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Multiport Vector Network Analyzers

From the beginning to modern signal integrity applications

IEEE-MTT Distinguished Microwave Lectures

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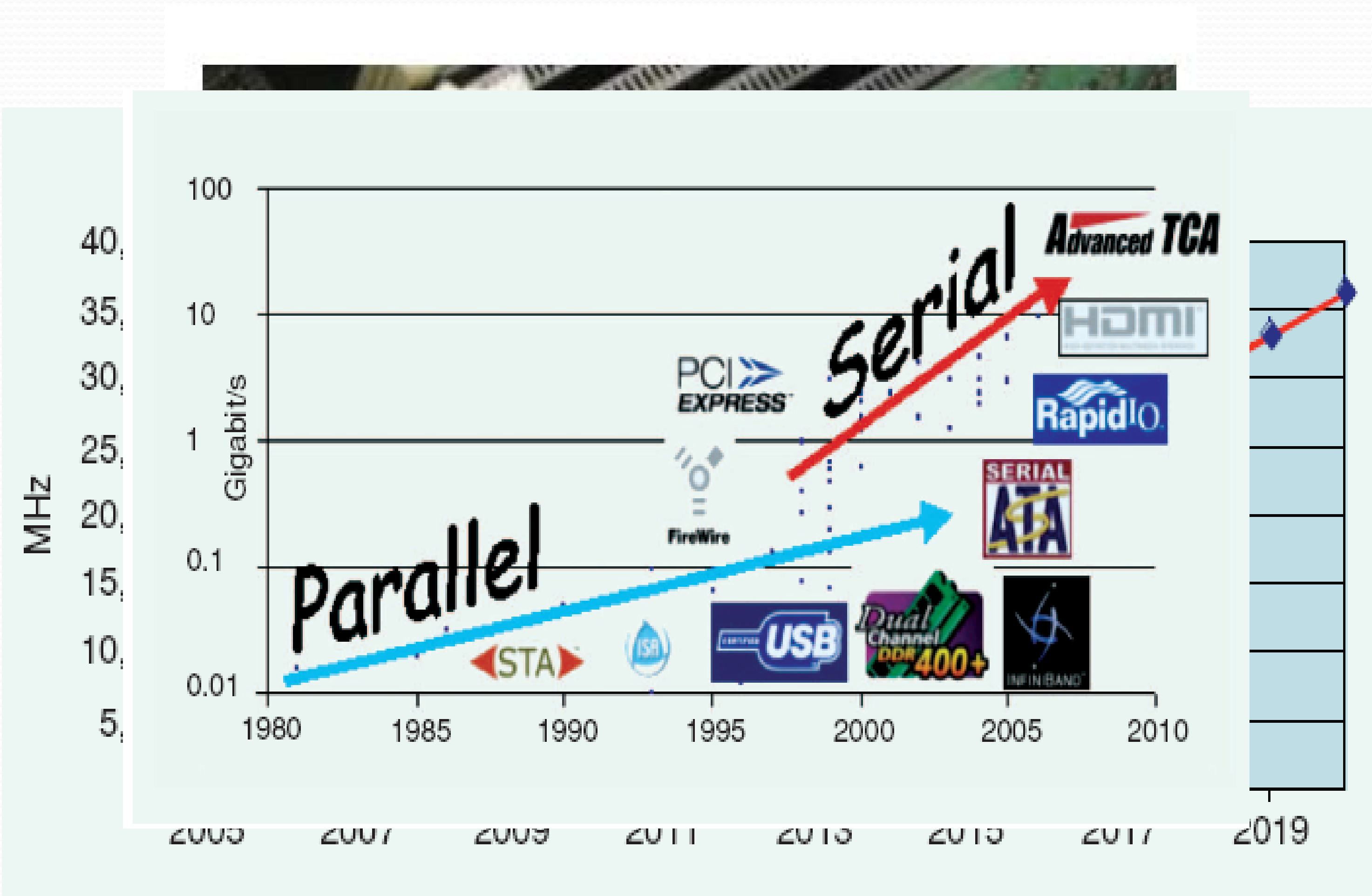
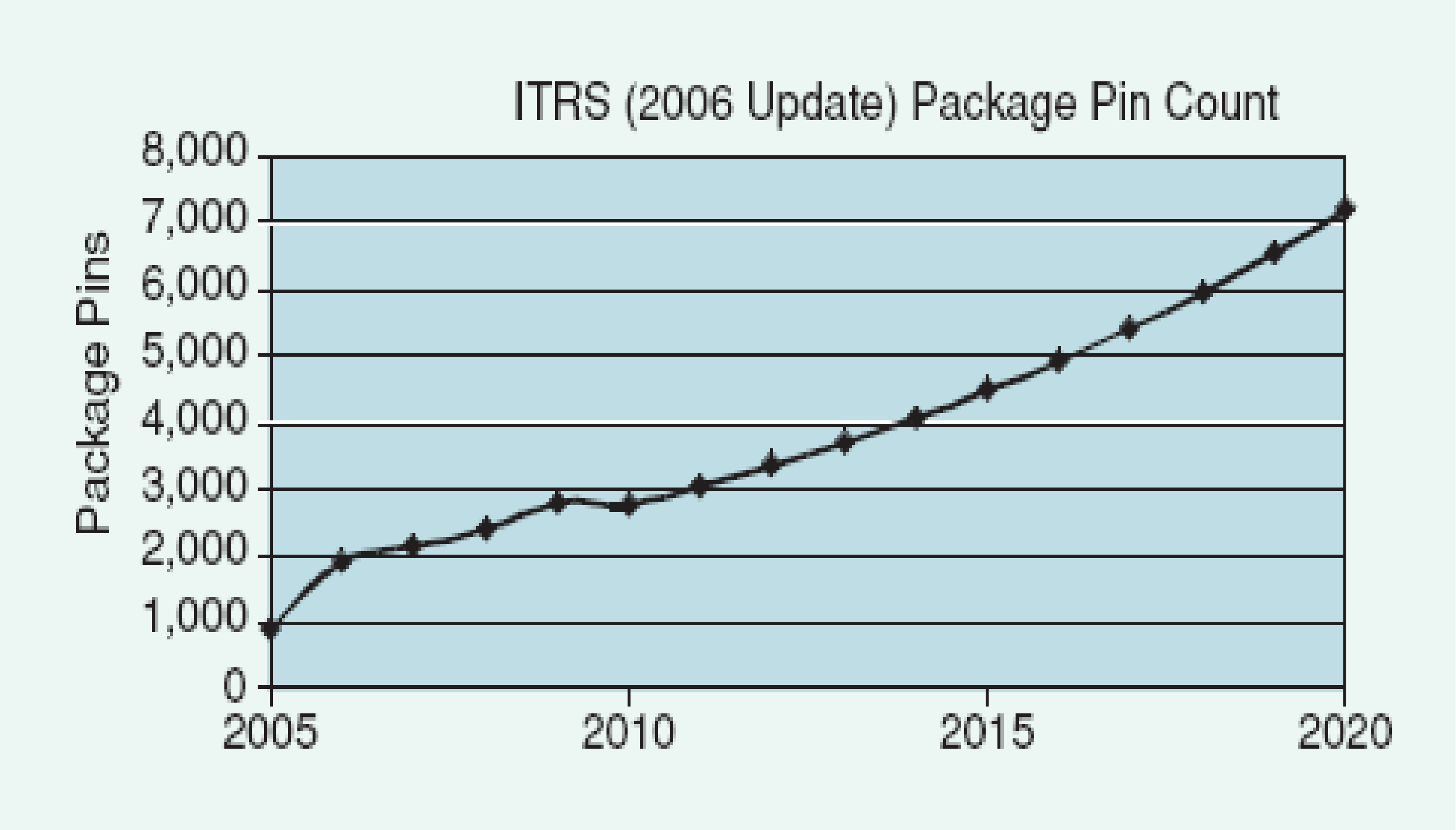
Summary

- 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?



The old questions Microwave Measurements

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

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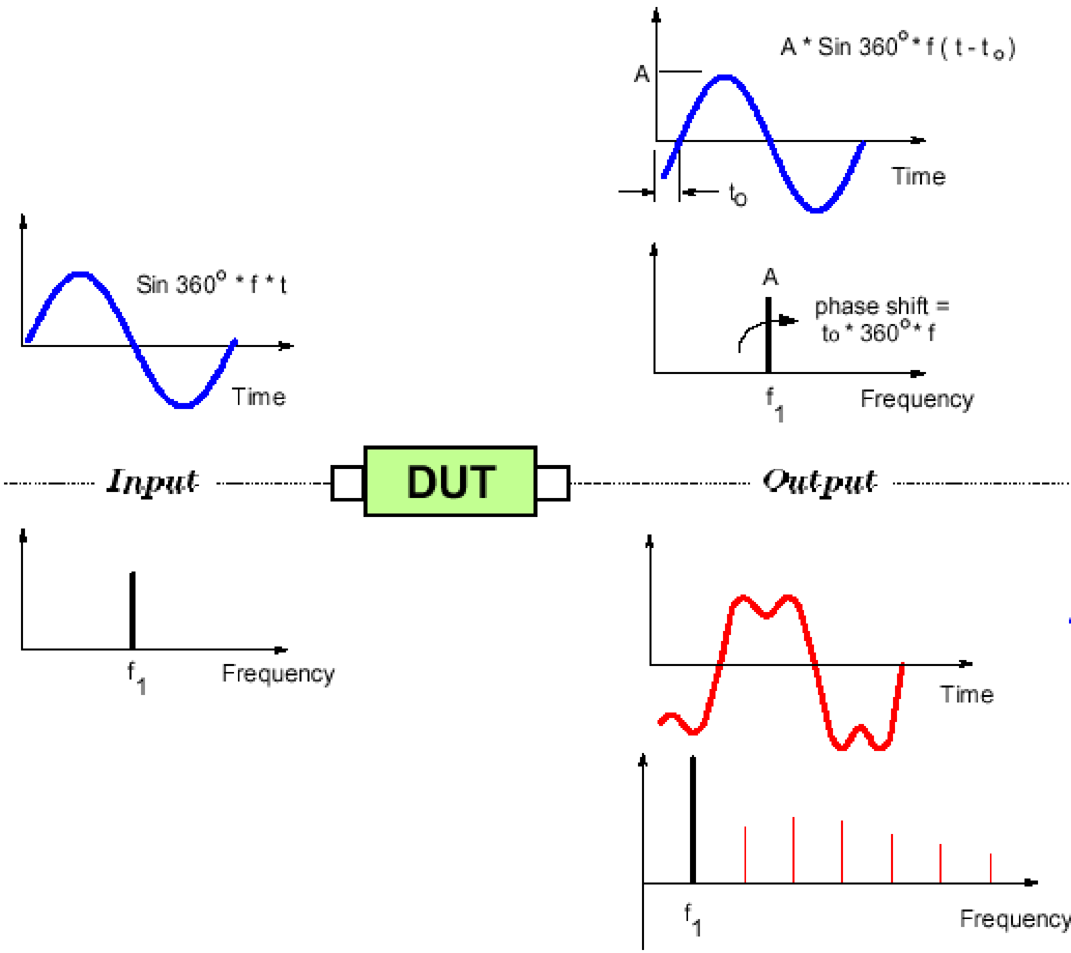
Plus new problems…

- 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:

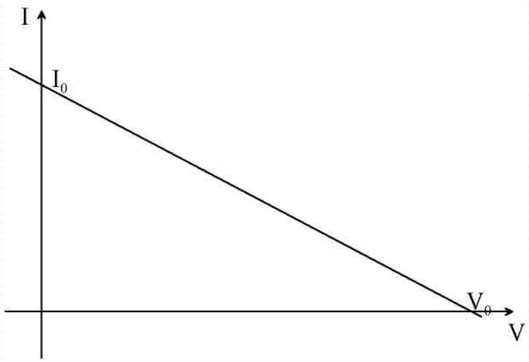
- input and output frequencies are the same (no additional frequencies created)
- output frequency only undergoes magnitude and phase change

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



- eq. Thevenin Model $V=-ZI+V_0$
- eq. Norton Model $I=-YV+I_0$

N-port Linear Circuit

Variables are grouped in vectors and the relationship become matrix equations

- Example: $\underline{V}=[Z]\,\underline{I}+\underline{V}_o$
- $\underline{I}=[Y]\underline{V}+\underline{I}_o$ where [Z], [Y] are the impedance/admittance matrices
- THERE ARE INFINITIVE 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 CHOICHE DEPENDS ON THE USEFULLNESS

How do we measure them?

- If $\underline{V_o}=\underline{I_o}=\underline{0}$
- Each parameter can be identify by the measurement:

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

- 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

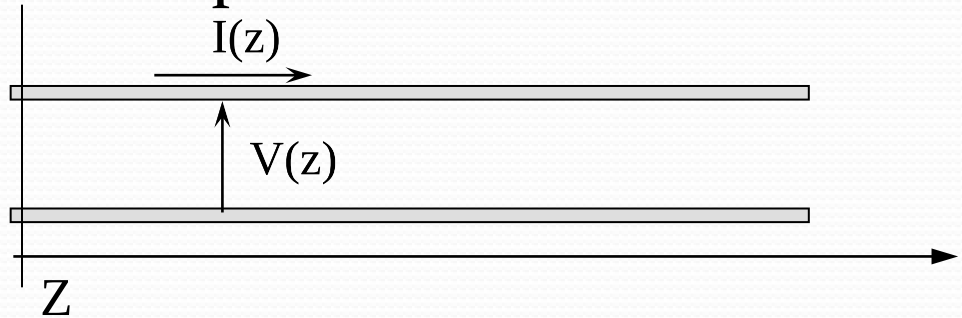
  NB: VECTORIAL MEASUREMENT AT DIFFERENT FREQUENCY

DIFFERENT PARAMETERS MEAN DIFFERENT MEASUREMENT TECHNIQUES

What's the best for the RF ?

- At RF frequencies everything become 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



$$\begin{cases} V(z) = V^+(z) + V^-(z) \\ I(z) = I^+(z) + I^-(z) = \dfrac{V^+(z) - V^-(z)}{Z_\infty} \end{cases}$$

$$\boxed{V^+(z) = V^+(0)e^{-jkz}}$$

$$\begin{cases} V^+(z) = \dfrac{V(z) + Z_\infty I(z)}{2} \\ V^-(z) = \dfrac{V(z) - Z_\infty I(z)}{2} \end{cases}$$

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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

- $V^{-}(z)=0$ 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:

$$a_i \equiv \frac{V_i + I_i Z_i}{2\sqrt{R_i}}$$

$$b_i \equiv \frac{V_i - I_i Z_i}{2\sqrt{R_i}}$$

$$a_i = \frac{V_i^{+}}{\sqrt{R_i^{rif}}}, \quad b_i = \frac{V_i^{-}}{\sqrt{R_i^{rif}}} \longrightarrow \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

- If $R=Z\infty$ many interesting properties occurs for the S parameters of a line I.e.:

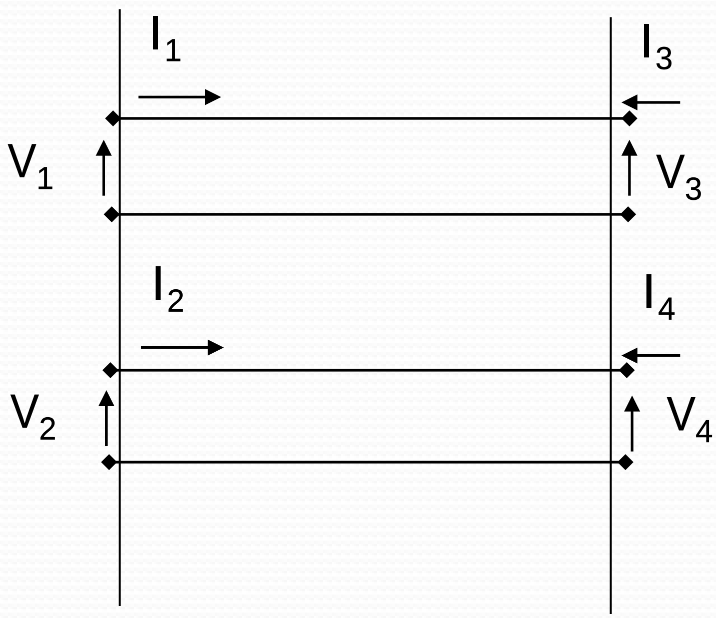
$$S(z) = \begin{bmatrix} 0 & e^{-jkz} \\ e^{-jkz} & 0 \end{bmatrix}$$

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 ?



For Each Couple

$$V_{djk} \equiv V_j - V_k$$
$$V_{cjk} \equiv (V_j + V_k)/2$$
$$I_{djk} \equiv (I_j - I_k)/2$$
$$I_{cjk} \equiv (I_j + I_k)$$

Differential S-parameters

- What are the propagation properties and is it usefull 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:

$$a_{djk} = \frac{1}{\sqrt{2}}(a_j - a_k)$$

$$b_{djk} = \frac{1}{\sqrt{2}}(b_j - b_k)$$

$$a_{cjk} = \frac{1}{\sqrt{2}}(a_j + a_k)$$

$$b_{cjk} = \frac{1}{\sqrt{2}}(b_j + b_k)$$

$$\Downarrow$$

$$\dot{\mathbf{S}} = \mathbf{MSM}^{-1}$$

BUT THESE ARE VALID ONLY IF

$$Z_{cjk} = \frac{R}{2} \quad \text{Real Only}$$

$$Z_{djk} = 2R \quad \text{Real Only}$$

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Generalized Mixed Mode

- In general we may have

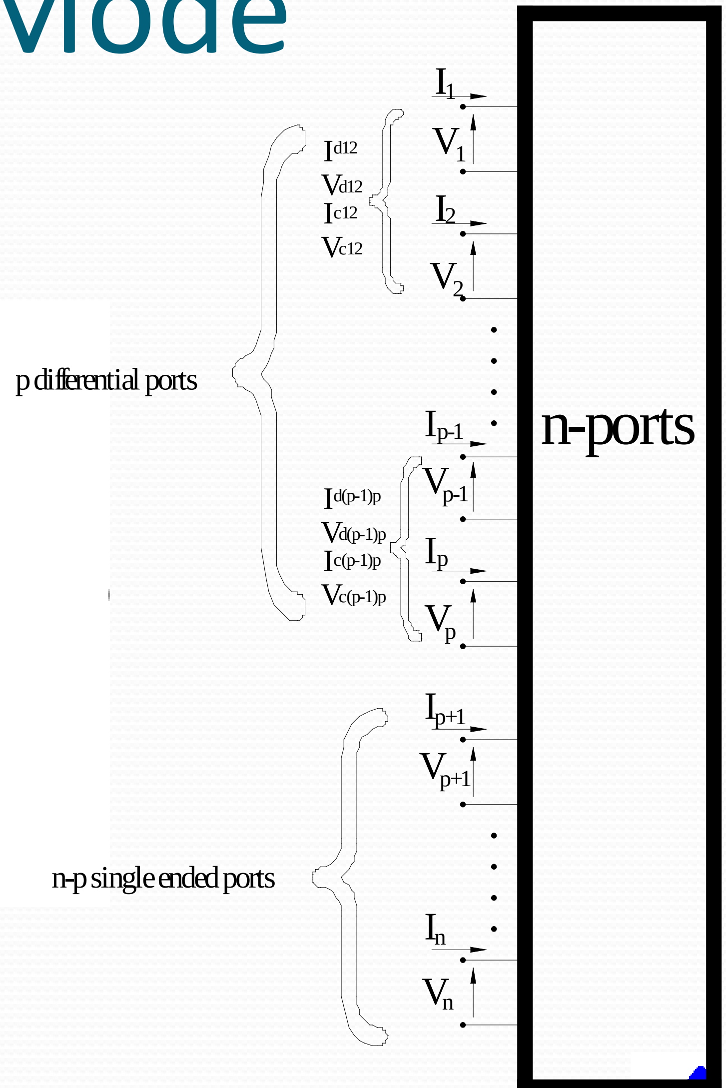
$$a_{djk} \equiv \sqrt{R_{djk}}\,\frac{V_{djk} + I_{djk} Z_{djk}}{2\left|Z_{djk}\right|}$$

$$b_{djk} \equiv \sqrt{R_{djk}}\,\frac{V_{djk} - I_{djk} Z_{djk}}{2\left|Z_{djk}\right|}$$

$$a_{cjk} \equiv \sqrt{R_{cjk}}\,\frac{V_{cjk} + I_{cjk} Z_{cjk}}{2\left|Z_{cjk}\right|}$$

$$b_{cjk} \equiv \sqrt{R_{cjk}}\,\frac{V_{cjk} - I_{cjk} Z_{cjk}}{2\left|Z_{cjk}\right|}$$

$$\mathring{\mathbf{a}} \equiv \begin{pmatrix} a_{d12} \\ a_{d34} \\ \cdot \\ \cdot \\ a_{d(p-1)p} \\ a_{c12} \\ a_{c34} \\ \cdot \\ \cdot \\ a_{c(p-1)p} \\ a_{p+1} \\ \cdot \\ \cdot \\ a_{n-1} \\ a_n \end{pmatrix} \qquad \mathring{\mathbf{b}} \equiv \begin{pmatrix} b_{d12} \\ b_{d34} \\ \cdot \\ \cdot \\ b_{d(p-1)p} \\ b_{c12} \\ b_{c34} \\ \cdot \\ \cdot \\ b_{c(p-1)p} \\ b_{p+1} \\ \cdot \\ \cdot \\ b_{n-1} \\ b_n \end{pmatrix}$$



$$\Downarrow$$

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

BILINEAR MATRIX TRANSFORM

S-parameter Measurement

- From the definition in a 2 port case:

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

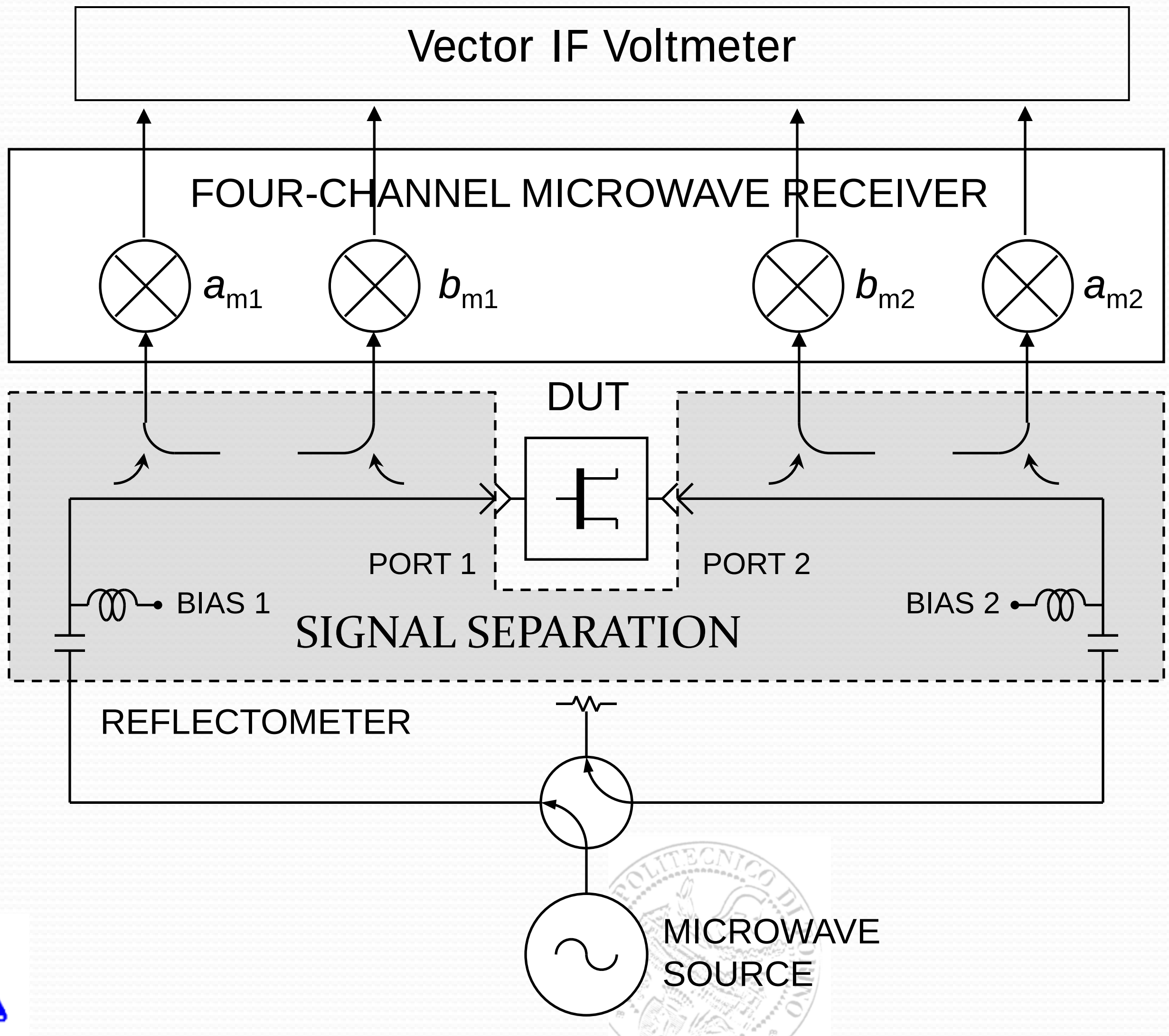
$$\begin{aligned} b_1 &= S_{11}a_1 + S_{12}a_2 \\ b_2 &= S_{21}a_0 + S_{22}a_2 \end{aligned}$$

