 f + C_2 f^2 + C_3 f^3 \]

- How do we get \( C_j \)
- FEM Methods
Standard Model: 40ps line
Let’s put everything together

- Interfacing:
  - On Board
  - On Wafer
- Standard design
- A complete example of socket board
Interfacing

- Custom Fixtures
Standard Design for Multiport Measurements

Requirements:
- Minimum Number of Connections
- Easy to fabricate
- Calibration and Verification Elements
Coax On-Board Simple Calibration Structures

Thru and Line Structures

Reflect and Match Structures
More complex On fixture Standard

3-TRL/TRM kits
- 0.2-20GHz
- 0.05-50GHz
- 0.05-65GHz

12-port Beatty standard

12-port simple & coupled ustrip

12-port unknown thru
On Wafer Verification Devices

Partially Leaky Structures

SOLT kits

TRL kits

20GHz, 50GHz, 65GHz

SOLT kits

20GHz, 50GHz, 65GHz
Socket Board Characterization

- The target is to obtain accurate measurements of a socket/board interface
Socket Board Characterization

- Define the effective structure to measure:
  - Number of ports
  - Port Location (on board on Socket)
  - Access Lines
- Define a Calibration Procedure
- Built the Required Standards
- Verify the calibration with verification devices
- PERFROM THE DUT MEASUREMENTS
8 Port Differential Socket Setup

D1
Bottom Board
1
2
5
6

CPU Socket

D2

D3

CPU Package
3
4
7
8

D4
Let’s Design the Cal
8-Port LRM Calibration Matrix

<table>
<thead>
<tr>
<th></th>
<th>Port 1</th>
<th>Port 2</th>
<th>Port 3</th>
<th>Port 4</th>
<th>Port 5</th>
<th>Port 6</th>
<th>Port 7</th>
<th>Port 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port 1</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>2P_LRM</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Port 2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Thru</td>
<td>Thru</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Port 3</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Thru</td>
<td>Thru</td>
<td>X</td>
</tr>
<tr>
<td>Port 4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Thru</td>
<td>Thru</td>
</tr>
<tr>
<td>Port 5</td>
<td>2P_LRM</td>
<td>Thru</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Port 6</td>
<td>X</td>
<td>Thru</td>
<td>Thru</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Port 7</td>
<td>X</td>
<td>X</td>
<td>Thru</td>
<td>Thru</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Port 8</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Thru</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Calibration Procedure:
- Thru Port 1, 5
- Thru Port 2, 6
- Thru Port 3, 7
- Thru Port 4, 8
- Thru Port 2, 5
- Thru Port 3, 6
- Thru Port 4, 7
- Reflect Port 1
- Reflect Port 5
- Load Port 1
- Load Port 5

Structure 1 (All ports touchdown)

Structure 2 (All ports touchdown)

Structures 3 – 4
What if the standard has xtalk?
Another Cal to avoid Xtalk
8-Port LRM/LSM Standards
(Probe tip Calibration)

Probes Touchdown:
1. Touchdown 1
2. Touchdown 2
3. Touchdown 3
4. Touchdown 4

Minimize probe tip Xtalk

X Length
8-Port LRM/LSM Multi-Calibration Matrix with Reciprocal Thrus

<table>
<thead>
<tr>
<th></th>
<th>Port 1</th>
<th>Port 2</th>
<th>Port 3</th>
<th>Port 4</th>
<th>Port 5</th>
<th>Port 6</th>
<th>Port 7</th>
<th>Port 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port 1</td>
<td></td>
<td>X</td>
<td>Recip</td>
<td>X</td>
<td>X</td>
<td>2P_LSM</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Port 2</td>
<td>Recip</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>2P_LSM</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Port 3</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Recip</td>
<td>X</td>
<td>X</td>
<td>2P_LSM</td>
</tr>
<tr>
<td>Port 4</td>
<td>X</td>
<td>X</td>
<td>Recip</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>2P_LSM</td>
</tr>
<tr>
<td>Port 5</td>
<td>2P_LSM</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Port 6</td>
<td>X</td>
<td>2P_LSM</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Recip</td>
<td>X</td>
</tr>
<tr>
<td>Port 7</td>
<td>X</td>
<td>X</td>
<td>2P_LSM</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Recip</td>
<td>X</td>
</tr>
<tr>
<td>Port 8</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>2P_LSM</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

- **Calibration Procedure:**
  - Thru Port 1, 5
  - Thru Port 2, 6
  - Thru Port 3, 7
  - Thru Port 4, 8
  - Recip 1, 2
  - Recip 3, 4
  - Recip 6, 7
  - Reflect Port 1, Reflect Port 5
  - Reflect Port 2, Reflect Port 6
  - Reflect Port 3, Reflect Port 7
  - Reflect Port 4, Reflect Port 8
  - Load Port 1, Load Port 5
  - Load Port 2, Load Port 6
  - Load Port 3, Load Port 7
  - Load Port 4, Load Port 8

  **Structure 1**

  - 4 separate 2-port LRM/LSM calibrations linked with reciprocal thru standards
    - No wasted probe touchdowns
    - Never move probe tips in x or y direction
    - Full characterization of every port
    - Could provide more accurate calibrations

  **Structure 2**

  - LRM requires reflect on all ports
  - LSM only requires 1 reflect per calibration
  => Only half of Structure 3 is needed for LSM
Socket/Board Example

On Socket PROBES Land Places

Cal Standards

On Board PROBES Land Places
Socket-Board Data

SDD11-SDD22-SDD33-SDD44

[Graph showing frequency response of SDDs]
Socket-Board Data

SDD12 - SDD34

![Graph showing frequency vs. dB for SDD12 and SDD34](chart.png)
Socket-Board Data

SD14 – SD23 (Far End Xtalk)
Socket-Board Data

SD13 – SD24 (Near End Xtalk)

[Graph showing frequency response for Bottom Board and Top Board.]
A similar case but 12 ports!
So at the beginning....

There were just knobs and waveguides
Then computers came in.....

and the situation gets.....
MESSY BUT..

With a well design Measurement Strategy
Even the Mess gets clean
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