$$S_{ij} = \left.\frac{b_i}{a_j}\right|_{a_{i \neq j} = 0}$$

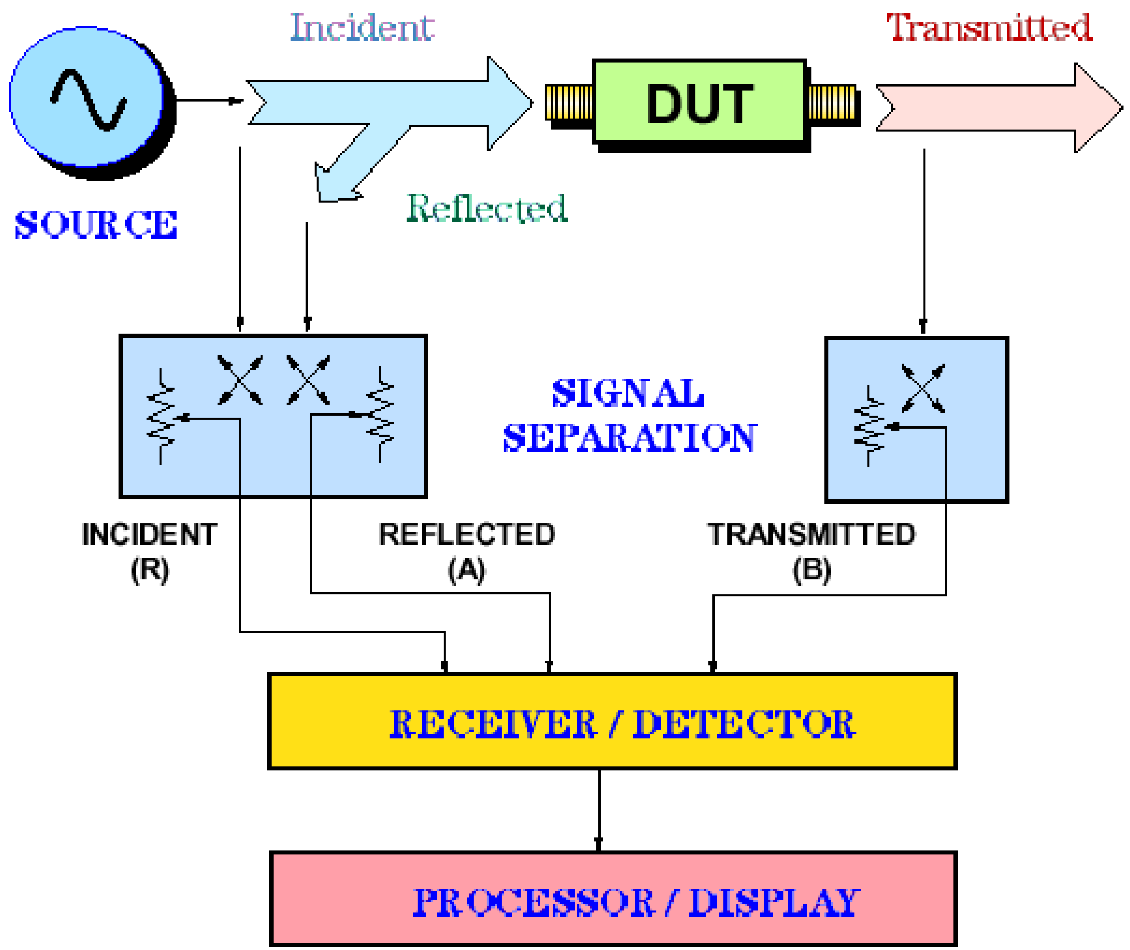
Which Means →

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

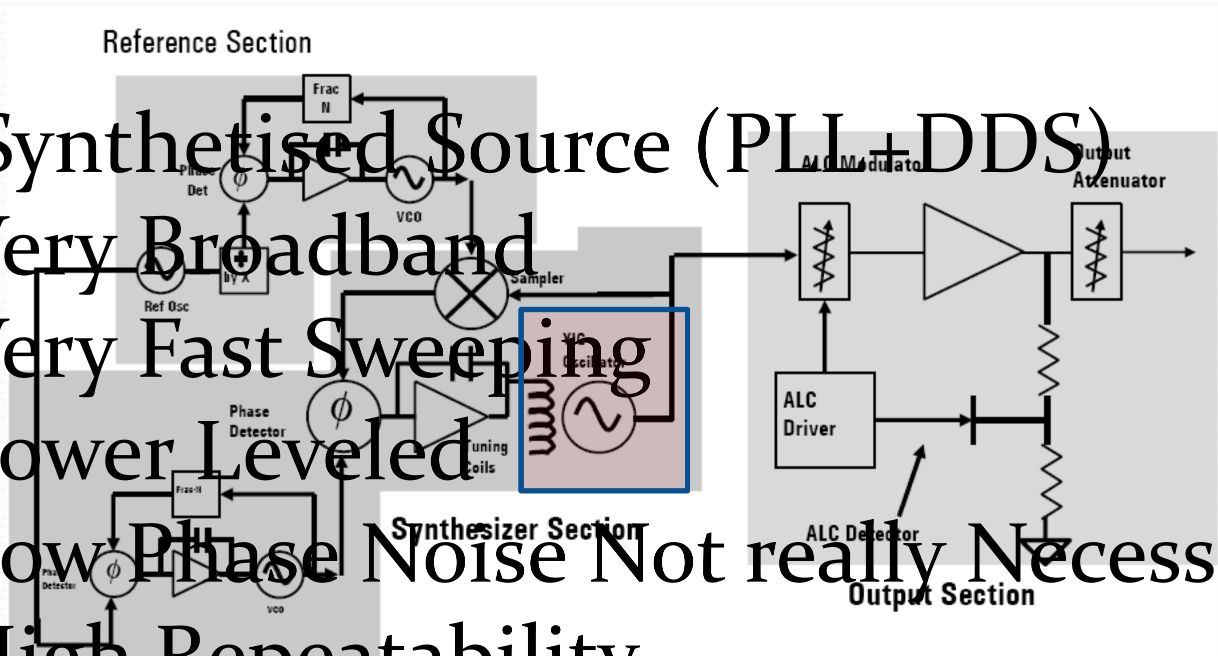
VNA BASIC SCHEME



3-Sampler VNA



VNA Source

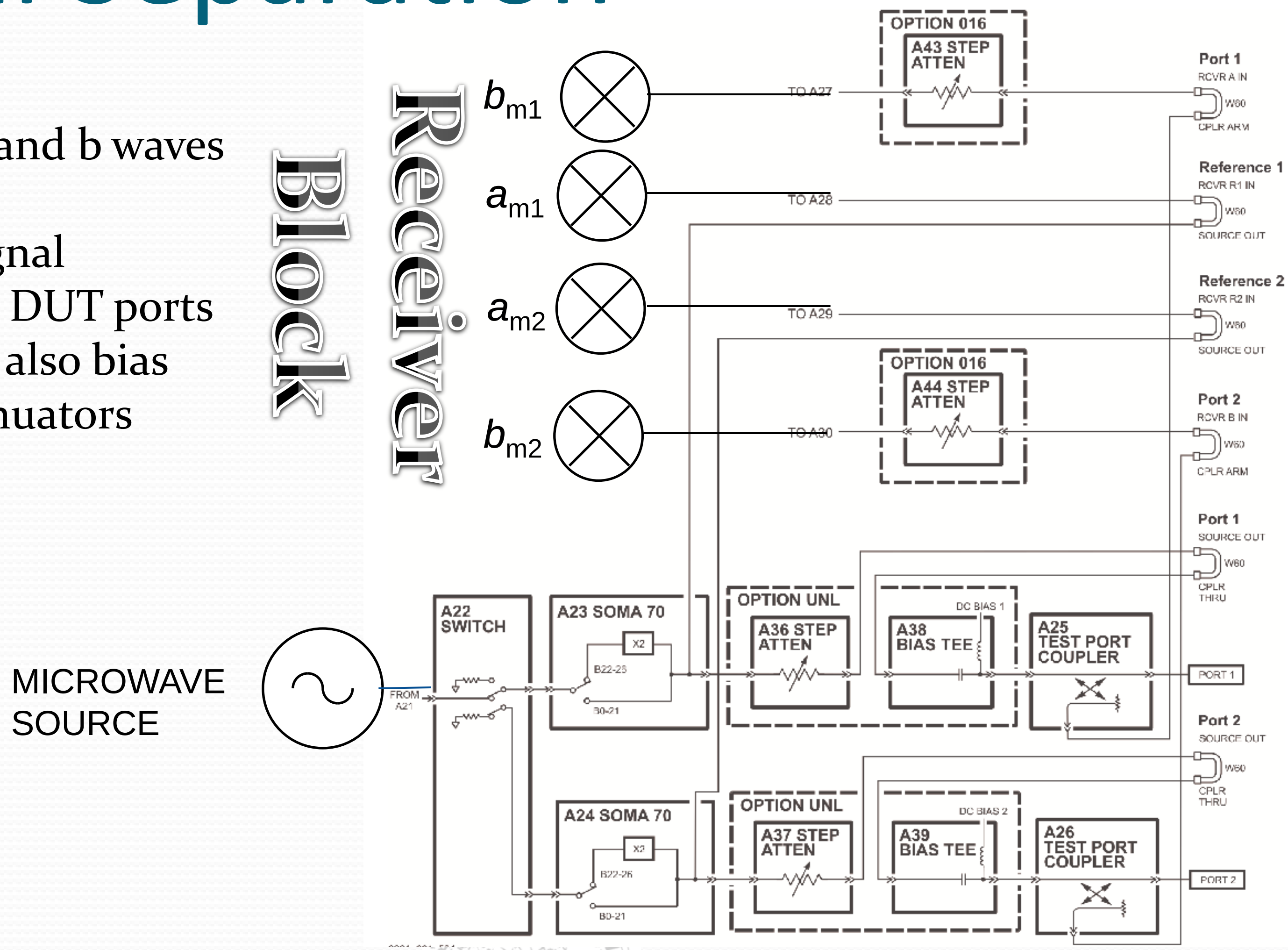


- Synthetised Source (PLL+DDS)
- Very Broadband
- Very Fast Sweeping
- Power Leveled
- Low Phase Noise Not really Necessary
- High Repeatability

Agilent PNA Source block

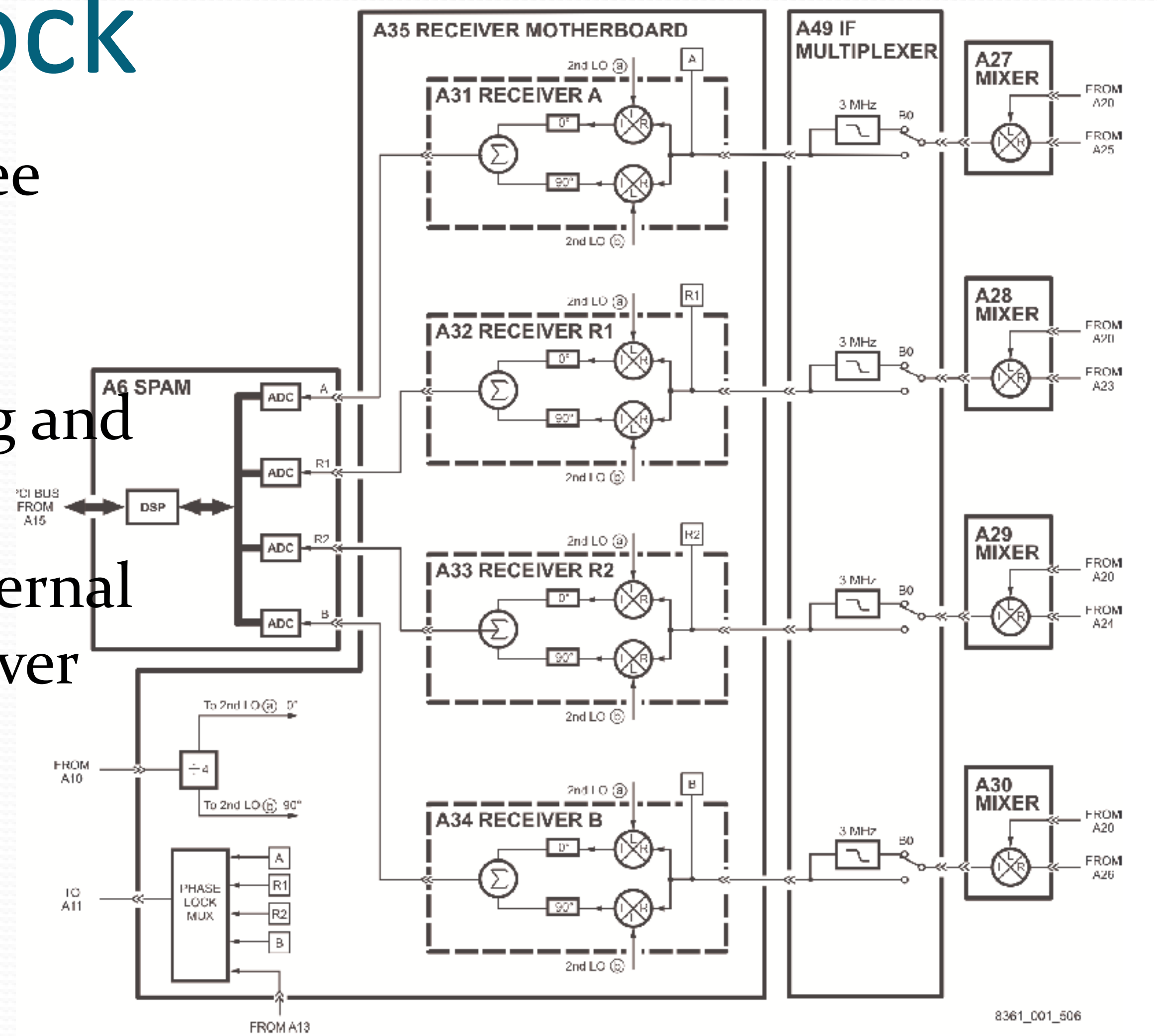
Signal Separation

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



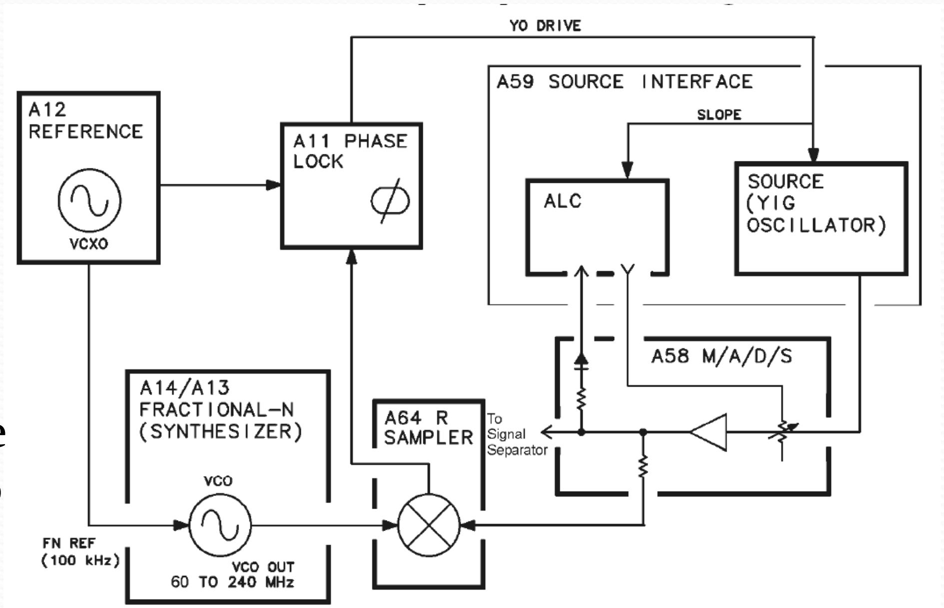
Receiver Block

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

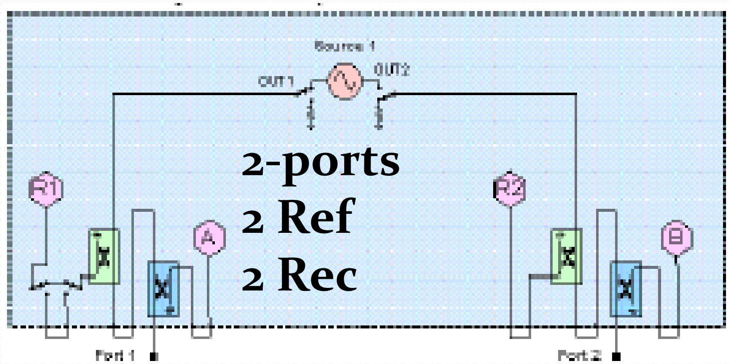


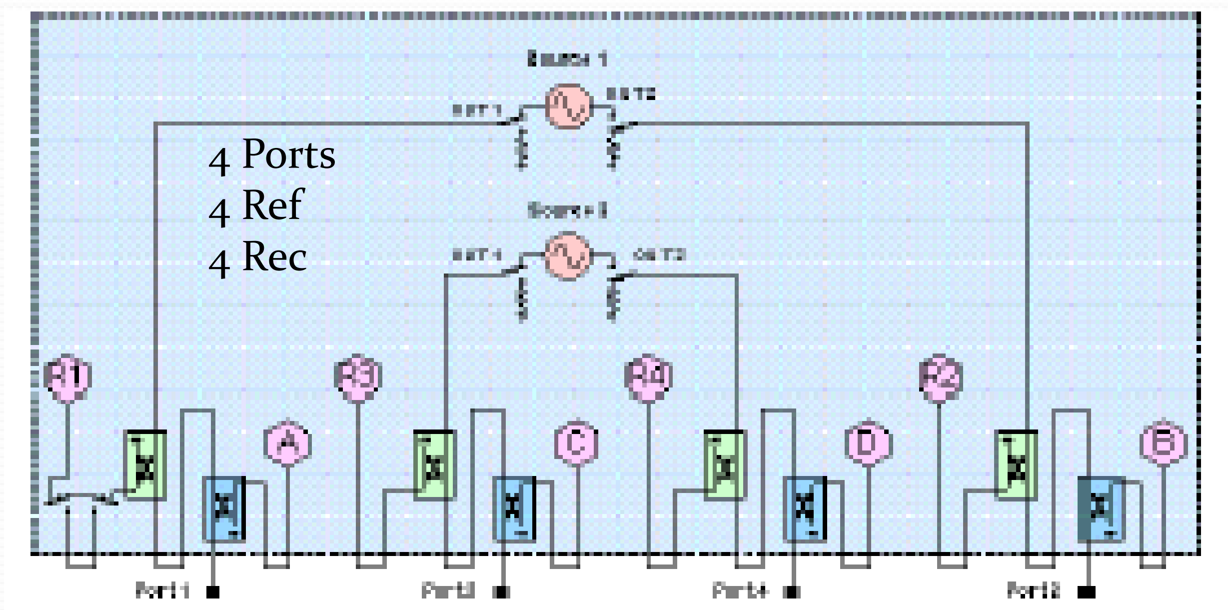
Phase Lock through its receiver

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 refenrence

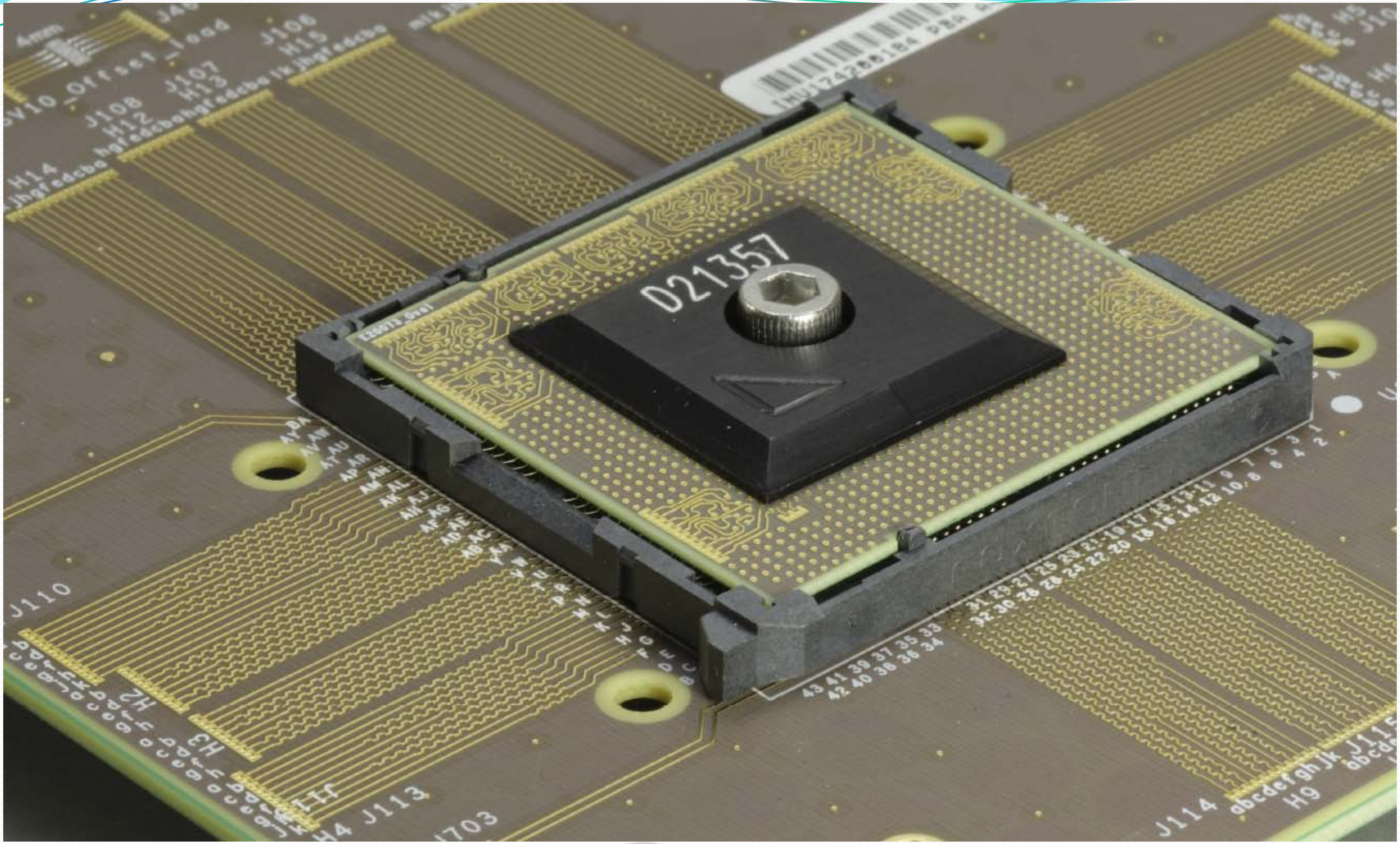


Going More than 2ports



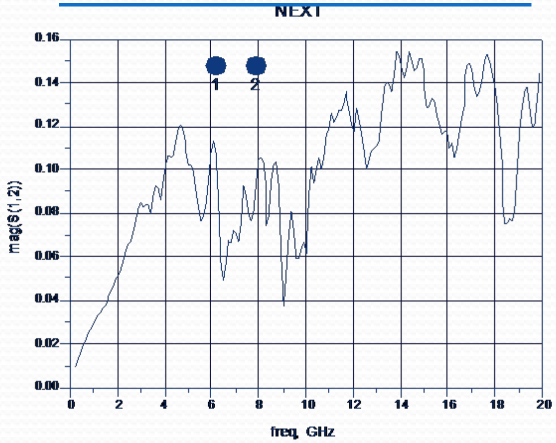


Are 4 ports VNA enough?

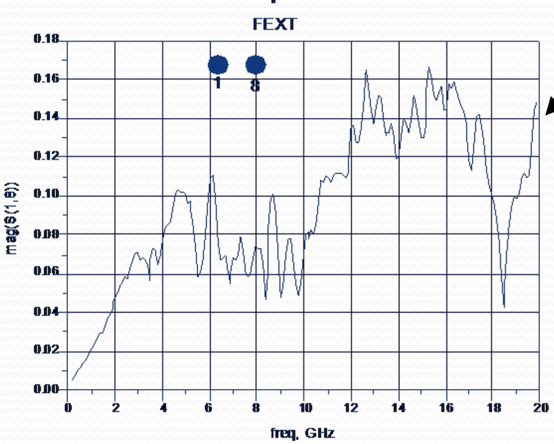


4-port Measurements w/symmetry

Crosstalk Measurements



4-port

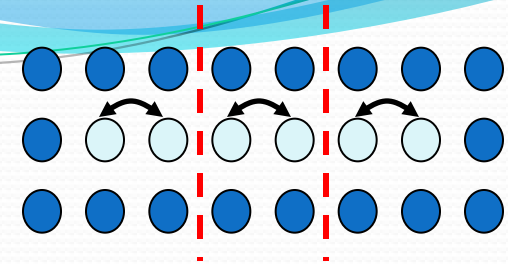


Coupling within pairs:
Measured, as long as symmetry is assumed

Coupling between pairs:
Unknown

Coupling within pairs

Package/Socket footprint



Measurement Matrix

	1	2	3	4	5	6	7	8	9	10	11	12
1					0	0	0	0	0	0	0	0
2					0	0	0	0	0	0	0	0
3					0	0	0	0	0	0	0	0
4					0	0	0	0	0	0	0	0
5	0	0	0	0					0	0	0	0
6	0	0	0	0					0	0	0	0
7	0	0	0	0					0	0	0	0
8	0	0	0	0					0	0	0	0
9	0	0	0	0	0	0	0	0				
10	0	0	0	0	0	0	0	0				
11	0	0	0	0	0	0	0	0				
12	0	0	0	0	0	0	0	0				

= data collected via measurement

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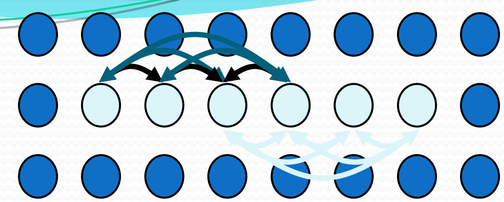
8-port Measurements w/symmetry

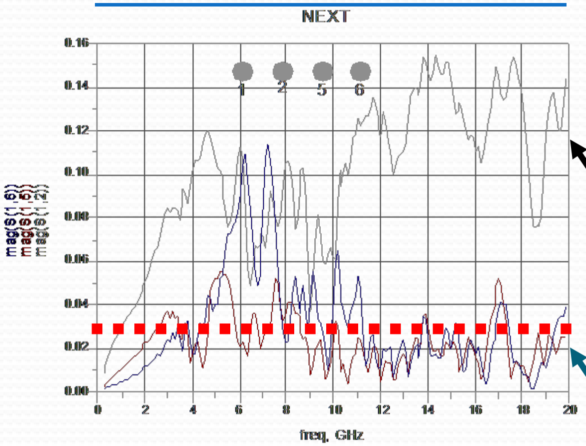
Package/Socket footprint



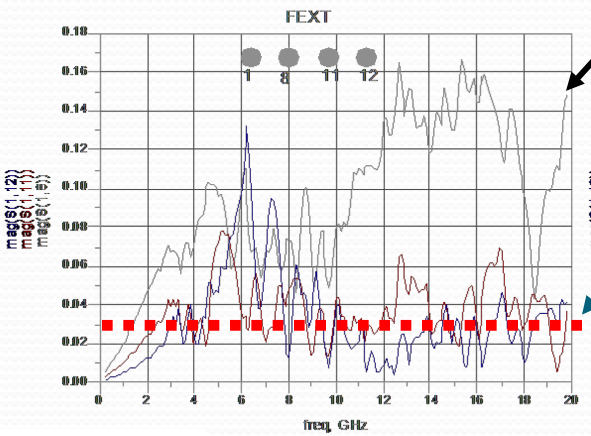
Coupling within pairs:
Measured, as long as symmetry is assumed

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

Crosstalk Measurements



8-port



Coupling within pairs

Coupling between pairs

Measurement Matrix

	1	2	3	4	5	6	7	8	9	10	11	12
1									0	0	0	0
2									0	0	0	0
3									0	0	0	0
4									0	0	0	0
5												
6												
7												
8												
9	0	0	0	0								
10	0	0	0	0								
11	0	0	0	0								
12	0	0	0	0								

= data collected via measurement

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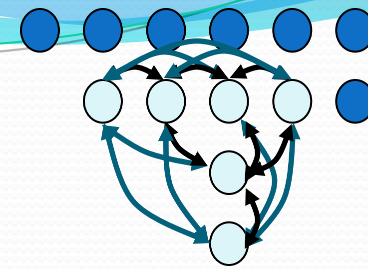
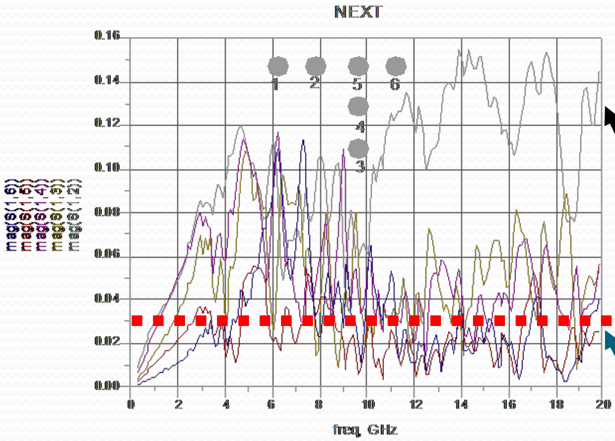
12-port Measurements

Coupling within pairs:
Measured
Coupling between pairs:
Measured

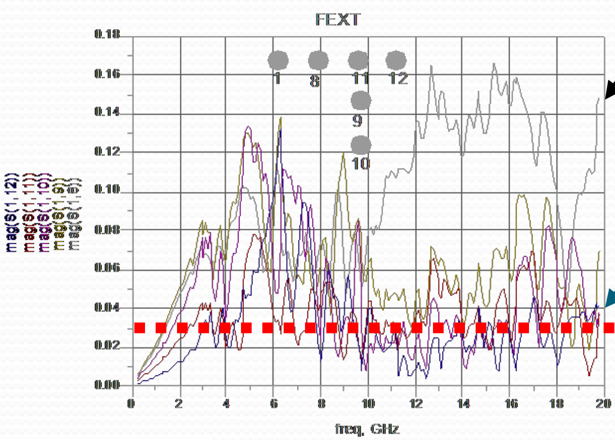
Package/Socket footprint



Crosstalk Measurements



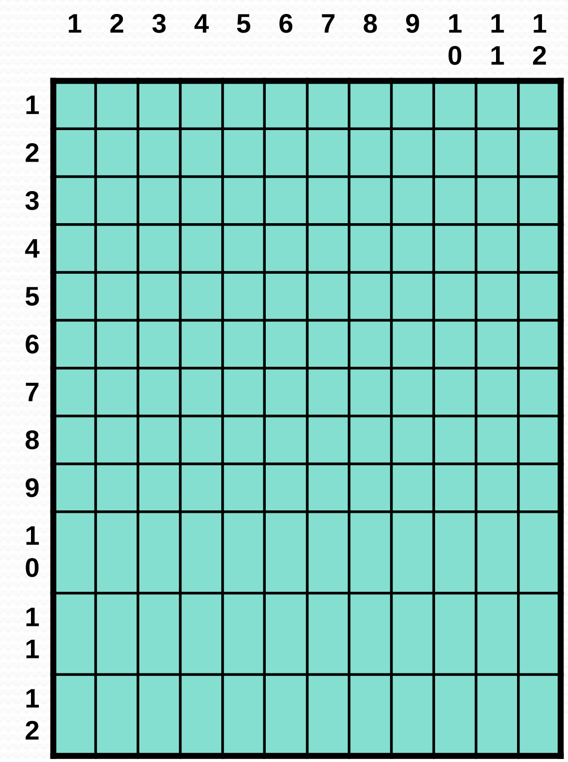
12-port



Coupling within pairs

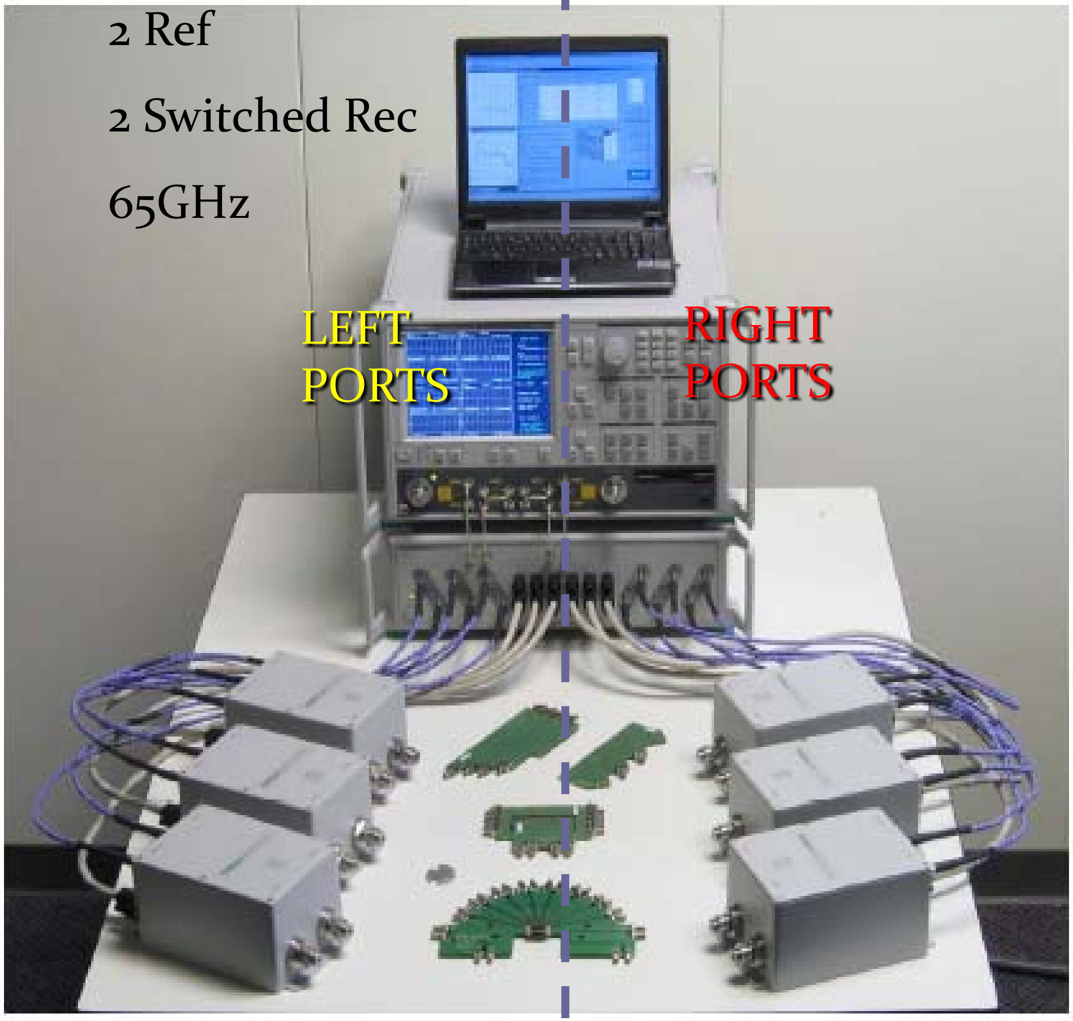
Coupling between pairs

Measurement Matrix

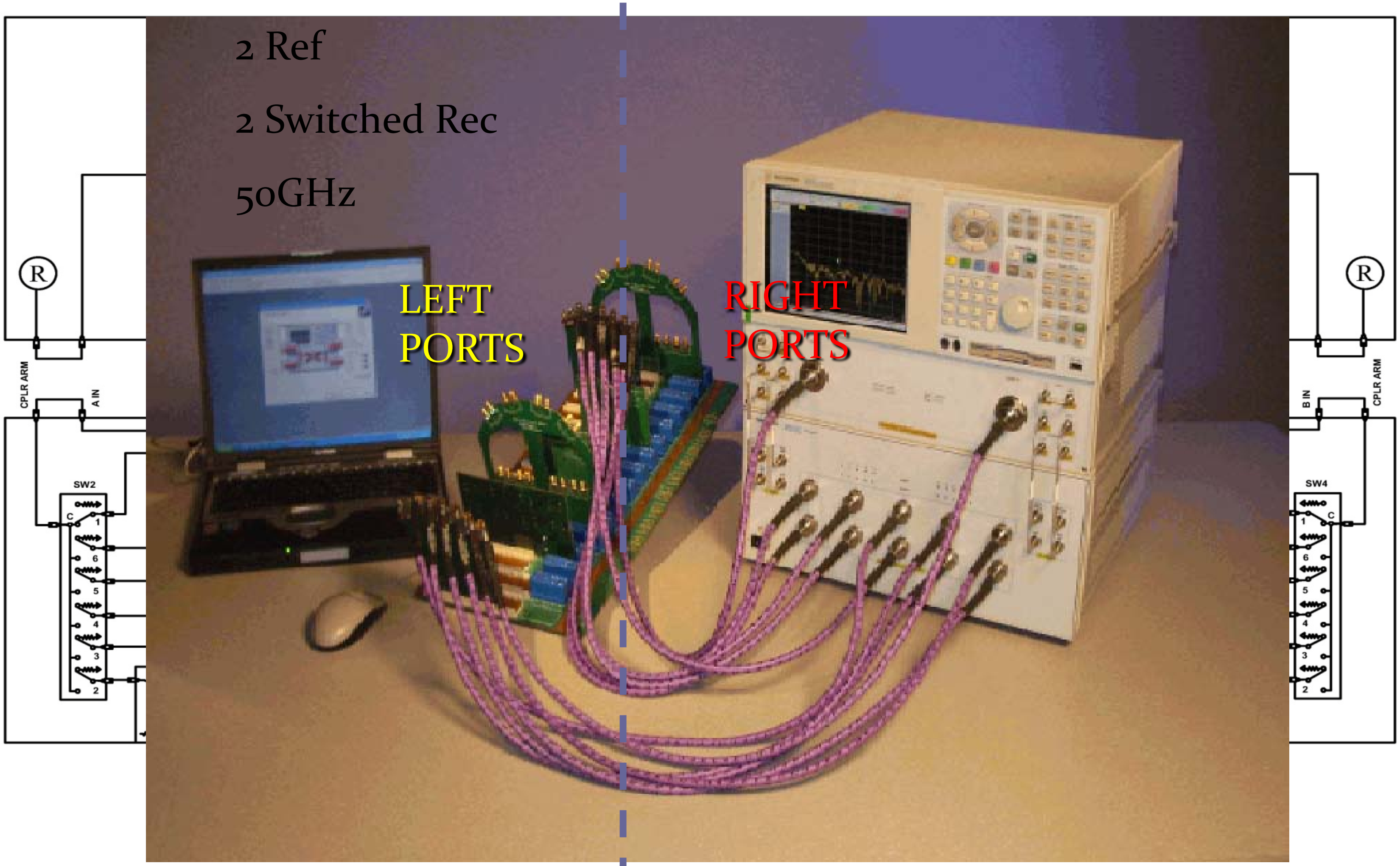


= data collected via measurement

12 ports



12 ports



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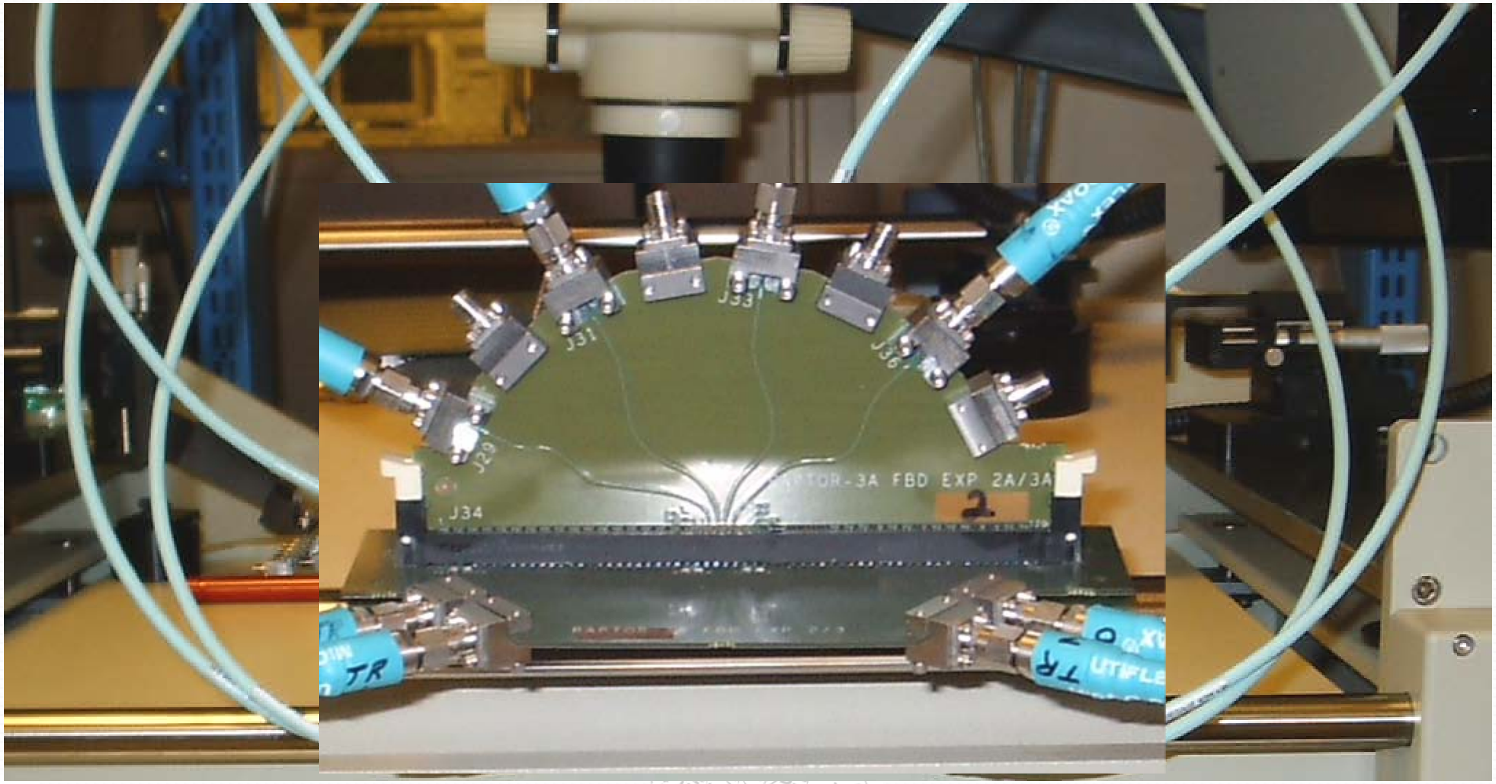
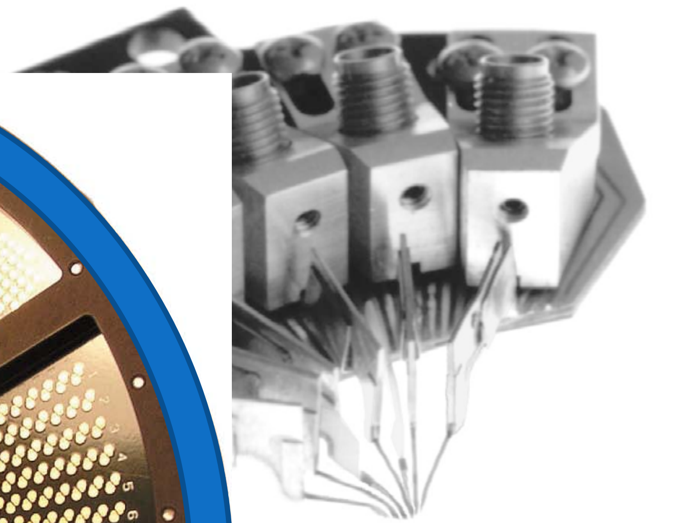
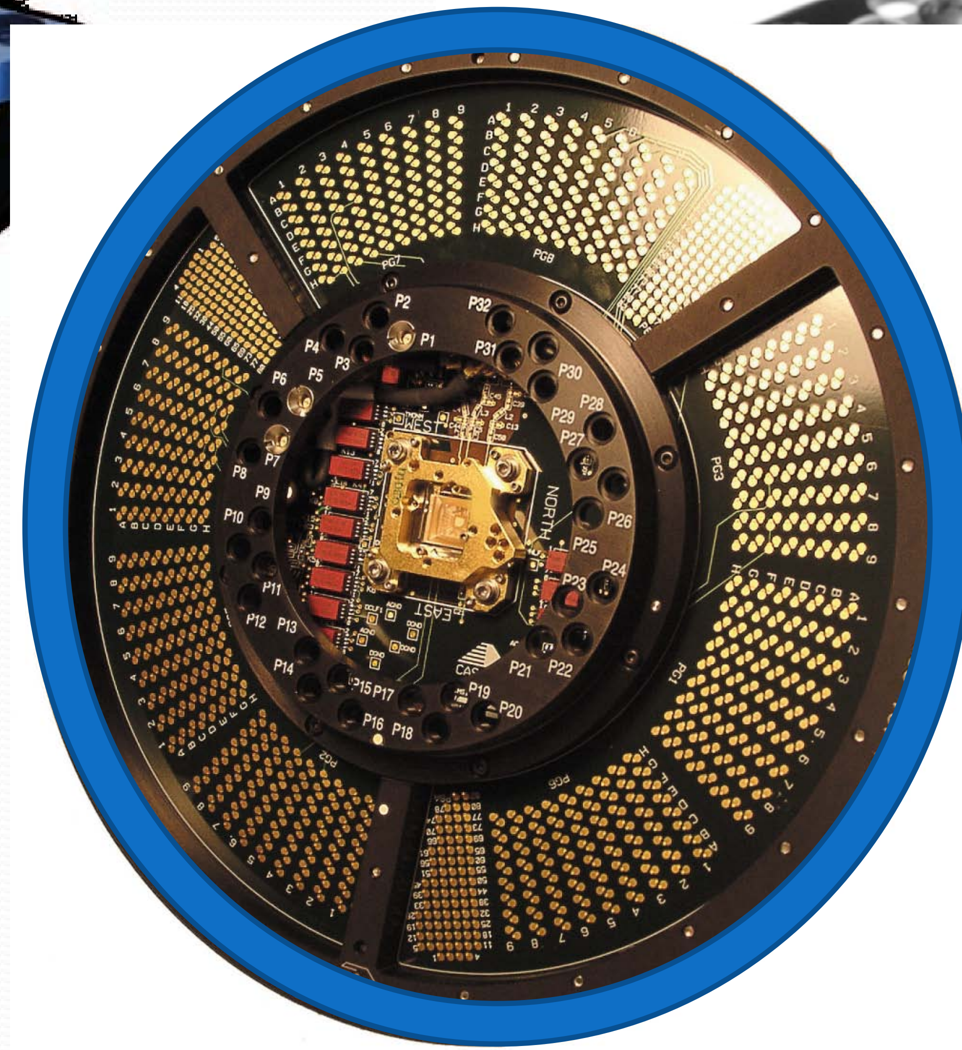
Interfacing

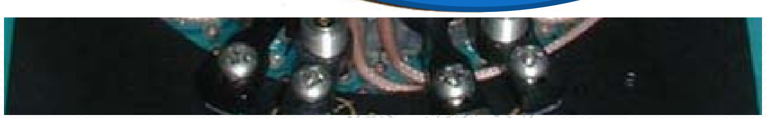
- Custom Fixtures



On Wafer







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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 repeatibility
   3. Non linearity of mixer/sampler
   4. ADC Dynamic Range & Speed
5. Interfacing effect

ACCURACY???

QUESTIONS UP TO NOW

Cause of Uncertainty

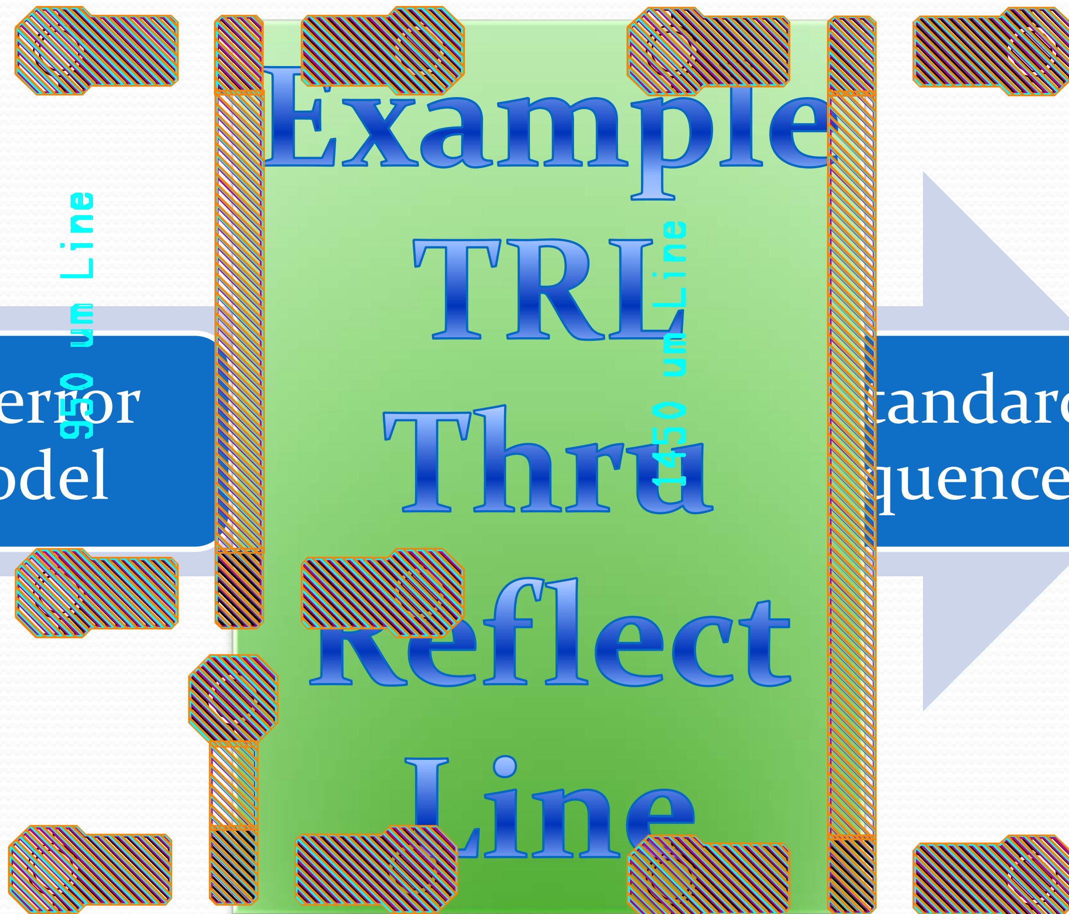
- Systematic Errors (85%)
  - Microwave Components
  - Interconnections
  - Incorrect Standard Modeling
  - Calibration Algorithm
- Random Error (10%)
  - Connection Repeatibility
  - Frequency Stability
  - Noise
- Drift (5%)

Calibration

Lab Care

Today 2-ports Calibrations

An error model



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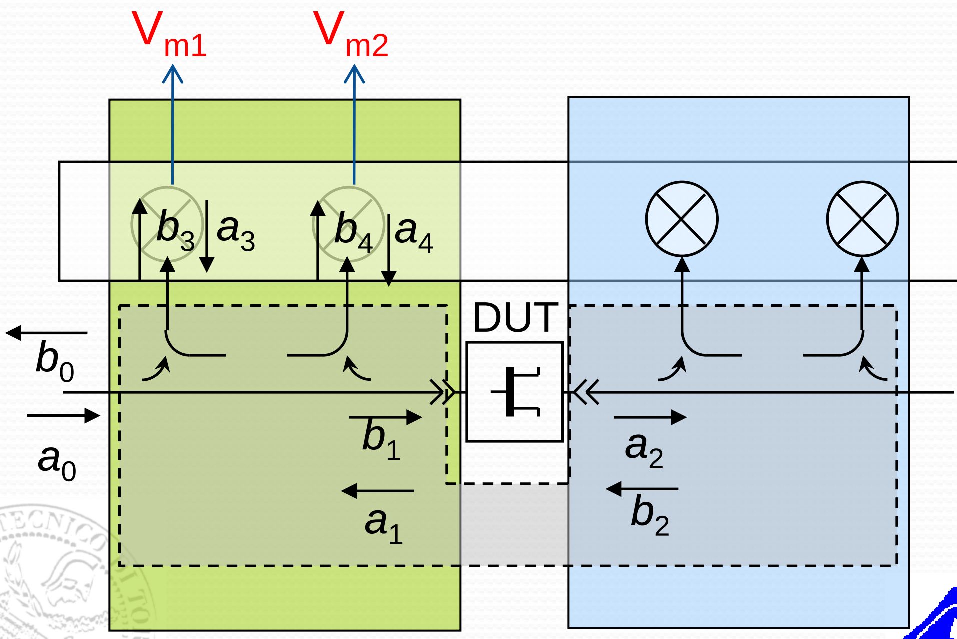
Error Model Definition I

- Ipothesis
  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 :
- $V_{m1}=k_1 b_3$, $V_{m2}=k_2 b_4$

Error Model Definition II

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

⟺ 4 port equation

$$a_3 = \Gamma_3 b_3 \qquad V_{m1} = k_3 b_3$$
$$a_4 = \Gamma_4 b_4 \qquad V_{m2} = k_4 b_4$$

⟺ 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:

$a_{m1} = V_{m1}$, $b_{m1} = V_{m2}$, $a_1 = a_{1DUT}$ e $b_1 = b_{1DUT}$ we find the following model

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Error Model Definition III

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

$$a_3 = \Gamma_3 b_3$$
$$a_4 = \Gamma_4 b_4$$

$$\begin{aligned} b_0 &= S_{11}a_0 + S_{12}a_1 + S_{13}a_3 + S_{14}a_4 \\ b_1 &= S_{21}a_0 + \dots. \\ b_3 &= S_{31}a_0 + \dots. \\ b_4 &= S_{41}a_0 + \dots. + S_{44}a_4 \end{aligned}$$

$$\begin{aligned} b_0 &= S_{11}a_0 + S_{12}a_1 + S_{13}\Gamma_3 b_3 + S_{14}\Gamma_4 b_4 \\ b_1 &= S_{21}a_0 + \dots. + S_{23}\Gamma_3 b_3 + S_{24}\Gamma_4 b_4 \\ b_3 &= S_{31}a_0 + \dots. + S_{33}\Gamma_3 b_3 + S_{34}\Gamma_4 b_4 \\ b_4 &= S_{41}a_0 + \dots. + S_{43}\Gamma_3 b_3 + S_{44}\Gamma_4 b_4 \end{aligned}$$

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Error Model Definition IV

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

$$\Downarrow$$

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

$$\Downarrow$$

$$
\mathbf{W}\begin{bmatrix} a_0 \\ b_0 \\ a_1 \\ b_1 \end{bmatrix} = \mathbf{Q}\begin{bmatrix} b_3 \\ b_4 \end{bmatrix}
$$

If we call a_{m1} and b_{m1}

$$
\begin{aligned}
V_{m1} &= a_{m1} = k_3 b_3 \\
V_{m2} &= b_{m1} = k_4 b_4
\end{aligned}
$$

$$
\begin{bmatrix} a_{m1} \\ b_{m1} \end{bmatrix} = \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix} \begin{bmatrix} b_3 \\ b_4 \end{bmatrix}
$$

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The famous error box

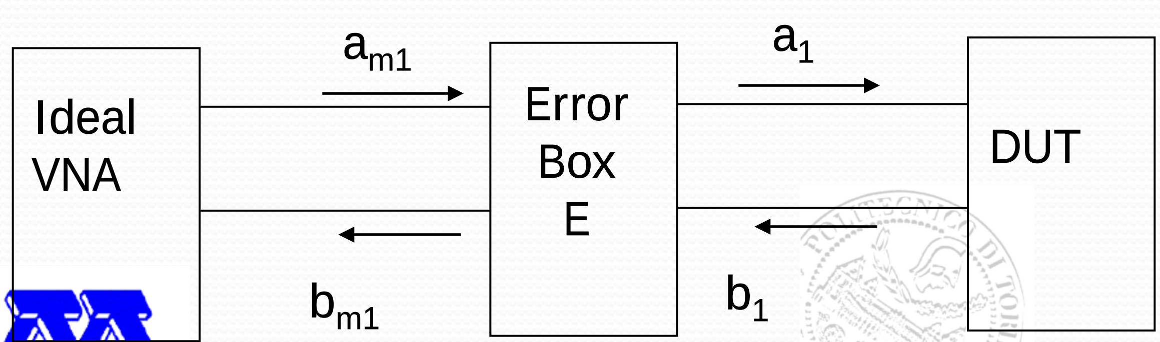
$$\mathbf{W}\begin{bmatrix} a_0 \\ b_0 \\ a_1 \\ b_1 \end{bmatrix} = \mathbf{Q}\begin{bmatrix} b_3 \\ b_4 \end{bmatrix} \qquad \begin{bmatrix} a_{m1} \\ b_{m1} \end{bmatrix} = \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix}\begin{bmatrix} b_3 \\ b_4 \end{bmatrix} = \mathbf{K}\begin{bmatrix} b_3 \\ b_4 \end{bmatrix}$$

$$\begin{bmatrix} a_0 \\ b_0 \\ a_1 \\ b_1 \end{bmatrix} = \mathbf{W}^{-1}\mathbf{Q}\mathbf{K}^{-1}\begin{bmatrix} a_{m1} \\ b_{m1} \end{bmatrix} = \mathbf{D}\begin{bmatrix} a_{m1} \\ b_{m1} \end{bmatrix}$$

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

Shuffle the last 2 Equations and rename as

$$\begin{aligned} b_{m1} &= e_{11}a_{m1} + e_{12}b_1 \\ a_1 &= e_{21}a_{m1} + e_{22}b_1 \end{aligned}$$



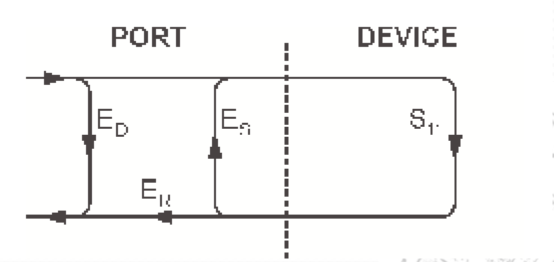
Error Box Property

- 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:

$$e_{11} = E_D \qquad \cong \qquad Directivity$$

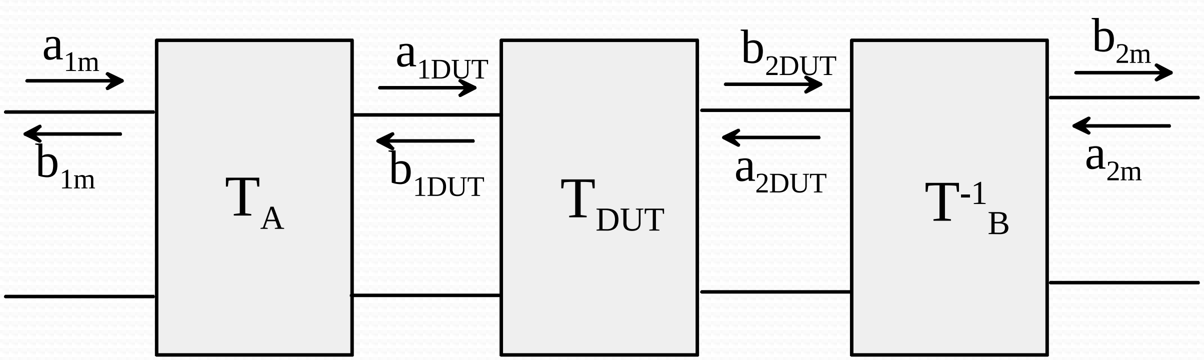
$$e_{22} = E_S \qquad \cong \qquad SourceMatch$$

$$e_{21}e_{12} = E_R \qquad \cong \qquad Tracking$$



Two Port Error Model

Two error boxes on the right and left



To apply this model, 4 independent readings on each source position are required

2-ports Measured S-matrix

$$\begin{bmatrix} b_{m1} \\ b_{m2} \end{bmatrix} = \mathbf{Sm} \begin{bmatrix} a_{m1} \\ a_{m2} \end{bmatrix}$$

$$\cancel{Sm_{ij} = \left.\frac{b_{mi}}{a_{mj}}\right|_{a_{mi \neq j}=0}}$$

NOT POSSIBLE

$$\begin{bmatrix} b'_{1m} \\ b'_{2m} \end{bmatrix} = \begin{pmatrix} S_{11m} & S_{12m} \\ S_{21m} & S_{22m} \end{pmatrix} \begin{bmatrix} a'_{1m} \\ a'_{2m} \end{bmatrix}, \quad \begin{bmatrix} b''_{1m} \\ b''_{2m} \end{bmatrix} = \begin{pmatrix} S_{11m} & S_{12m} \\ S_{21m} & S_{22m} \end{pmatrix} \begin{bmatrix} a''_{1m} \\ a''_{2m} \end{bmatrix}$$

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

FULL 2-Ports Error Model

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

8 error terms, but

7 UNKNOWS TO GET Tdut

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

T_A, T_B are the transmission matrix equivalent of the two E matrices of left and right side while Tm is the transmission matrix equivalent of S_m

$$\begin{bmatrix} b_{m1} \\ a_{m1} \end{bmatrix} = \mathbf{Tm} \begin{bmatrix} a_{m2} \\ b_{m2} \end{bmatrix} \Rightarrow \boxed{\begin{bmatrix} b_{1m} \\ a_{1m} \end{bmatrix} = T_A T_{DUT} T_B^{-1} \begin{bmatrix} a_{2m} \\ b_{2m} \end{bmatrix}}$$

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

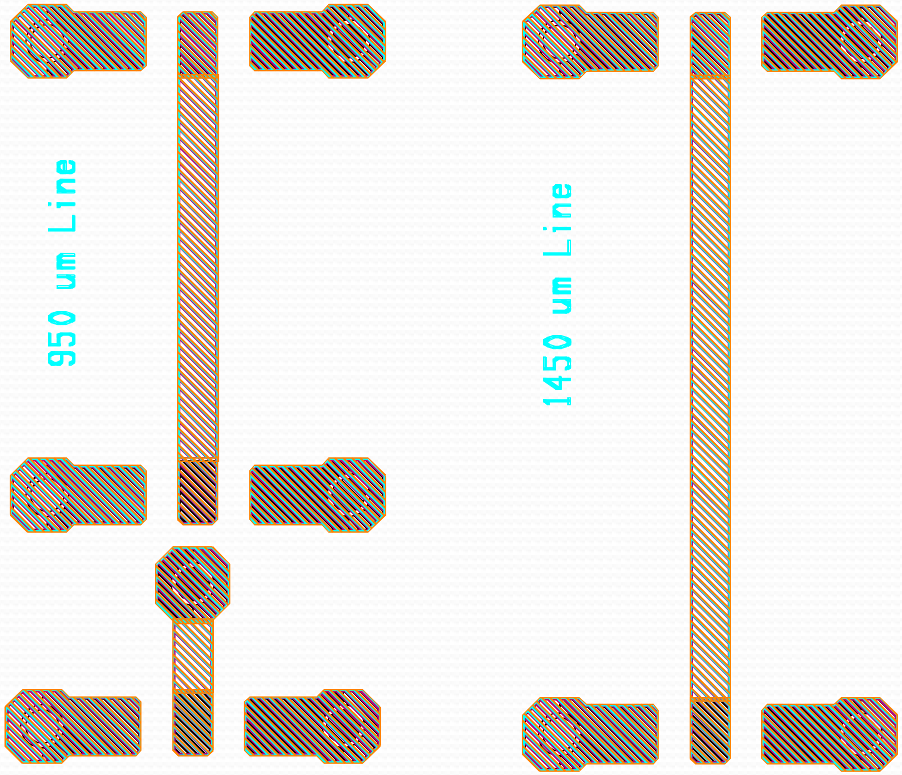
- The old good cal: **S**hort, **O**pen, **L**oad and **T**hru
- It measures 3 standards at port 1, 3 at port 2 and the THRU.
- It obviously overdetermed with the 8 port model (10 equations for 8 unknows)but it's the proper choice for the 3-sampler architecture

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

TSD-TRL II

- The length diff from the THRU and the LINE should avoid λ/2 and its multiple
- To have broadband TRL more line are usefull (different line lenght)
- Side Result: The propagation constant of the line comes from free



TSD-TRL III :MATH

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

Transmission matrix of the Line with Zref=$Z_{\text{¥}}$

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

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

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

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

T_{Lm} e T_{Tm} Measure Transmission Line of Line and Thru

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TSD-TRL IV : MATH

$$R_m = T_{Lm} T_{Tm}^{-1} = T_A T_L T_T^{-1} T_A^{-1} = T_A \Lambda T_A^{-1}$$ R_m : from measurement

$$R_n = T_{Tm}^{-1} T_{Lm} = T_B T_T^{-1} T_L T_B^{-1} = T_B \Lambda T_B^{-1}$$ R_n : from measurement

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

$\downarrow$

L Diagonal Matrix

T_A Eingenvector matrix of R_m, T_B Eingenvector matrix of R_n

TSD-TRL V:MATH

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

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

Deembedding:

$$T_{DUT} = {}^{p}\!/_{w}\, X_A T_m X_B^{-1} = \alpha X_A T_m X_B^{-1}$$

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})

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

$$\Gamma_{Sm2} = \frac{f + \frac{u}{w} g\Gamma_s}{1 + \frac{u}{w}} \Rightarrow \frac{u}{w} = \frac{f - \Gamma_{Sm2}}{\left(\Gamma_S - g\right)\Gamma_{Sm2}}$$

TSD II

3. Once *k/p e u/w are known, from the measurment of* Thru S_{21m} we finally find a:

$$\alpha = \frac{(g - f)\dfrac{u}{w}}{S_{21m}(1 - \dfrac{k}{p}\dfrac{u}{w})}$$

TRL

1. The one port standard is unknown Γ_S
2. And measured at port 1 (Γ_{Sm1}) and 2 (Γ_{Sm2})
3. There are 3 unknowns:

$$\Gamma_s, \frac{k}{p}, \frac{u}{w}$$

And 3 equations:

$$\Gamma_{sm1} = \frac{b + \frac{k}{p} a \Gamma_s}{1 + \frac{k}{p}}, \quad \Gamma_{sm2} = \frac{f + \frac{u}{w} g \Gamma_s}{1 + \frac{u}{w}}, \quad \frac{T_{Tm12}}{T_{Tm22}} = S_{Tm11} = \frac{-\frac{k}{p} a \frac{u}{w} + b}{-\frac{k}{p}\frac{u}{w} + 1}$$

$$\Gamma_S^2 = \frac{\left(b - \Gamma_{Sm1}\right)\left(f - \Gamma_{Sm2}\right)\left(S_{11m} - a\right)}{\left(a - \Gamma_{Sm1}\right)\left(g - \Gamma_{Sm2}\right)\left(S_{11m} - a\right)}$$

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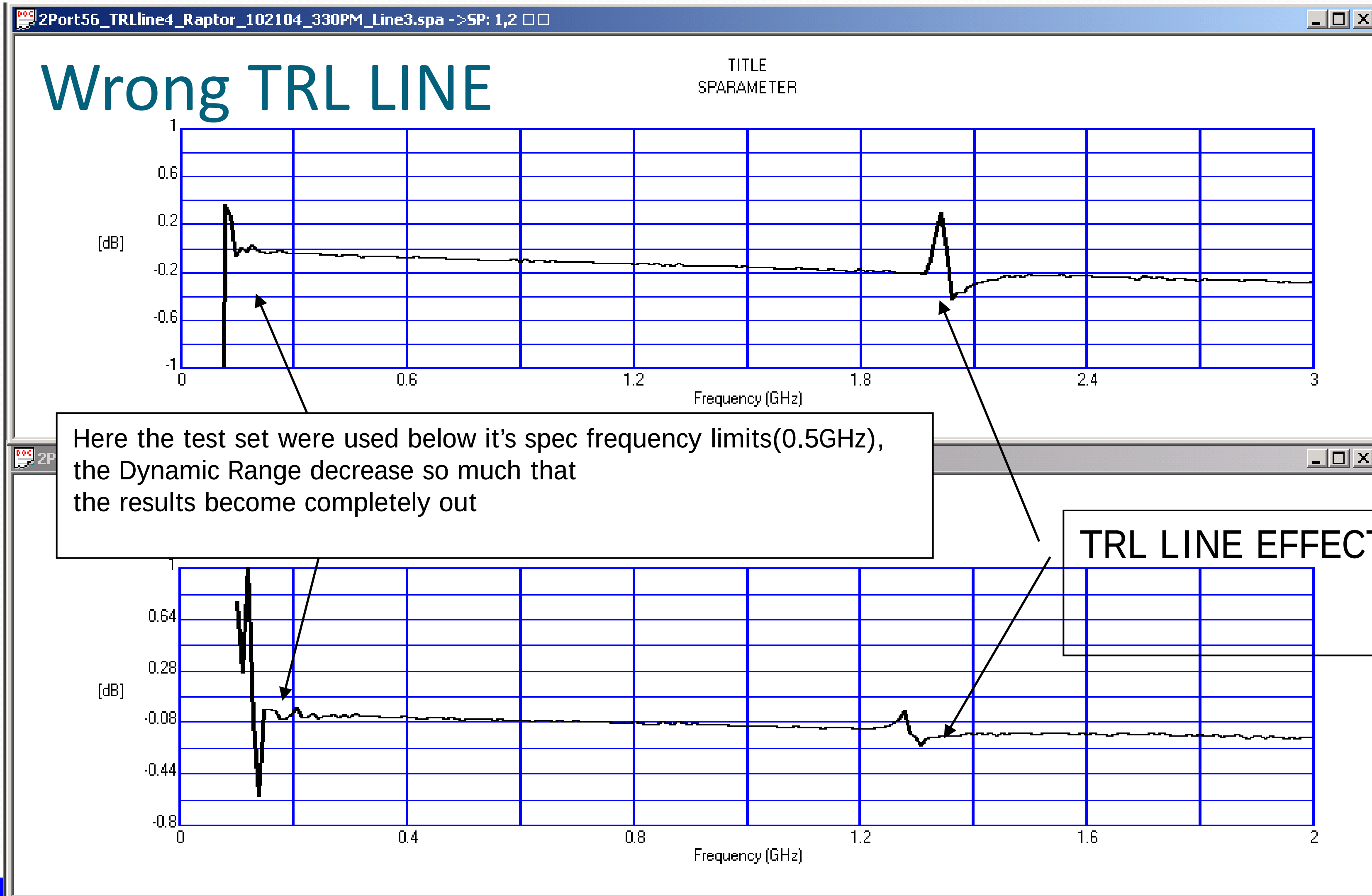
Summary of TRL-TSD

- Thru and Line have the same Zref=Z_∞ 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^o of phase difference
- IT REQUIRES TO MOVE THE PROBE LATERALLY

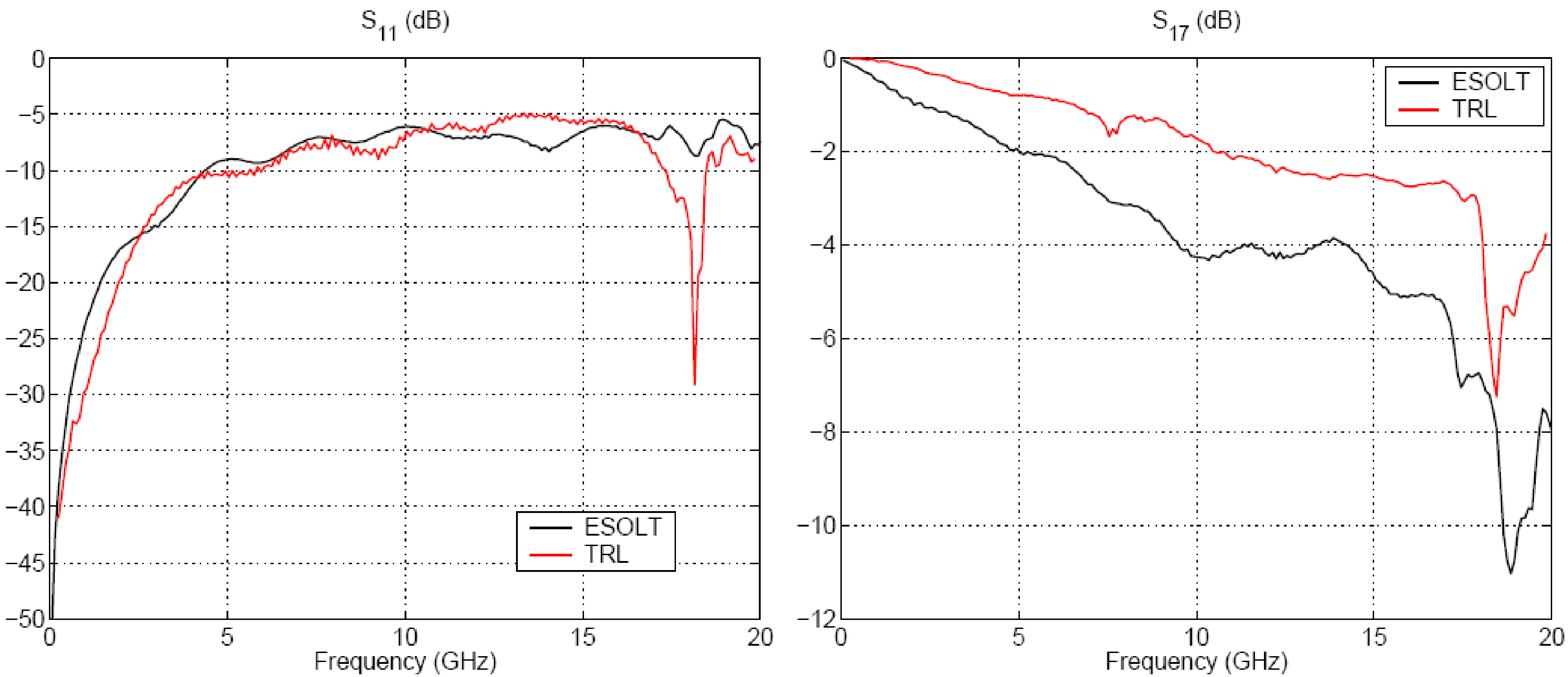
Wrong TRL LINE



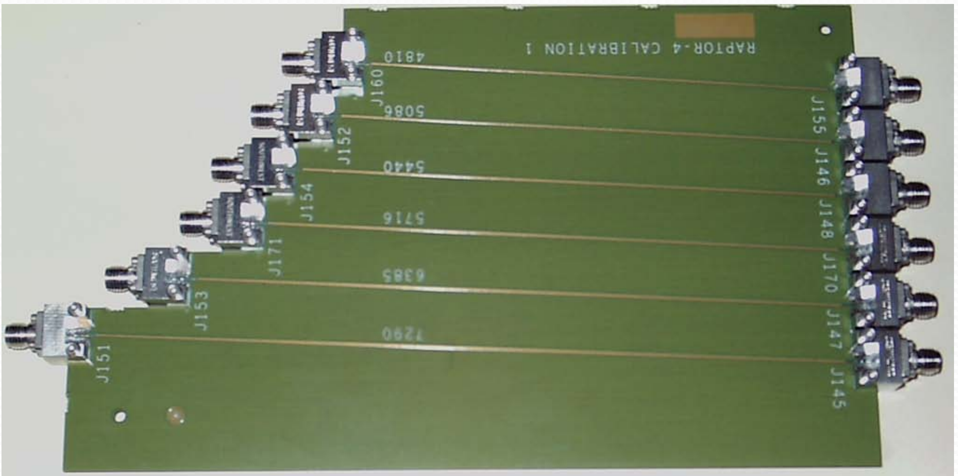
Here the test set were used below it's spec frequency limits(0.5GHz), the Dynamic Range decrease so much that the results become completely out

TRL LINE EFFECTS

Different Algorithms

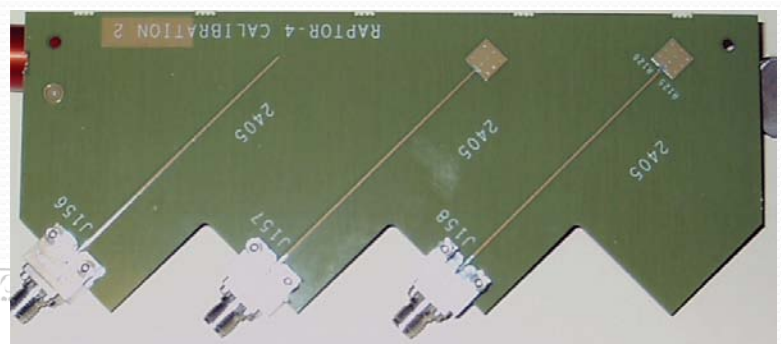


Coax TRL On-Board Calibration/Verification Structures

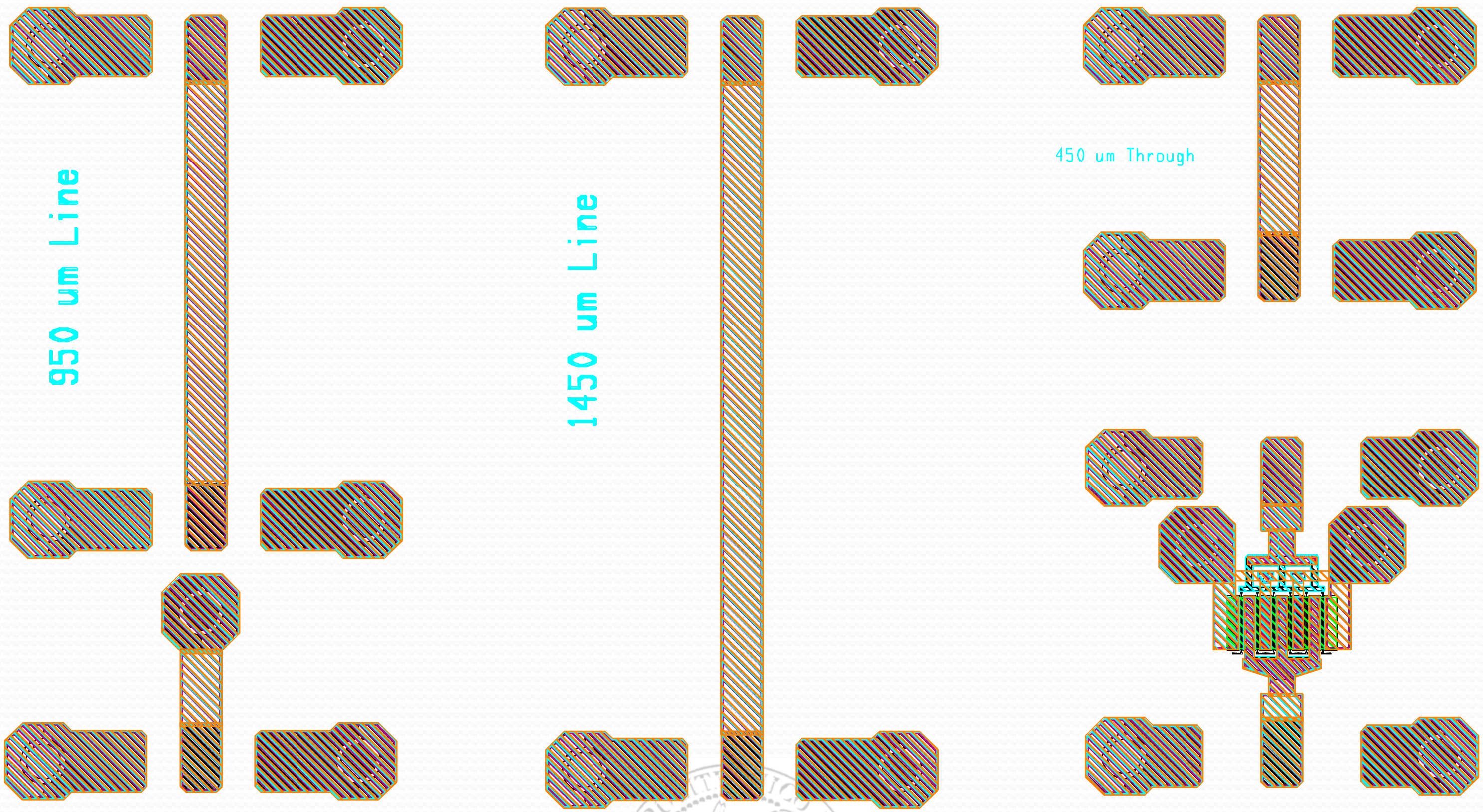


Thru and Line Structures

Reflect and Match Structures



On-wafer Standard



SOLR

- **S**hort, **O**pen, **L**oad 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

SOLR MATH I

- Let's take again X_a e X_b and $\Gamma_{sm1,2}$

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

$$\Gamma_{Sm1} = \frac{\frac{k}{p}a\Gamma_S + b}{1 + \frac{k}{p}\Gamma_S}, \quad \Gamma_{Sm2} = \frac{\frac{u}{w}g\Gamma_S + f}{1 + \frac{u}{w}\Gamma_S}$$

SOLR II

- With 3 fully known loads at port 1 we get:

$$a\,{}^{k}\!/_{p}\,,\ {}^{k}\!/_{p}\,,\ b$$

Thus X_a is now known

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

$$f\,{}^{u}\!/_{w}\,,\ {}^{u}\!/_{w}\,,\ g$$

Thus even X_b is now fully know what is left is

$$\alpha = \frac{p}{w}$$

SOLR III

$$\mathbf{T}_m = \frac{p}{w}\mathbf{X}_a\mathbf{T}_{dut}(\mathbf{X}_b)^{-1} = \alpha\mathbf{X}_a\mathbf{T}_{dut}(\mathbf{X}_b)^{-1}$$

$$\det(\mathbf{T}_m) = \alpha^2 \frac{\det(\mathbf{X}_a)\det(\mathbf{T}_{dut})}{\det(\mathbf{X}_b)}$$

$\det(T_{dut})= 1$
for the reciprocity

$$\boxed{\alpha = \pm\sqrt{\frac{\det(\mathbf{T}_m)\det(\mathbf{X}_b)}{\det(\mathbf{X}_a)}}}$$

- 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 !

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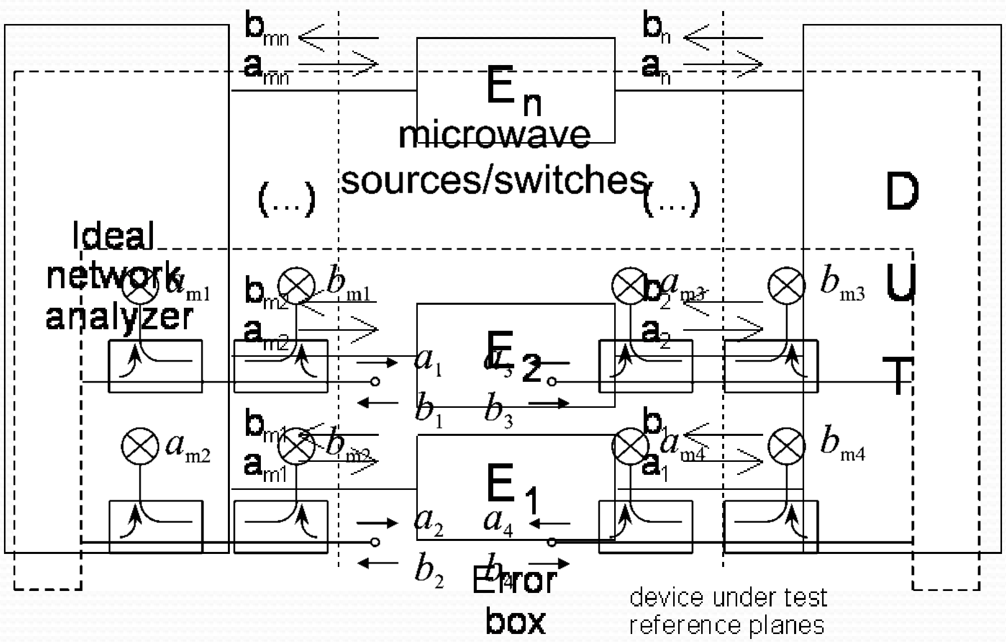
Classical multiport error model



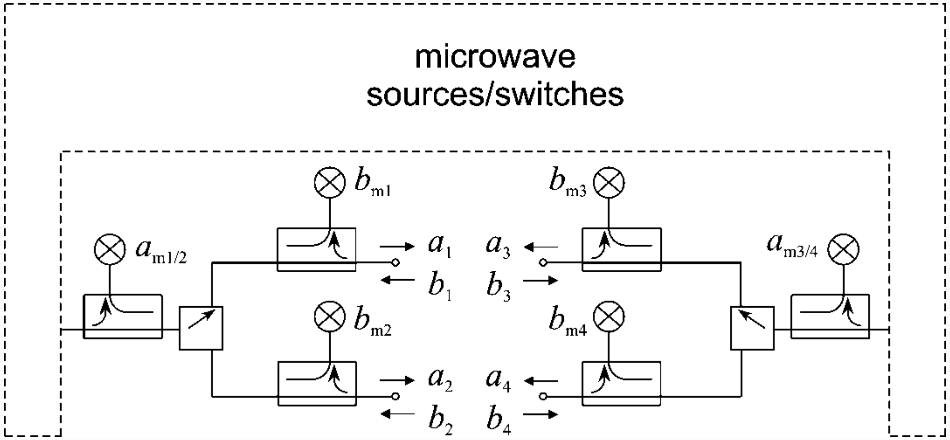
- Complete reflectometer multiport architecture: two directional couplers @ each port
- Error box extension as

$$a_i = l_i b_{mi} - h_i a_{mi} \qquad \boldsymbol{a} = \boldsymbol{L}\,\boldsymbol{b}_{\mathrm{m}} - \boldsymbol{H}\,\boldsymbol{a}_{\mathrm{m}}$$

$$b_i = k_i b_{mi} - m_i a_{mi} \qquad \boldsymbol{b} = \boldsymbol{K}\,\boldsymbol{b}_{\mathrm{m}} - \boldsymbol{M}\,\boldsymbol{a}_{\mathrm{m}}$$

$4n$ -1 unknowns

Partial Reflectometer error model

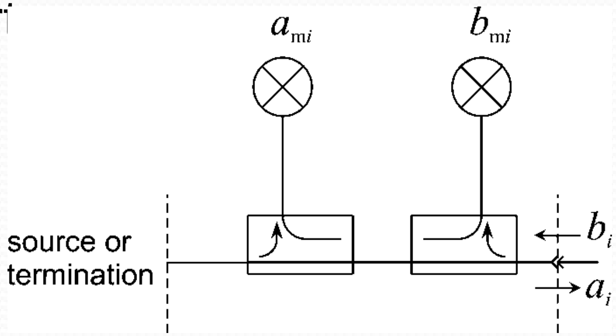


- Partial reflectometer multiport architecture: two directional couplers @ each port are not always available
- This architecture has the advantages of costs (n-2 couplers are saved) and speed

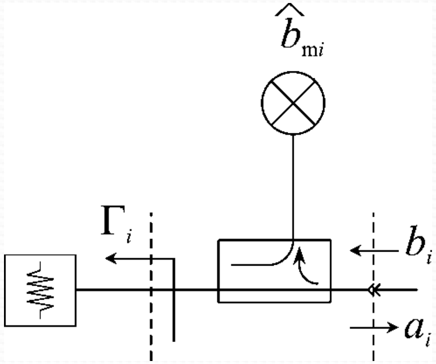
- The model for these case must be:
  - of general validity (i.e. not valid for only one calibration algorithm and scalable)
  - compatible with the complete reflectometer one
  - easy to be calibrated

The new formulation

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



STATE A



STATE B

$$\boldsymbol{a} = \begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{pmatrix}$$

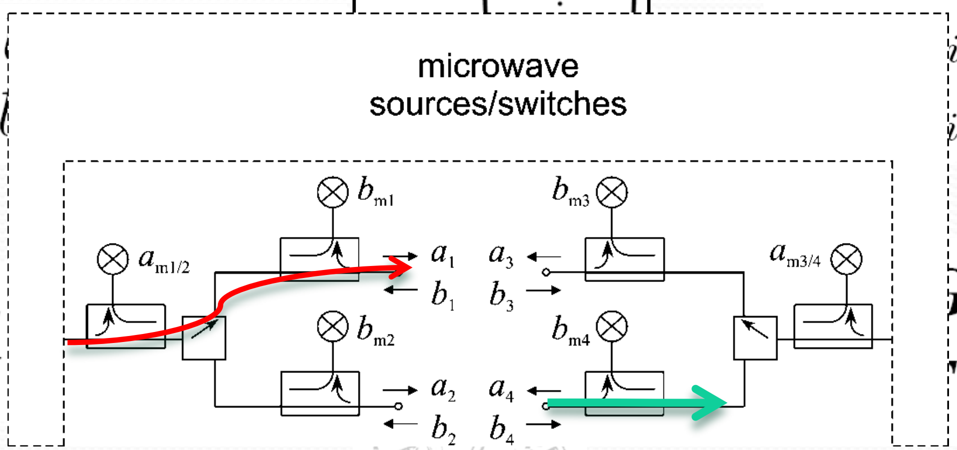
$$\boldsymbol{a}_{\mathrm{m}} = \begin{pmatrix} a_{\mathrm{m}1} \\ a_{\mathrm{m}2} \\ \vdots \end{pmatrix}$$

$a_i = l_i$ … $\widehat{b}_{\mathrm{m}i}$

$b_i = k_i$ … $\widehat{b}_{\mathrm{m}i}$

$\boldsymbol{a} = \boldsymbol{L}$ … $\widehat{\boldsymbol{b}}_{\mathrm{m}}$

$\boldsymbol{b} = \boldsymbol{K}$ … $\widehat{\boldsymbol{b}}_{\mathrm{m}}$



- 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.:

$$\begin{aligned} a_i &= l_i b_{\mathrm{m}i} - h_i a_{\mathrm{m}i} \\ b_i &= k_i b_{\mathrm{m}i} - m_i a_{\mathrm{m}i} \end{aligned} \quad = \quad \begin{aligned} a_i &= g_i \widehat{b}_{\mathrm{m}i} \\ b_i &= f_i \widehat{b}_{\mathrm{m}i} \end{aligned}$$

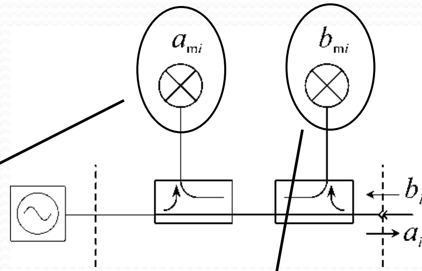
- All these equations can be written for each source position, and stacked together in matrix form:

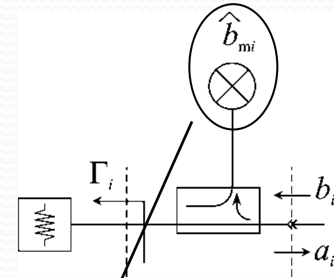
different source positions, n = number of ports

$$\boldsymbol{a}_1 = \begin{pmatrix} a'_1 \\ a'_2 \\ \vdots \\ a'_n \end{pmatrix} \quad \boldsymbol{a}_2 \ldots \boldsymbol{a}_n], \; \boldsymbol{B} = [\boldsymbol{b}_1\, \boldsymbol{b}_2 \ldots \boldsymbol{b}_n]$$

$$\boldsymbol{A}_{\mathrm{m}} = [\boldsymbol{a}_{\mathrm{m}1}\, \boldsymbol{a}_{\mathrm{m}2} \ldots \boldsymbol{a}_{\mathrm{m}n}], \; \boldsymbol{B}_{\mathrm{m}} = [\boldsymbol{b}_{\mathrm{m}1}\, \boldsymbol{b}_{\mathrm{m}2} \ldots \boldsymbol{b}_{\mathrm{m}n}]$$

- Let:





$$\widetilde{\boldsymbol{A}}_{\mathrm{m}} \equiv \begin{bmatrix} a_{\mathrm{m}11} & 0 & \cdots & 0 \\ 0 & a_{\mathrm{m}22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & a_{\mathrm{m}nn} \end{bmatrix} \quad \widetilde{\boldsymbol{B}}_{\mathrm{m}} \equiv \begin{bmatrix} b_{\mathrm{m}11} & 0 & \cdots & 0 \\ 0 & b_{\mathrm{m}22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & b_{\mathrm{m}nn} \end{bmatrix} \quad \widehat{\boldsymbol{B}}_{\mathrm{m}} \equiv \begin{bmatrix} 0 & \hat{b}_{\mathrm{m}12} & \hat{b}_{\mathrm{m}13} & \cdots & \hat{b}_{\mathrm{m}1n} \\ \hat{b}_{\mathrm{m}21} & 0 & \hat{b}_{\mathrm{m}23} & \cdots & \hat{b}_{\mathrm{m}2n} \\ \hat{b}_{\mathrm{m}31} & \hat{b}_{\mathrm{m}32} & 0 & \cdots & \hat{b}_{\mathrm{m}3n} \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ \hat{b}_{\mathrm{m}n1} & \hat{b}_{\mathrm{m}n2} & \cdots & \hat{b}_{\mathrm{m}nn-1} & 0 \end{bmatrix}$$

- As well as:

$$\boldsymbol{A} = \widetilde{\boldsymbol{A}} + \widehat{\boldsymbol{A}} \qquad \boldsymbol{B} = \widetilde{\boldsymbol{B}} + \widehat{\boldsymbol{B}}$$

$$\widetilde{\boldsymbol{A}} \equiv \begin{bmatrix} a_{11} & 0 & \cdots & 0 \\ 0 & a_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & a_{nn} \end{bmatrix} \quad \widehat{\boldsymbol{A}} \equiv \begin{bmatrix} 0 & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & 0 & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & 0 & \cdots & a_{3n} \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn-1} & 0 \end{bmatrix}$$

- **Since** for each source position at each port we may have:

$$a_i = l_i b_{mi} - h_i a_{mi}$$
$$b_i = k_i b_{mi} - m_i a_{mi}$$

$$\widetilde{\boldsymbol{A}} = \boldsymbol{L}\widetilde{\boldsymbol{B}}_{\mathrm{m}} - \boldsymbol{H}\widetilde{\boldsymbol{A}}_{\mathrm{m}}$$
$$\widetilde{\boldsymbol{B}} = \boldsymbol{K}\widetilde{\boldsymbol{B}}_{\mathrm{m}} - \boldsymbol{M}\widetilde{\boldsymbol{A}}_{\mathrm{m}}$$

or

$$a_i = g_i \widehat{b}_{mi}$$
$$b_i = f_i \widehat{b}_{mi}$$

$$\widehat{\boldsymbol{A}} = \boldsymbol{G}\widehat{\boldsymbol{B}}_{\mathrm{m}}$$
$$\widehat{\boldsymbol{B}} = \boldsymbol{F}\widehat{\boldsymbol{B}}_{\mathrm{m}}$$

and

$$\boldsymbol{A} = \widetilde{\boldsymbol{A}} + \widehat{\boldsymbol{A}} \qquad \boldsymbol{B} = \widetilde{\boldsymbol{B}} + \widehat{\boldsymbol{B}}$$

$$\boldsymbol{A} = \widetilde{\boldsymbol{A}} + \widehat{\boldsymbol{A}} = \boldsymbol{L}\widetilde{\boldsymbol{B}}_{\mathrm{m}} - \boldsymbol{H}\widetilde{\boldsymbol{A}}_{\mathrm{m}} + \boldsymbol{G}\widehat{\boldsymbol{B}}_{\mathrm{m}}$$
$$\boldsymbol{B} = \widetilde{\boldsymbol{B}} + \widehat{\boldsymbol{B}} = \boldsymbol{K}\widetilde{\boldsymbol{B}}_{\mathrm{m}} - \boldsymbol{M}\widetilde{\boldsymbol{A}}_{\mathrm{m}} + \boldsymbol{F}\widehat{\boldsymbol{B}}_{\mathrm{m}}$$

$$\boldsymbol{B} = \boldsymbol{K}\widetilde{\boldsymbol{B}}_{\mathrm{m}} - \boldsymbol{M}\widetilde{\boldsymbol{A}}_{\mathrm{m}} + \boldsymbol{F}\widehat{\boldsymbol{B}}_{\mathrm{m}} \qquad \boldsymbol{A} = \boldsymbol{L}\widetilde{\boldsymbol{B}}_{\mathrm{m}} - \boldsymbol{H}\widetilde{\boldsymbol{A}}_{\mathrm{m}} + \boldsymbol{G}\widehat{\boldsymbol{B}}_{\mathrm{m}}$$

$$\boldsymbol{B} = \boldsymbol{S}\boldsymbol{A}$$

$$\boxed{-\boldsymbol{S}\boldsymbol{G}\widehat{\boldsymbol{B}}_{\mathrm{m}} + \boldsymbol{F}\widehat{\boldsymbol{B}}_{\mathrm{m}} - \boldsymbol{S}\boldsymbol{L}\widetilde{\boldsymbol{B}}_{\mathrm{m}} + \boldsymbol{K}\widetilde{\boldsymbol{B}}_{\mathrm{m}} + \boldsymbol{S}\boldsymbol{H}\widetilde{\boldsymbol{A}}_{\mathrm{m}} - \boldsymbol{M}\widetilde{\boldsymbol{A}}_{\mathrm{m}} = \boldsymbol{0}}$$

6n -1 unknowns

- And the de-embedding is:

$$\boldsymbol{S} = \left[\boldsymbol{K}\widetilde{\boldsymbol{B}}_{\mathrm{m}} - \boldsymbol{M}\widetilde{\boldsymbol{A}}_{\mathrm{m}} + \boldsymbol{F}\widehat{\boldsymbol{B}}_{\mathrm{m}}\right]\left[\boldsymbol{L}\widetilde{\boldsymbol{B}}_{\mathrm{m}} - \boldsymbol{H}\widetilde{\boldsymbol{A}}_{\mathrm{m}} + \boldsymbol{G}\widehat{\boldsymbol{B}}_{\mathrm{m}}\right]^{-1}$$

"A Novel Calibration Algorithm for a Special Class of Multiport Vector Network Analyzers",Ferrero, A.; Teppati, V.; Garelli, M.; Neri, A.
IEEE Transactions on Microwave Theory and Techniques, Volume 56, Issue 3, March 2008

Let's look at the cal equation

$$-\boldsymbol{SG}\widehat{\boldsymbol{B}}_{\mathrm{m}}+\boldsymbol{F}\widehat{\boldsymbol{B}}_{\mathrm{m}}-\boldsymbol{SL}\widetilde{\boldsymbol{B}}_{\mathrm{m}}+\boldsymbol{K}\widetilde{\boldsymbol{B}}_{\mathrm{m}}+\boldsymbol{SH}\widetilde{\boldsymbol{A}}_{\mathrm{m}}-\boldsymbol{M}\widetilde{\boldsymbol{A}}_{\mathrm{m}}=\boldsymbol{0}$$

- 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

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Even a more

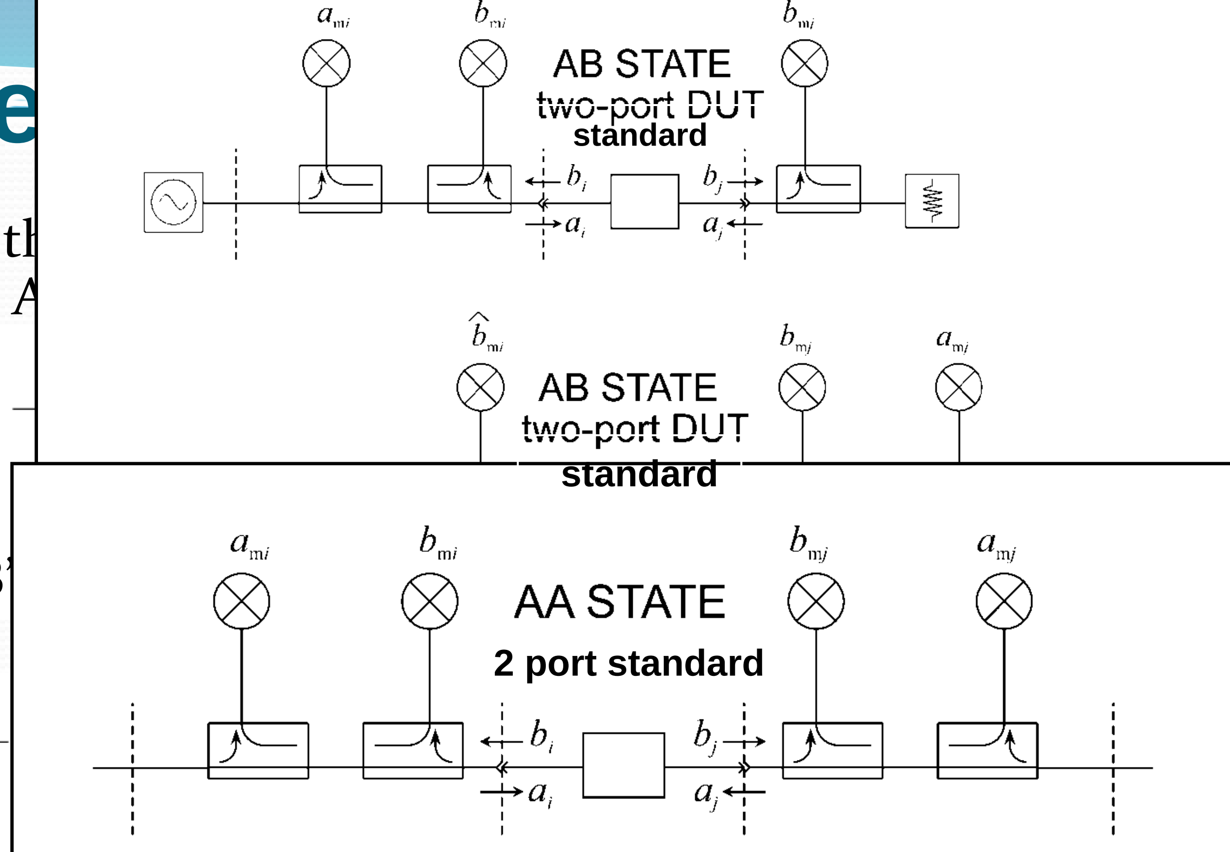
- For the calibration th
i.e. for an “all state A

$$\sum_{p=1}^{n} S_{ip} l_p b_{mpj} -$$

- and for a “state A-B”

$$-\sum_{p=1}^{n}(1 -$$

$$(i = 1, \dots, n)$$
$$(j = 1, \dots, n)$$



- during calibration, each standard measurement will give type A equations, or type B equations, accordingly to the measurement configuration used (AA or AB)

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Dynamic Calibration

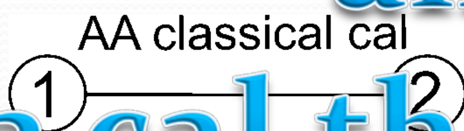
Since no constrains are given on the standard type and the math can combine whatever sequence, the calibration becomes *dynamic* i.e. the software can generate the standard sequence which gives a set of enough linear independent equations as well as it accomplished for:

- 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

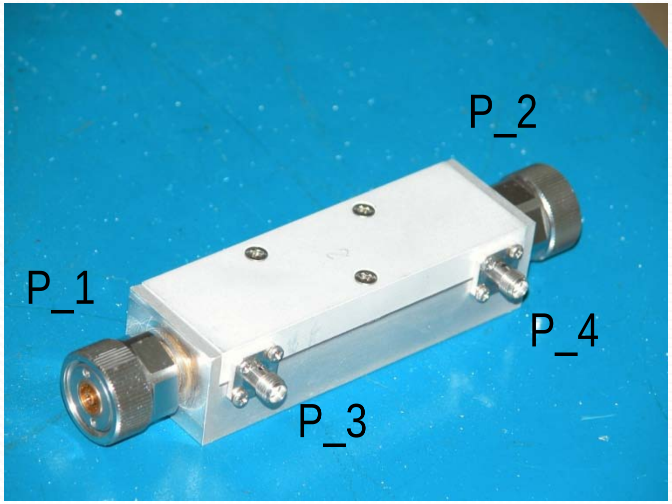
- **If two ports can go in state A contemporarily, classical SOLT, LRM, TRL, SOLR etc. algorithms can be applied to these ports because the new error model is compatible with the classical one!**

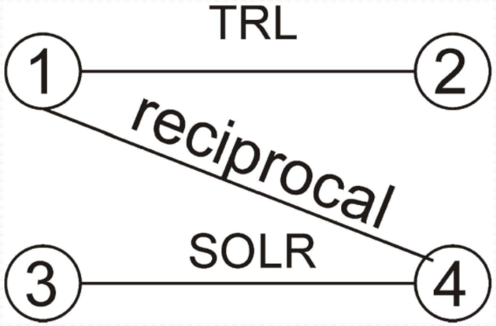
Let's combine everything and design a cal that fits the DUT



SO...

Example: Design CAL for the DUT





Connection Property

	P_1	P_2	P_3	P_4
P_1	X	TRL	X	Recip
P_2	TRL	X	X	X
P_3	X	X	SOL	Recip
P_4	Recip	X	Recip	SOL

Standard Sequence

Standard	Port	Port
APC7THRU	1	2
APC7-AirLine	1	2
APC7REFLECT	1	
APC7REFLECT	2	
3.5mm BroadBand Load-F	3	
3.5mm Female Open	3	
5mm Coaxial Female Short	3	
3.5mm BroadBand Load-F	4	
3.5mm Female Open	4	
5mm Coaxial Female Short	4	
APC7-3.5mmF	1	4
3.5mm F-F Adapter	3	4

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Cause of Uncertainty

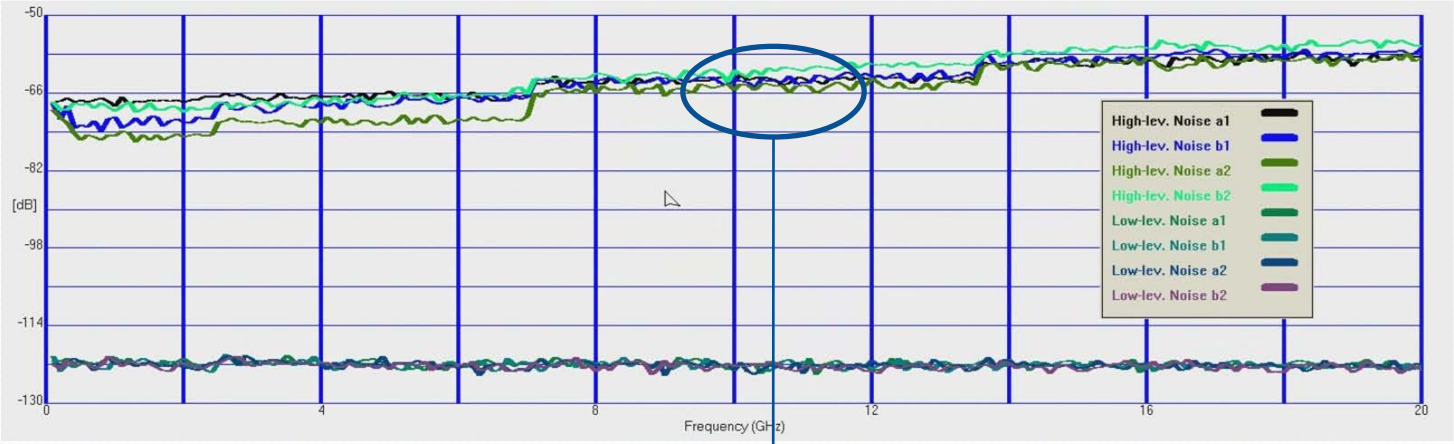
- Systematic Errors (85%)
  - Microwave Components
  - Interconnections
  - Incorrect Standard Modeling
  - Calibration Algorithm
- Random Error (10%)
  - Connection Repeatability
  - Frequency Stability
  - Noise
- Drift (5%)

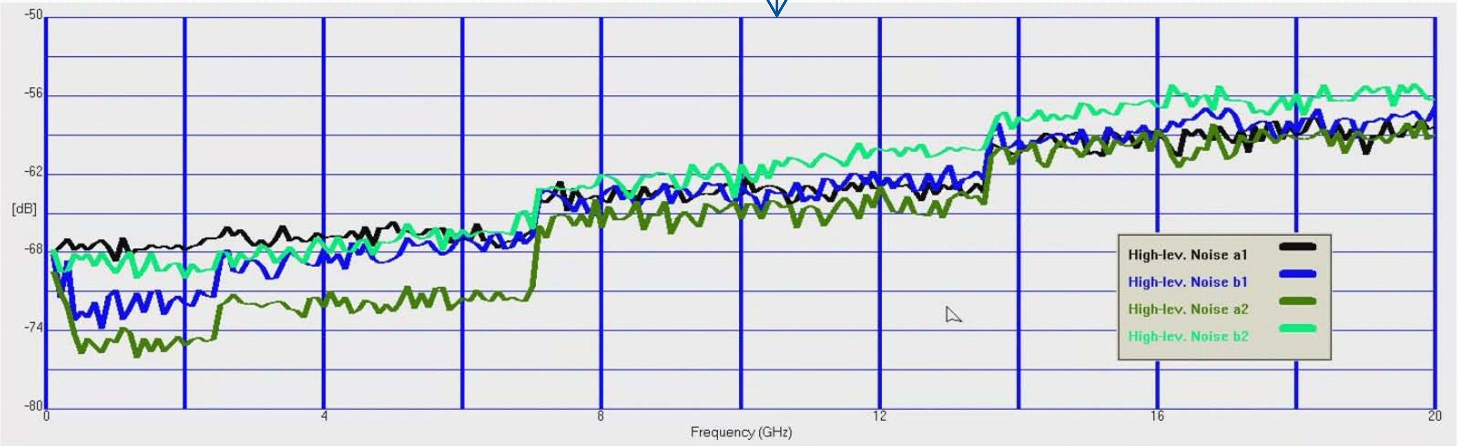
Calibration

Lab Care

VNA Noise

THE GOOD OLD 8510:RAW DATA NOISE





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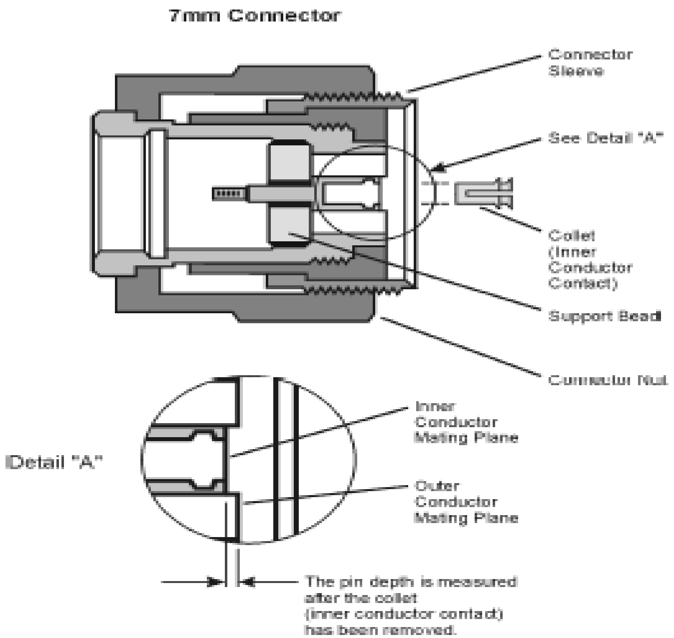
Repeatability an example:APC7mm



A close look to the connector

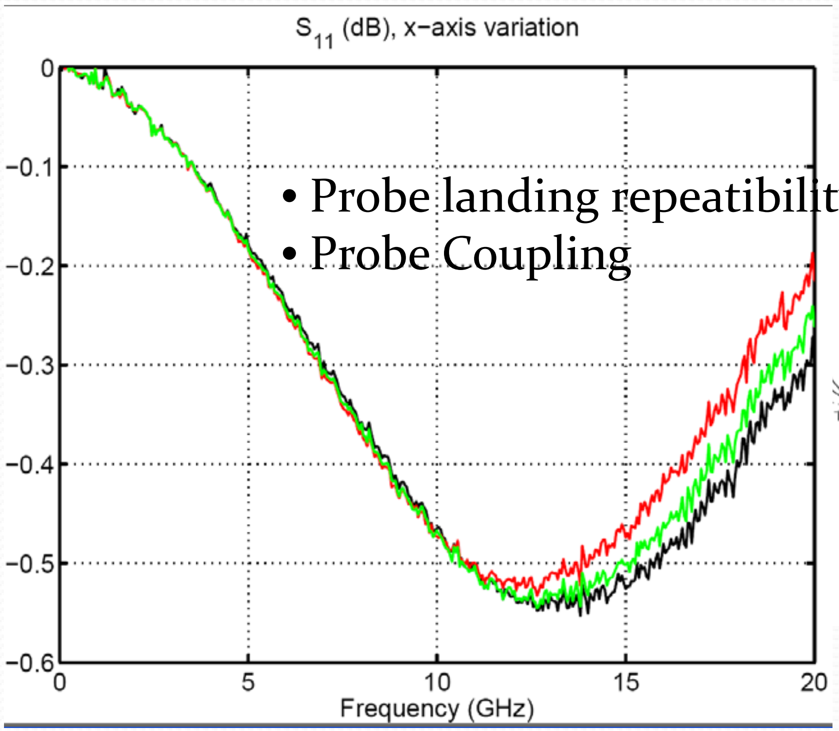
Device	Typical Pin Depth micrometers (10^{-4} inches)	Measurement Uncertainty[a] micrometers (10^{-4} inches)	Observed Pin Depth Limits[b] micrometers (10^{-4} inches)
Opens	0 to −12.7 (0 to −5.0)	+10.02 to −10.2 (+ 4.0 to −4.0)	+10.2 to −22.91 (+ 4.0 to −9.0)
Shorts	0 to −5.1 (0 to −2.0)	+6.4 to −6.4 (+ 2.5 to −2.5)	+6.4 to −11.4 (+ 2.5 to −4.5)
Broadband loads	0 to −7.62 (0 to −3.0)	+4.1 to −4.1 (+ 1.6 to −1.6)	+4.1 to −11.7 (+ 1.6 to −4.6)

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

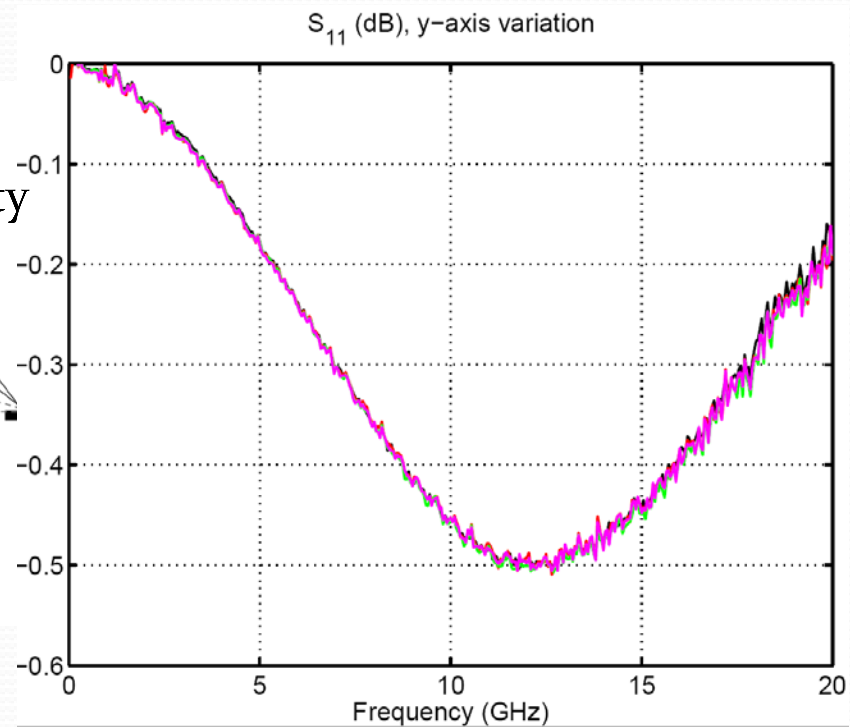
Device	Specification	Frequency (GHz)
Broadband loads	≥ 38 dB Return loss	dc to 18 GHz
Short[a] collet style	± 0.2° from nominal	dc to 2 GHz[b]
	± 0.3° from nominal	2 to 8 GHz[b]
	± 0.5° from nominal	8 to 18 GHz[b]
Open[a] with collet pusher	± 0.3° from nominal	dc to 2 GHz[b]
	± 0.4° from nominal	2 to 18 GHz[b]
	± 0.6° from nominal	8 to 18 GHz[b]

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 repeatibility
- Probe Coupling



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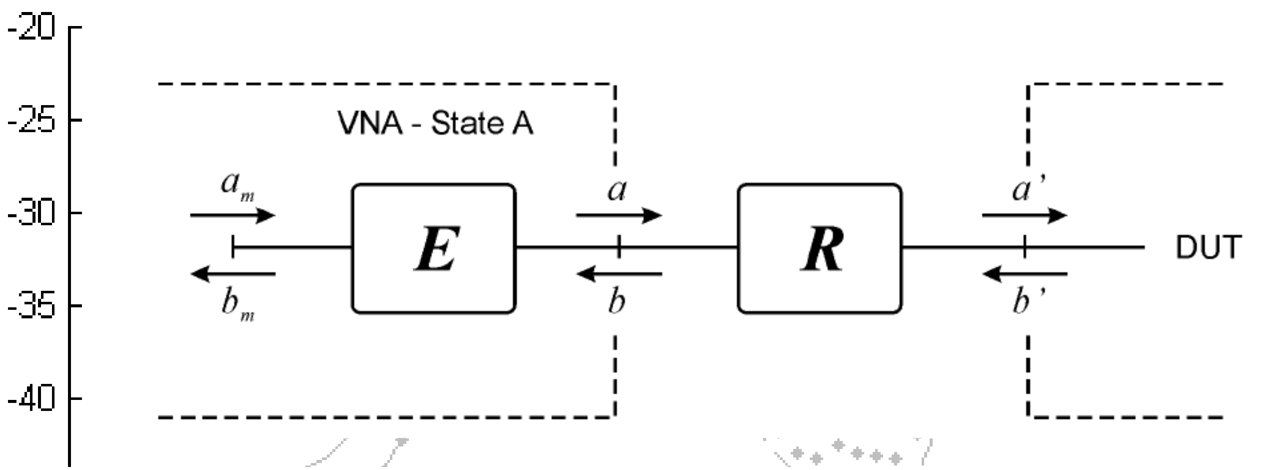
Repeatability Model



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 $\delta_{11} = \delta_{22} = \delta_R$)

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

-55
-60
-65
-70
0 5 10 15 20 25 30

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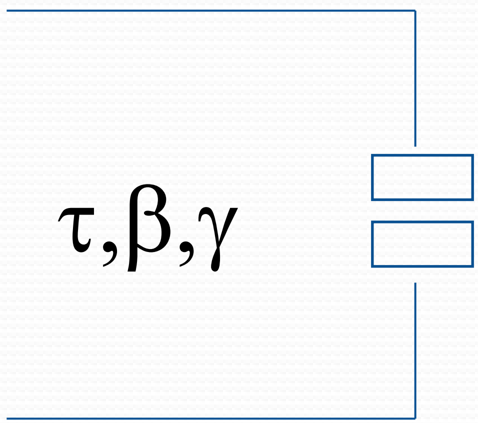
Standard Accuracy

- Standard Model
- Model Identification
- Parameter Accuracy

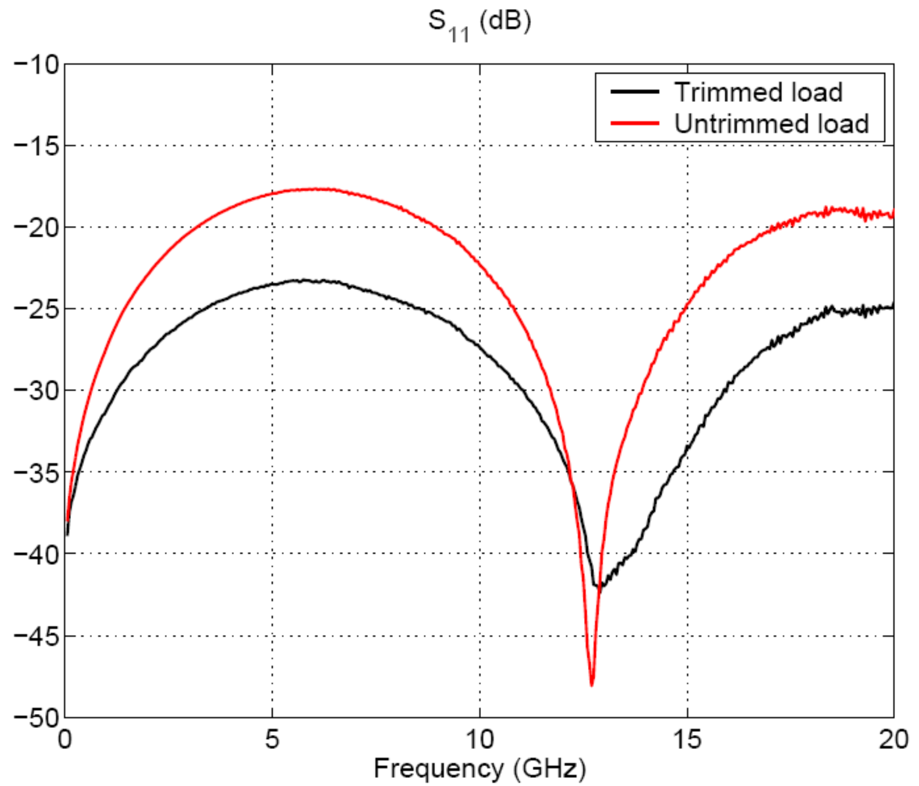
Standard Model



$$C = C_0 + C_1 f + C_2 f^2 + C_3 f^3$$

- How do we get Cj
- FEM Methods

Standard Model: 40ps line

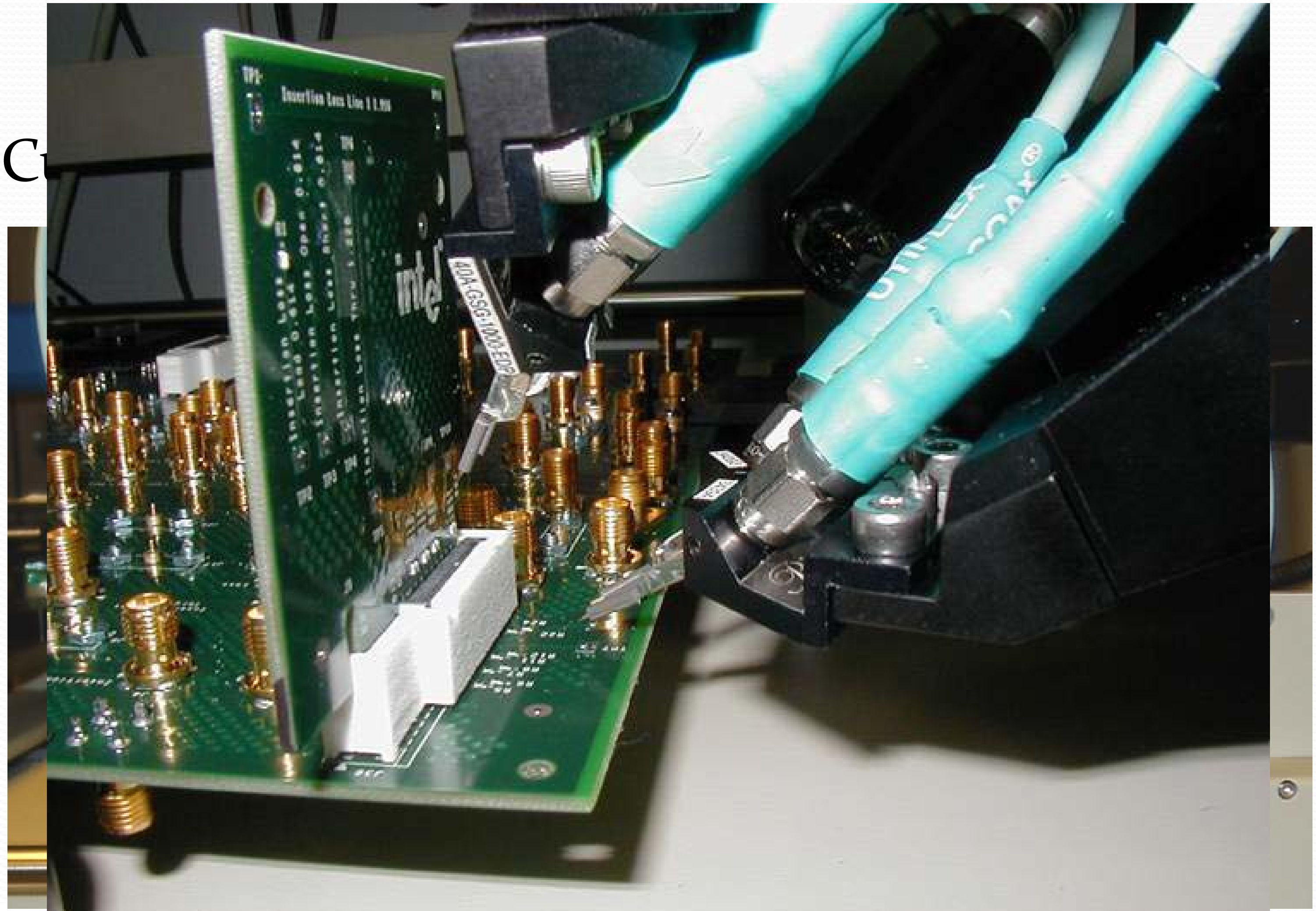


Let's put everything together

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

Interfacing

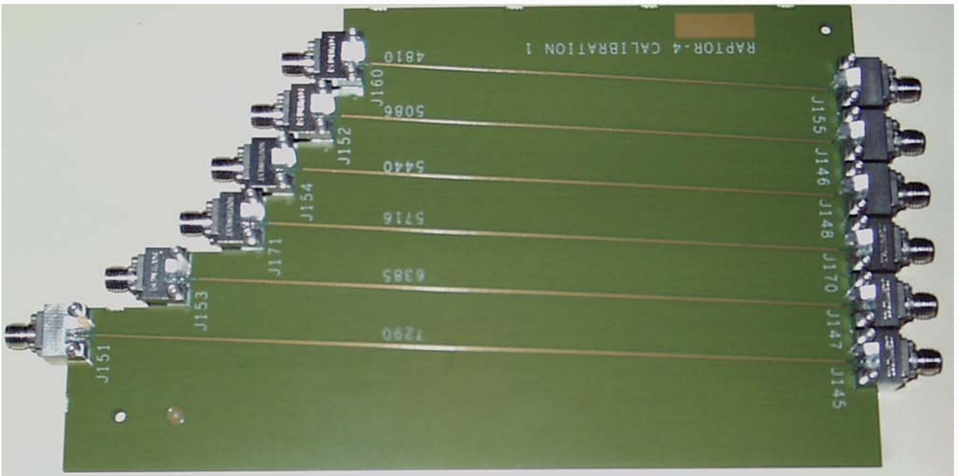
- C



Standard Design for Multiport Measurements

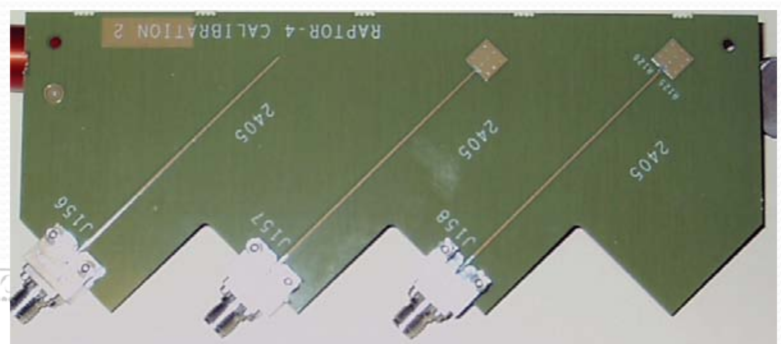
- Requirements:
  - Minimum Number of Connections
  - Easy to fabbricate
  - Calibration and Verification Elements

Coax On-Board Simple Calibration Structures



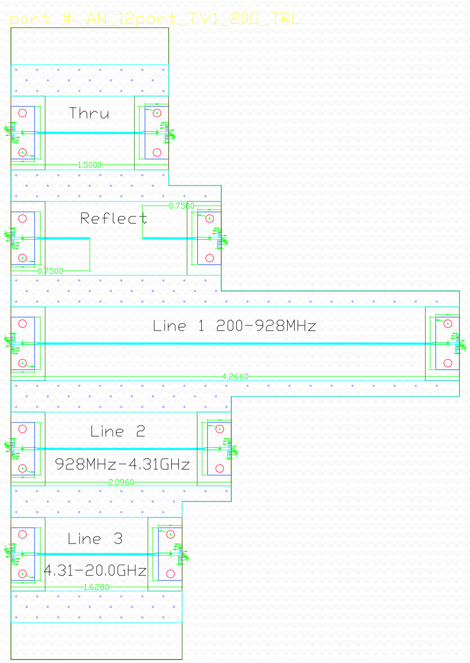
Thru and Line Structures

Reflect and Match Structures

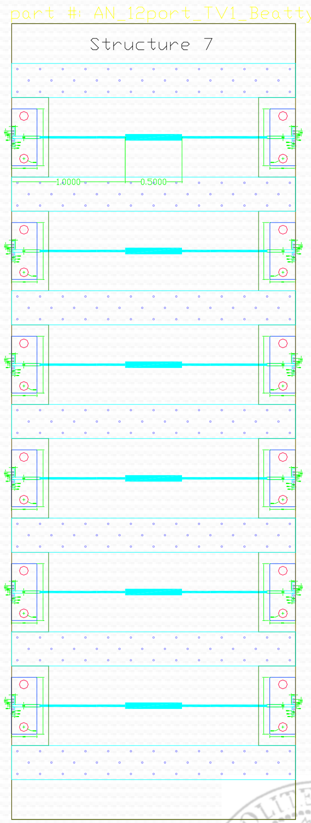


More complex On fixture Standard

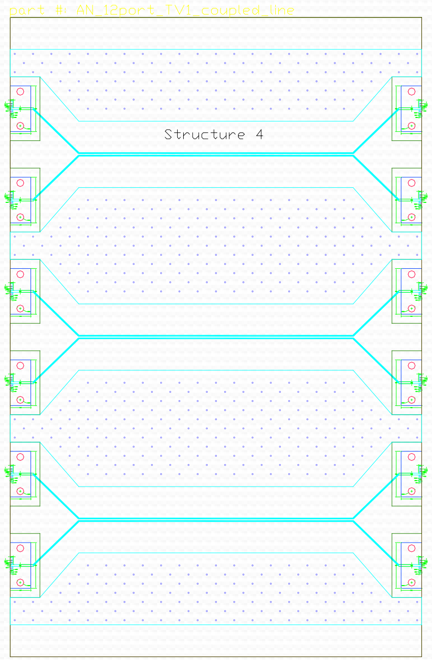
3-TRL/TRM kits
0.2-20GHz
0.05-50GHz
0.05-65GHz



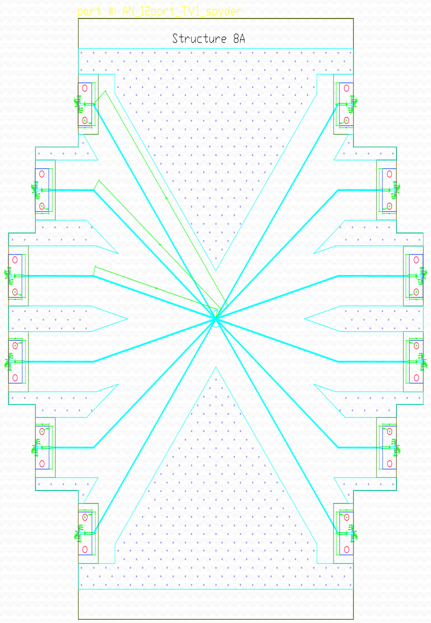
12-port
Beatty standard



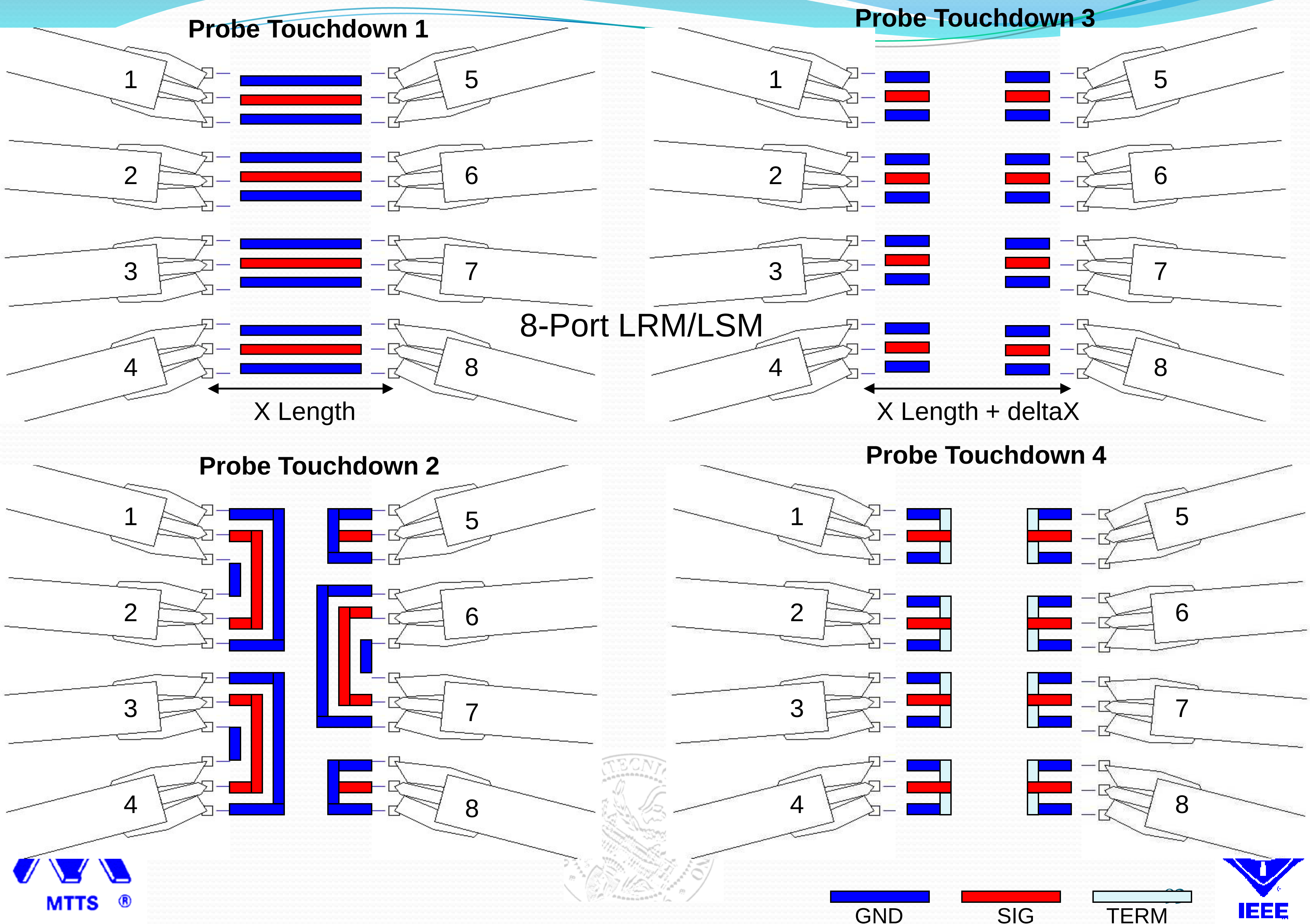
12-port
simple & coupled ustrip



12-port
unknown thru



ON WAFER STANDARD KIT

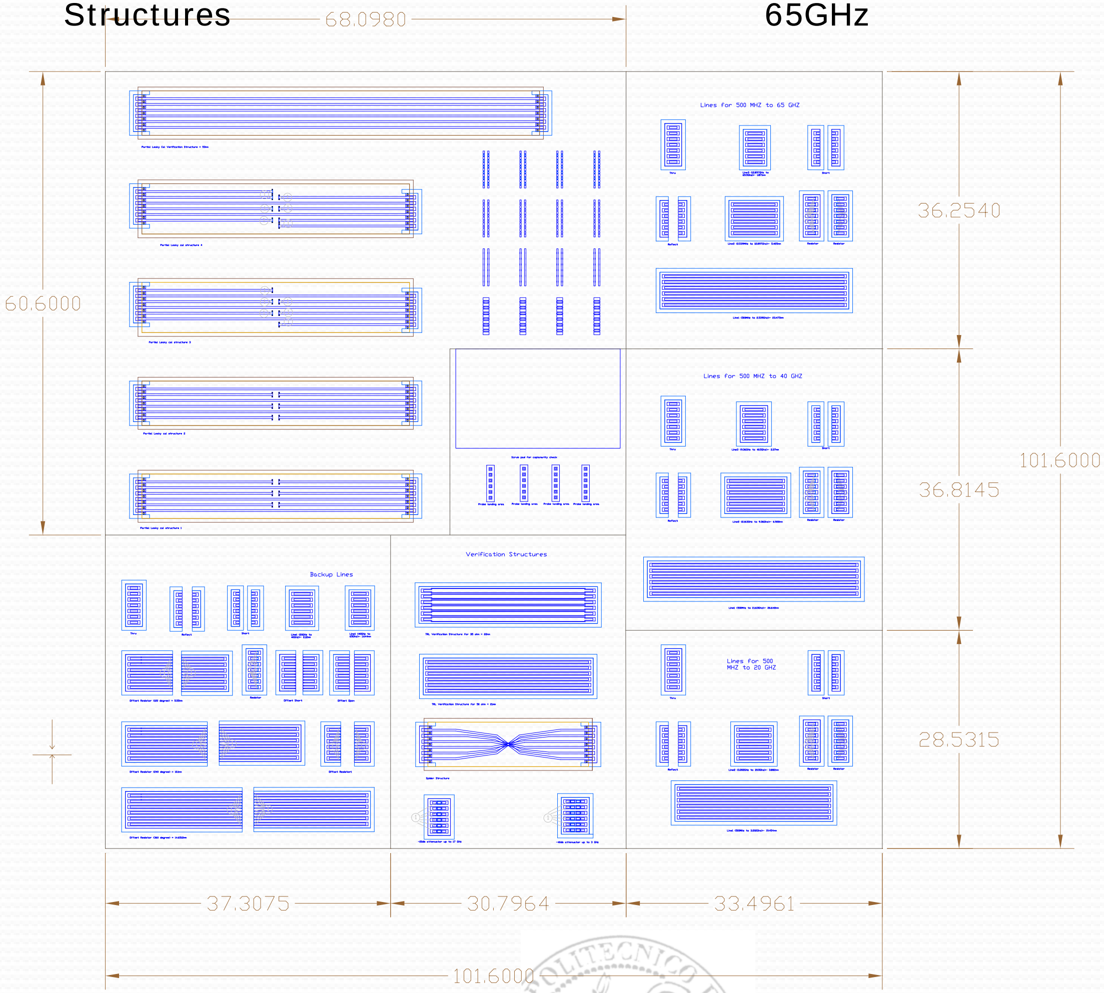


On Wafer Verification Devices

Partially Leaky Structures

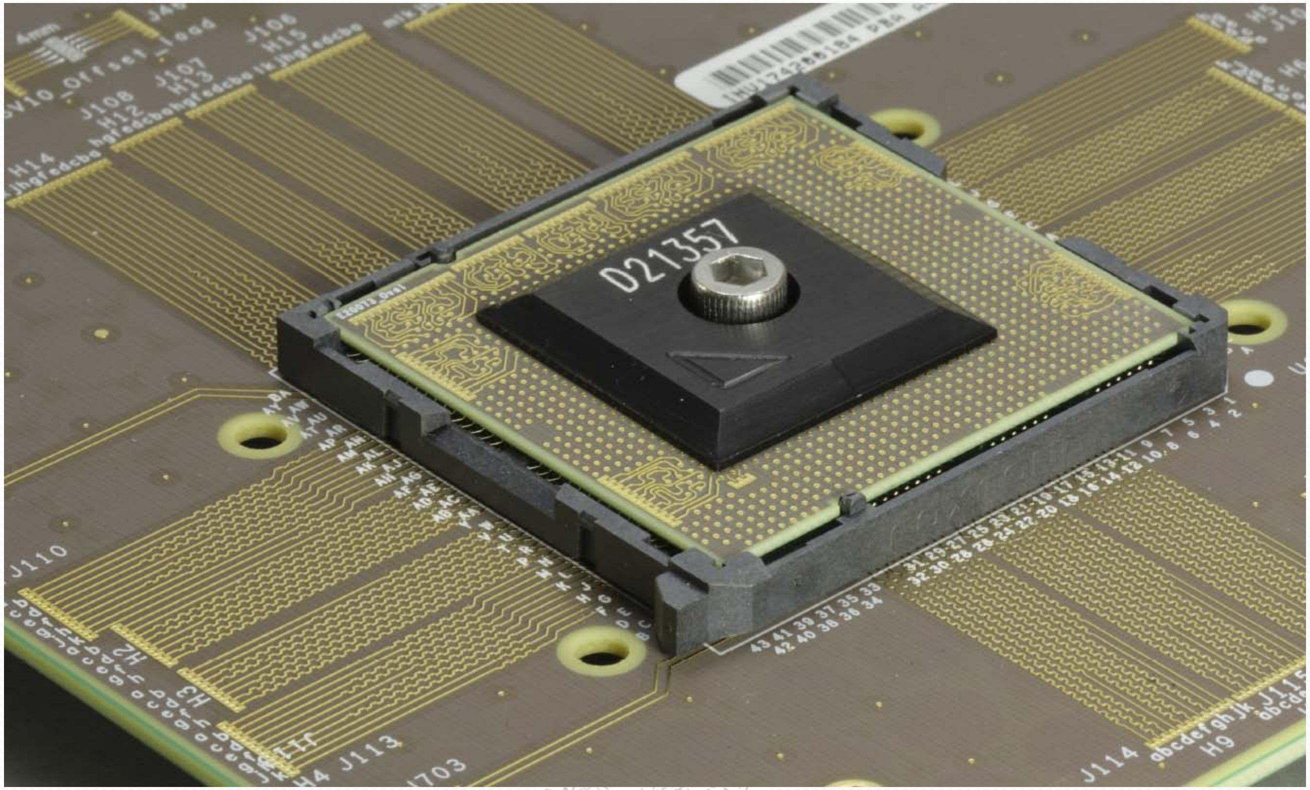
SOLT kits

TRL 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

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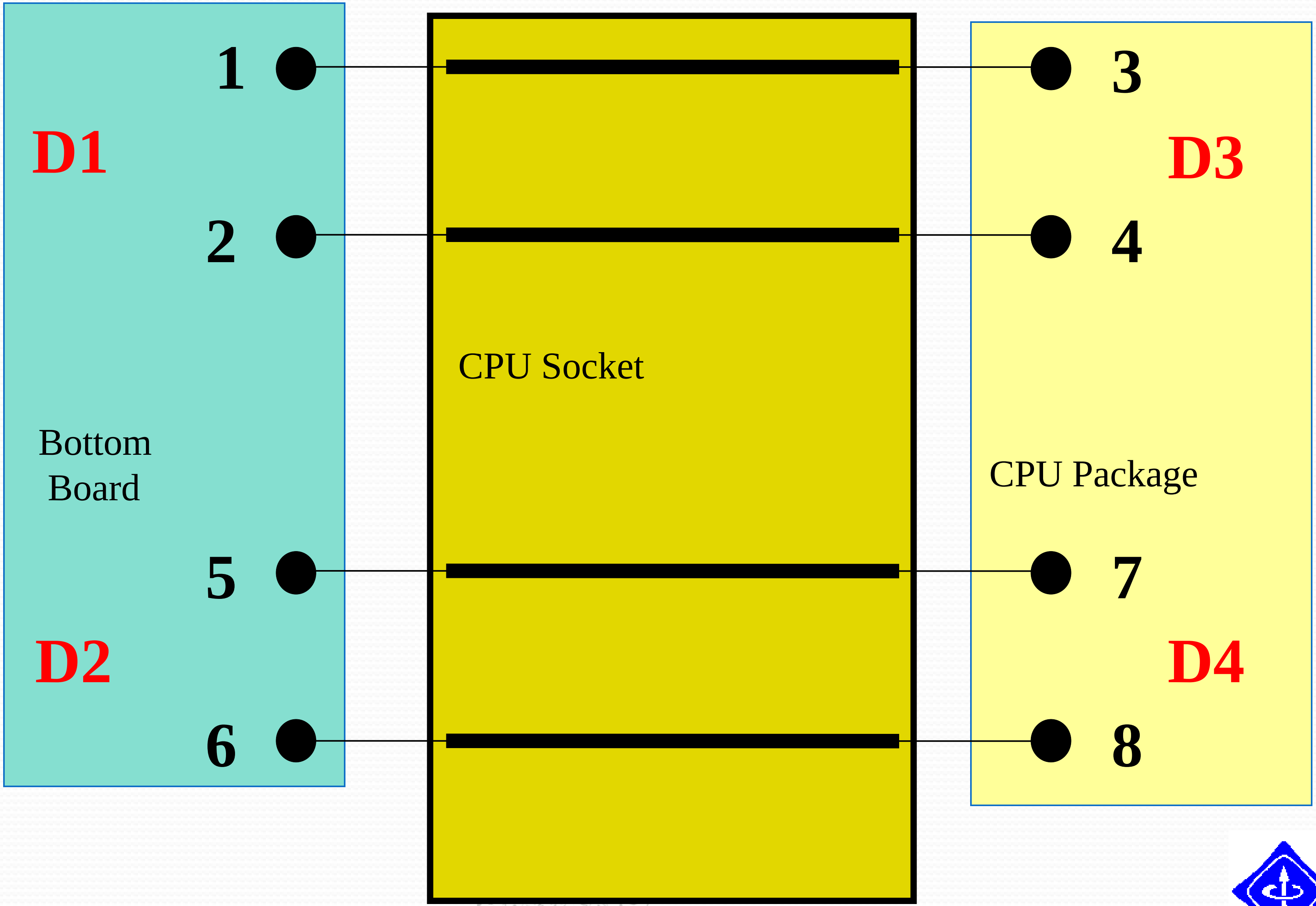
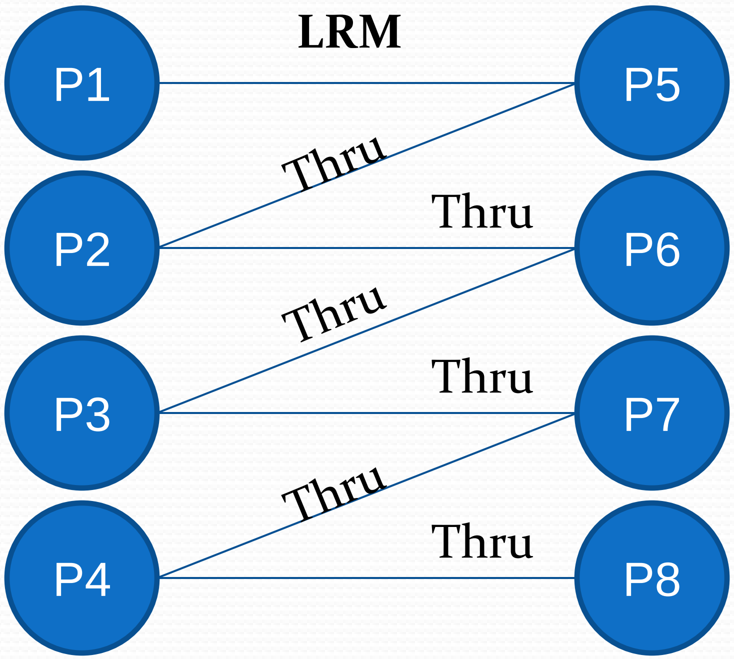
8 Port Differential Socket Setup



Let's Design the Cal



8-Port LRM Calibration Matrix

	Port 1	Port 2	Port 3	Port 4	Port 5	Port 6	Port 7	Port 8
Port 1	X	X	X	X	2P_LRM	X	X	X
Port 2	X	X	X	X	Thru	Thru	X	X
Port 3	X	X	X	X	X	Thru	Thru	X
Port 4	X	X	X	X	X	X	Thru	Thru
Port 5	2P_LRM	Thru	X	X	X	X	X	X
Port 6	X	Thru	Thru	X	X	X	X	X
Port 7	X	X	Thru	Thru	X	X	X	X
Port 8	X	X	X	Thru	X	X	X	X

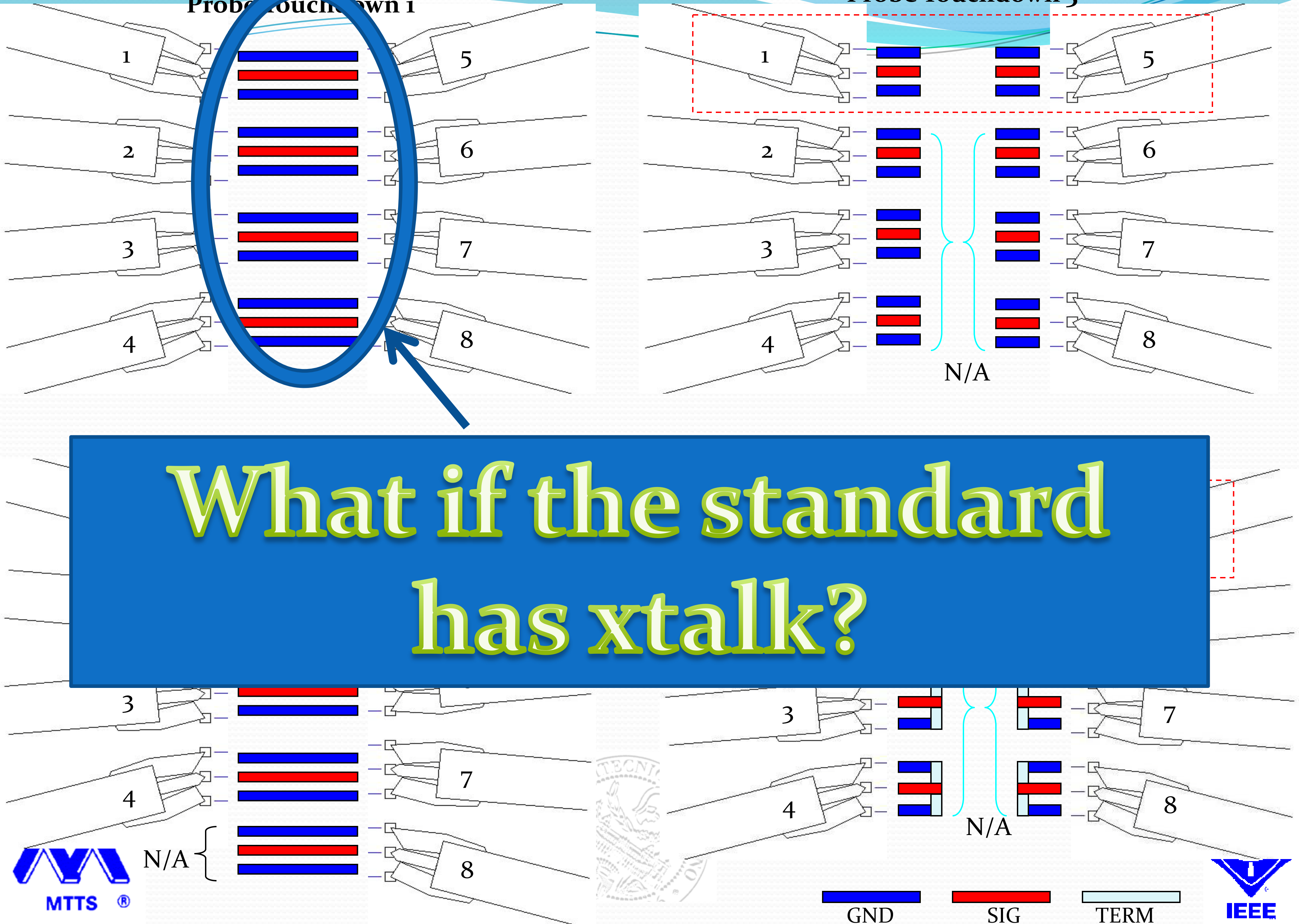
- Calibration Procedure:
  - Thru Port 1, 5
  - Thru Port 2, 6
  - Thru Port 3, 7
  - Thru Port 4, 8

    Structure 1 (All ports touchdown)
  - Thru Port 2, 5
  - Thru Port 3, 6
  - Thru Port 4, 7

    Structure 2 (All ports touchdown)
  - Reflect Port 1
  - Reflect Port 5
  - Load Port 1
  - Load Port 5

    Structures 3 – 4

8-Port LRM



What if the standard has xtalk?

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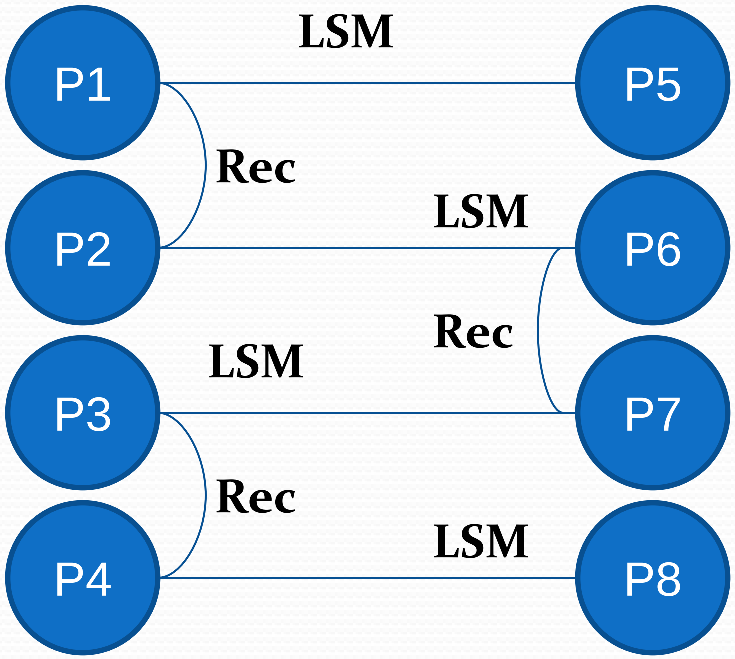
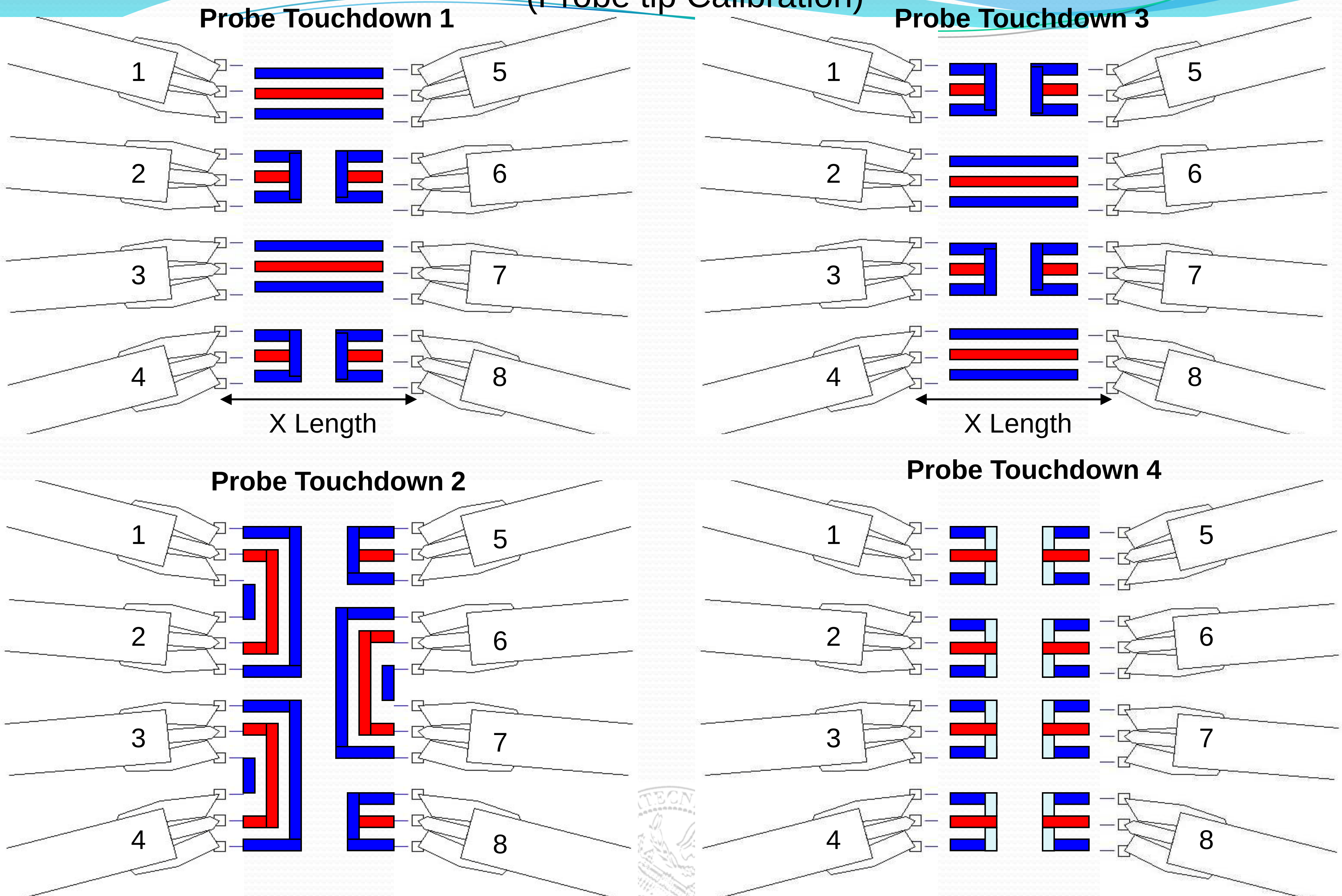
Another Cal to avoid Xtalk



8-Port LRM/LSM Standards
(Probe tip Calibration)



Minimize probe tip Xtalk

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

	Port 1	Port 2	Port 3	Port 4	Port 5	Port 6	Port 7	Port 8
Port 1	X	Recip	X	X	2P_LSM	X	X	X
Port 2	Recip	X	X	X	X	2P_LSM	X	X
Port 3	X	X	X	Recip	X	X	2P_LSM	X
Port 4	X	X	Recip	X	X	X	X	2P_LSM
Port 5	2P_LSM	X	X	X	X	X	X	X
Port 6	X	2P_LSM	X	X	X	X	Recip	X
Port 7	X	X	2P_LSM	X	X	Recip	X	X
Port 8	X	X	X	2P_LSM	X	X	X	X

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

    Structure 1
  - Recip 1, 2
  - Recip 3, 4
  - Recip 6, 7

    Structure 2
  - Reflect Port 1, Reflect Port 5
  - Reflect Port 2, Reflect Port 6
  - Reflect Port 3, Reflect Port 7
  - Reflect Port 4, Reflect Port 8

    Structures 3
  - Load Port 1, Load Port 5
  - Load Port 2, Load Port 6
  - Load Port 3, Load Port 7
  - Load Port 4, Load Port 8

    Structures 4

4 separate 2-port LSM/LRM calibrations linked with reciprocal thru standards

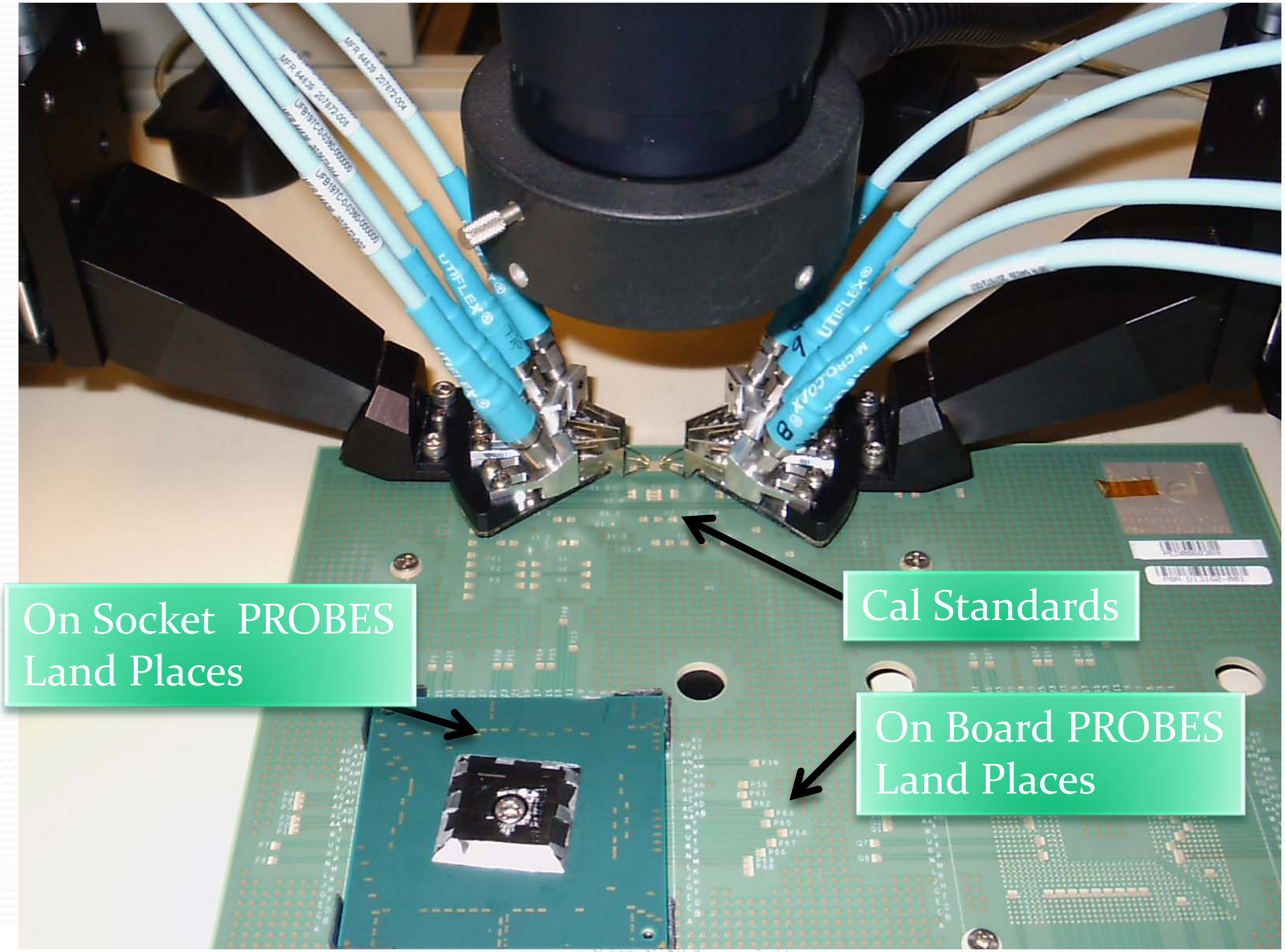
- No wasted probe touchdowns
- Never move probe tips in x or y direction
- Full characterization of every port
- Could provide more accurate calibrations

LRM requires reflect on all ports

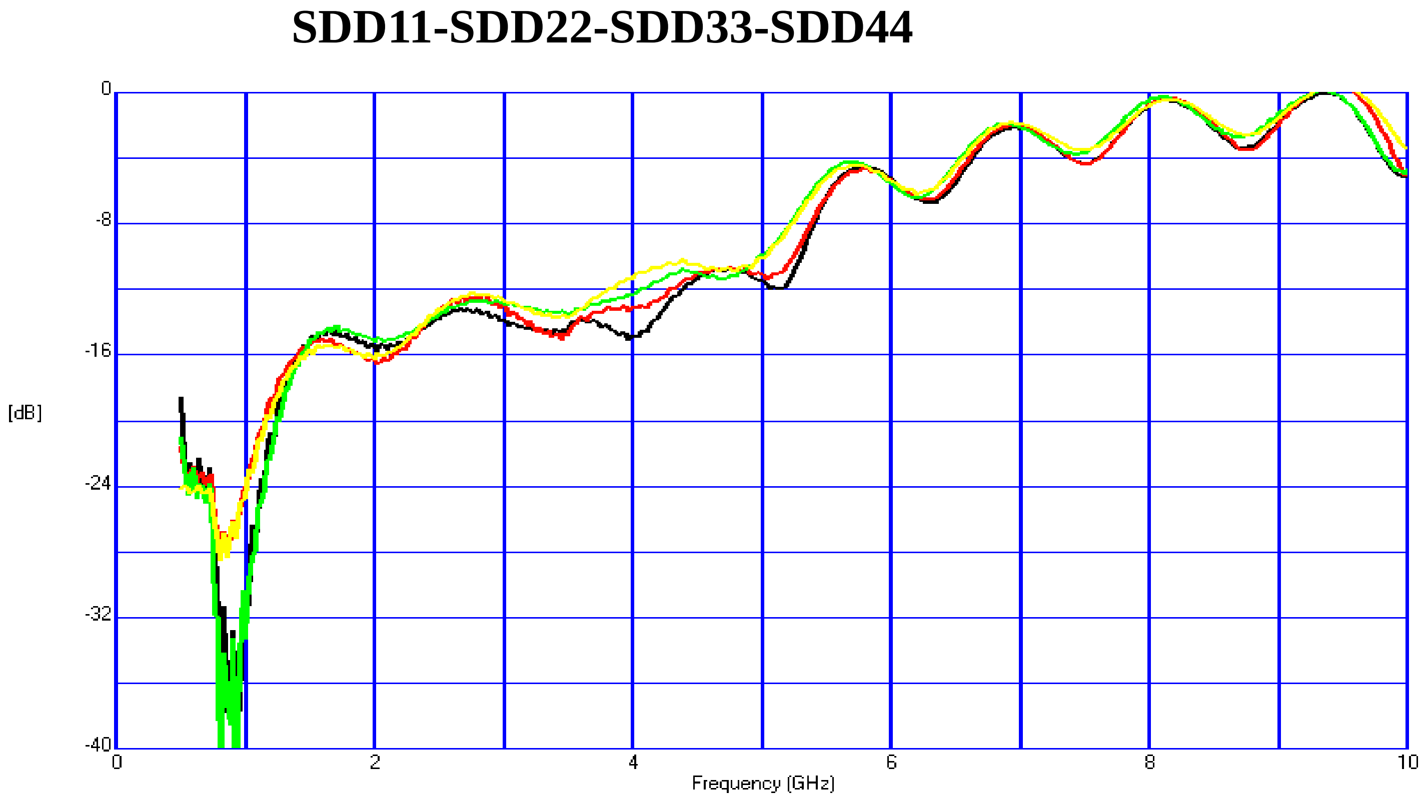
LSM only requires 1 reflect per calibration

=> Only half of Structure 3 is needed for LSM

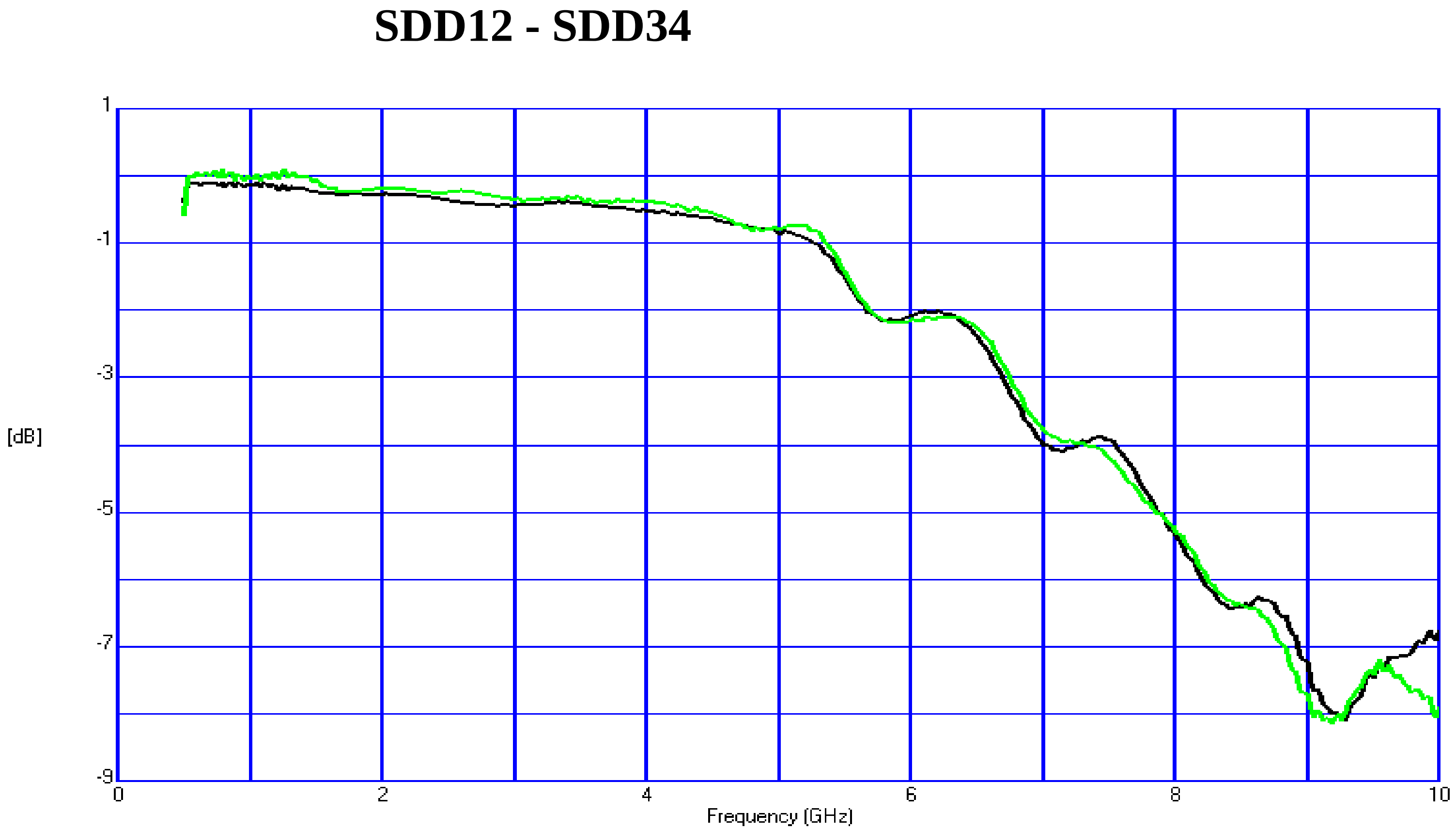
Socket/Board Example



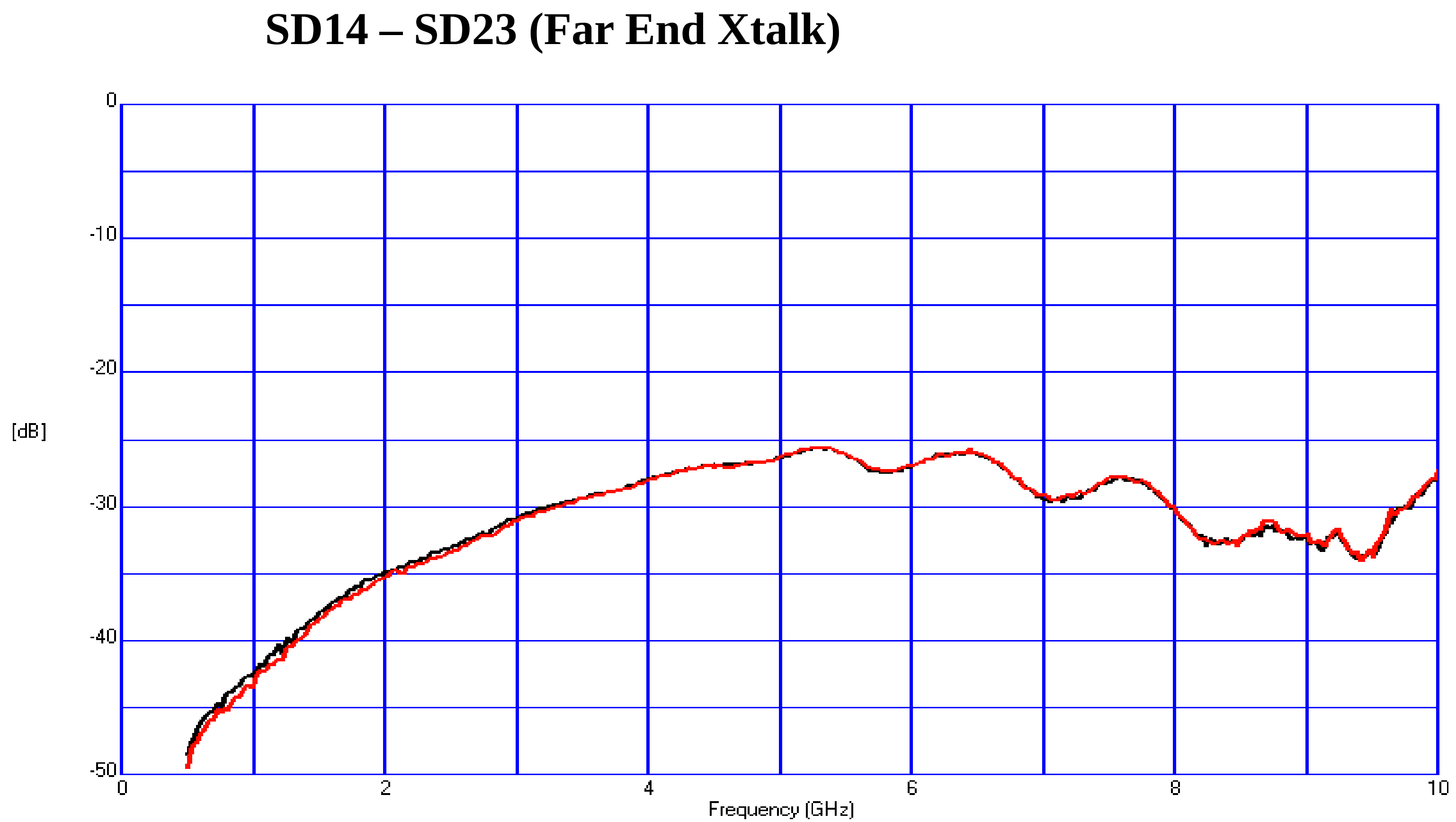
Socket-Board Data



Socket-Board Data

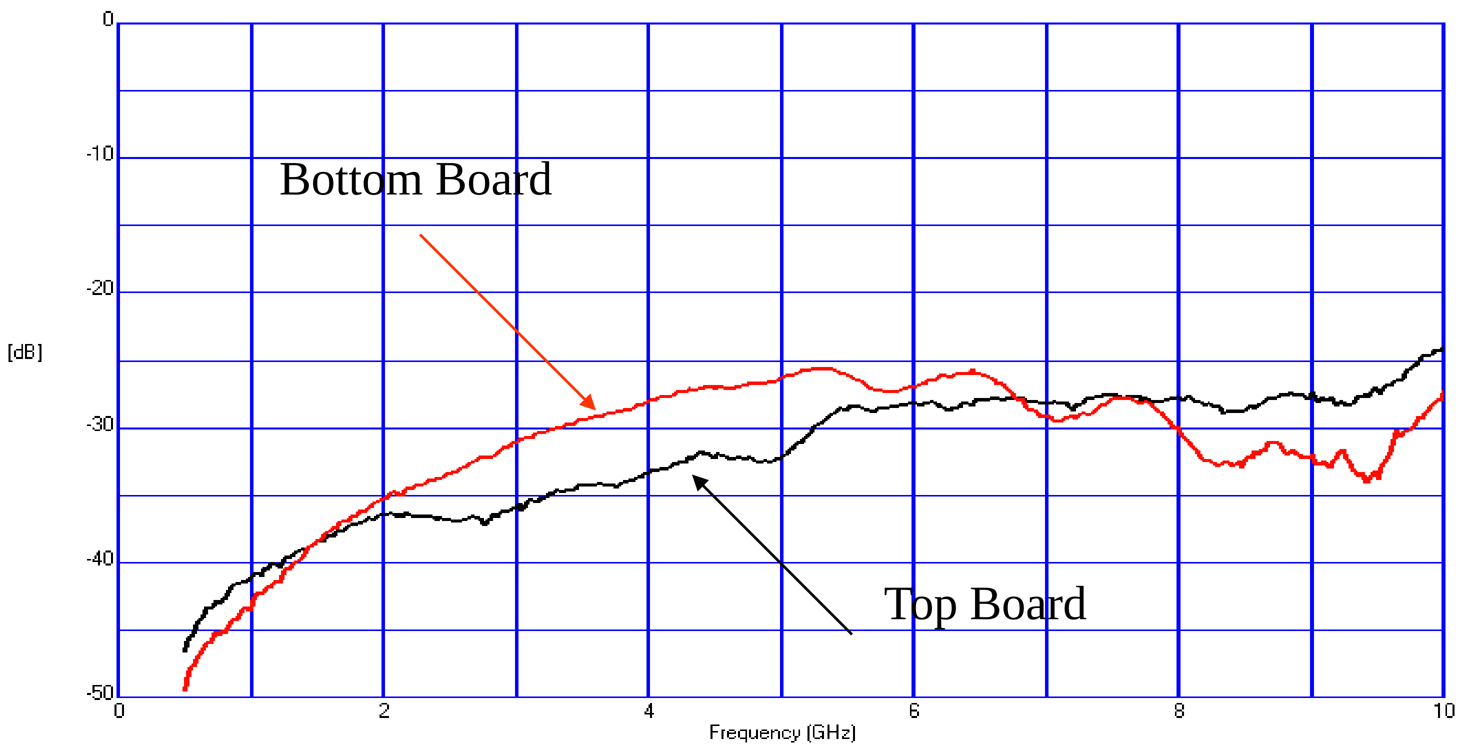


Socket-Board Data

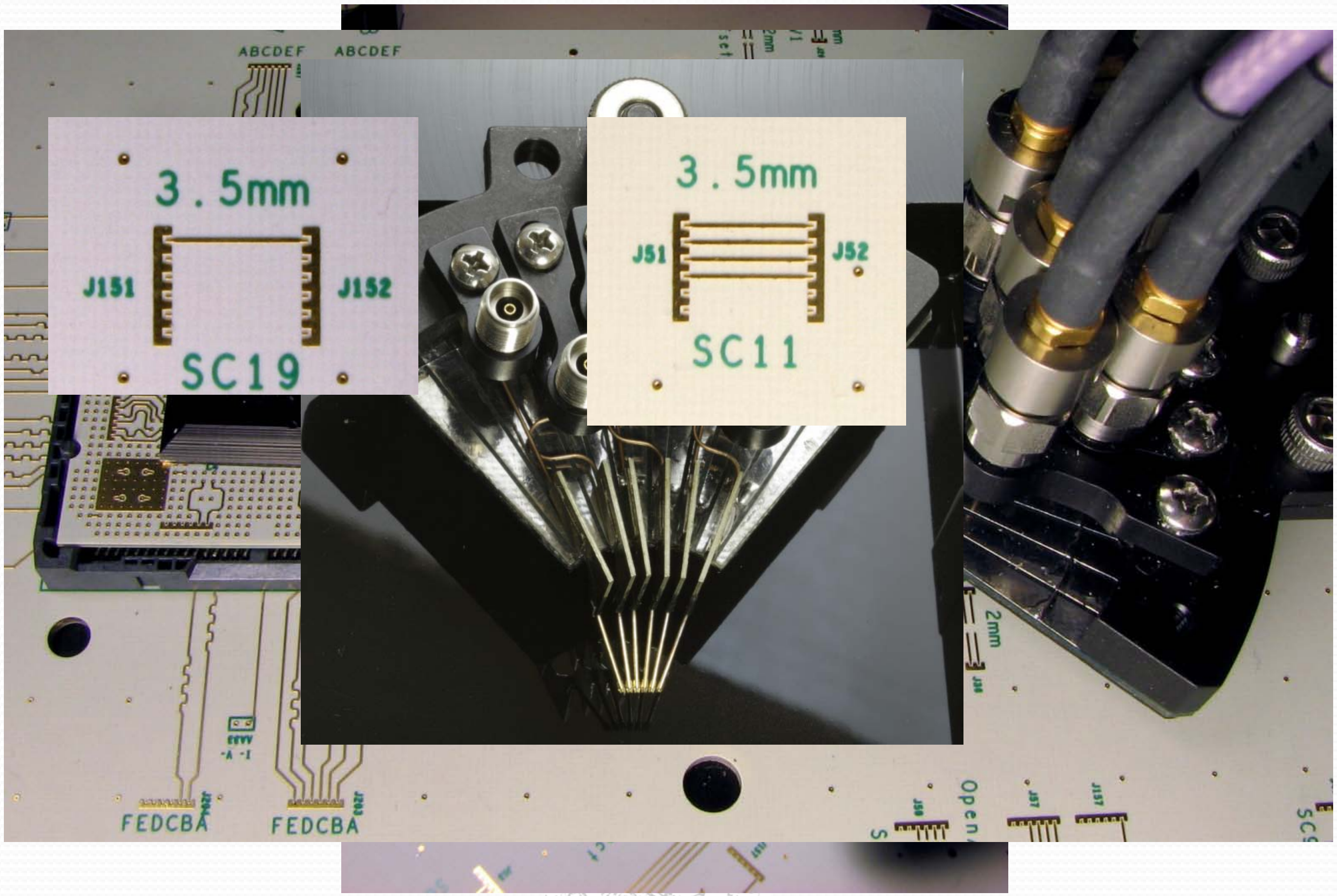


Socket-Board Data

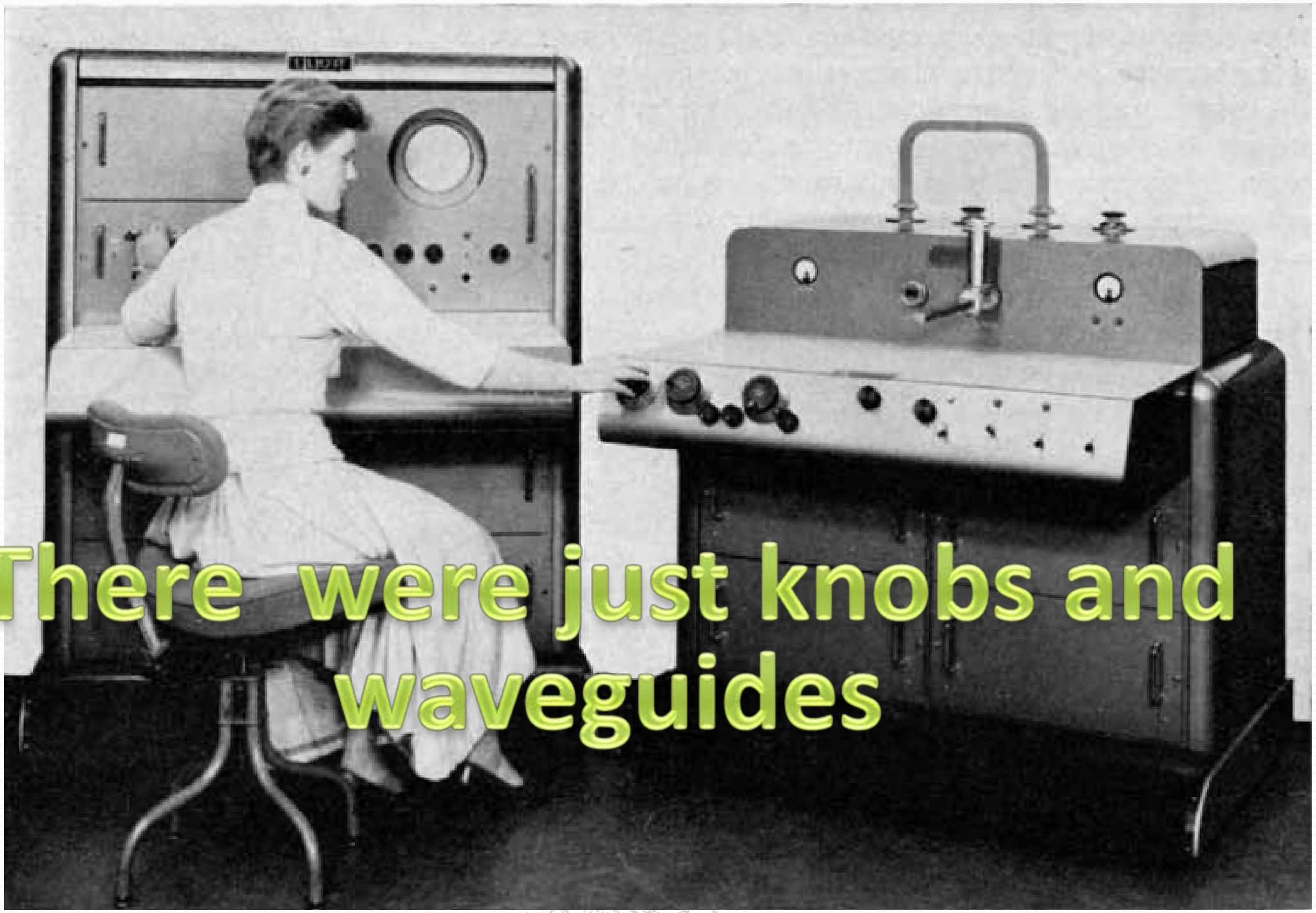
SD13 – SD24 (Near End Xtalk)



A similar case but 12ports !



So at the begginning….



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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Acknoledgements

- Valeria Teppati, Serena Bonino
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  Anritsu Corp
- Dave Blackham
  Agilent
- Doug Rytting

THANK YOU

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