



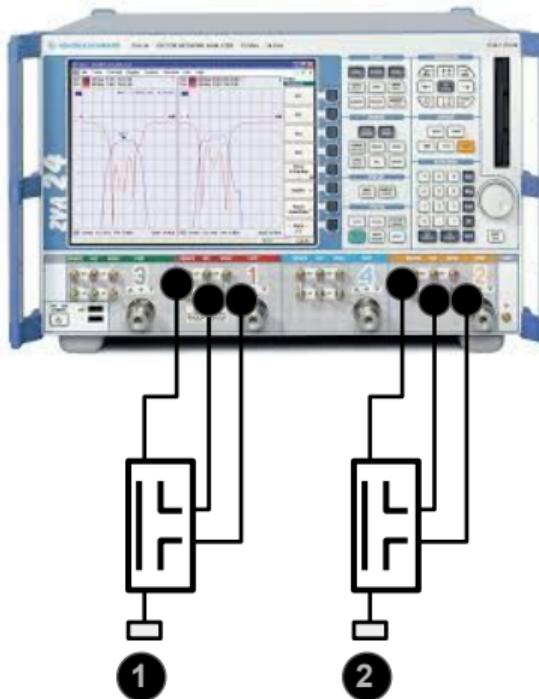
# SOLT and SOLR calibration methods using a single multiport “thru” standard connection

T. Reveyrand, S. Hernández, S. Mons, and E. Ngoya



# Introduction

## Standard 2-port NVNA System



Signal

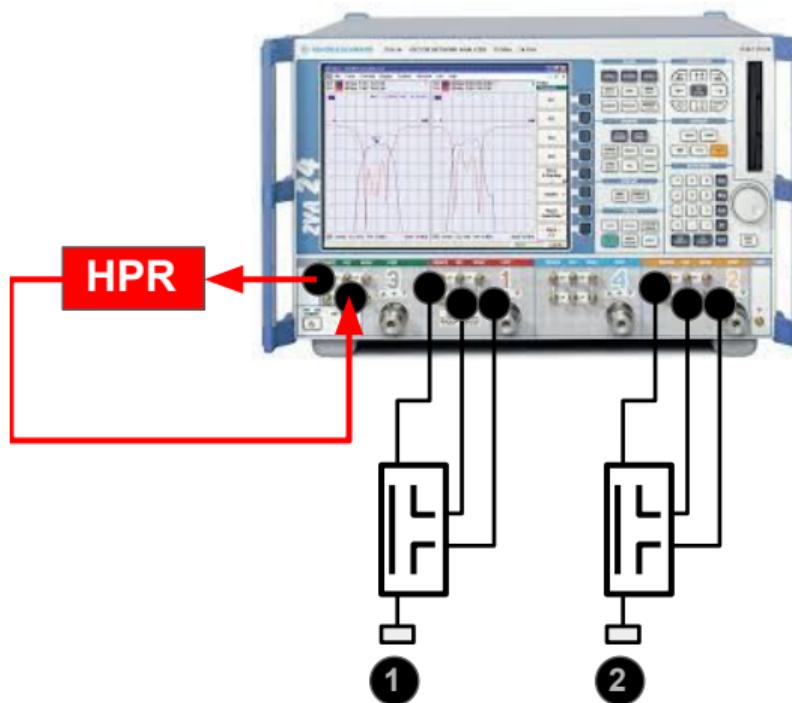


CW measurements in the frequency domain:

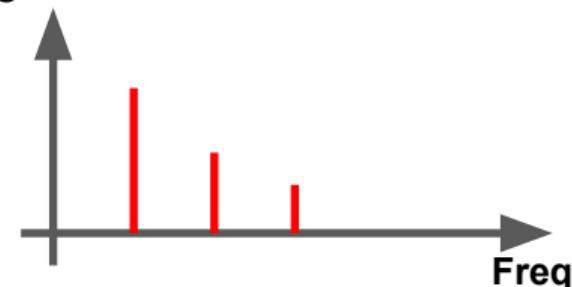
- do not need for a Harmonic Phase Reference (HPR) ;
- require only one RF source ;
- make up to 4 ports available on most NVNA ;

# Introduction

## Standard 2-port NVNA System



Signal



### Time domain measurements:

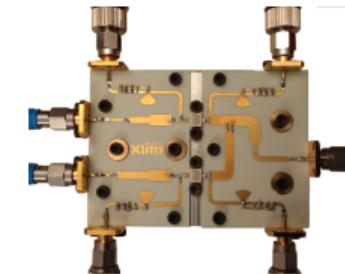
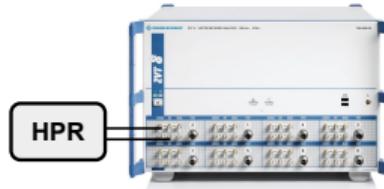
- require a mandatory HPR ;
- require two independent RF sources ;
- require a 4-port VNA to make a 2-port NVNA ;



# Introduction

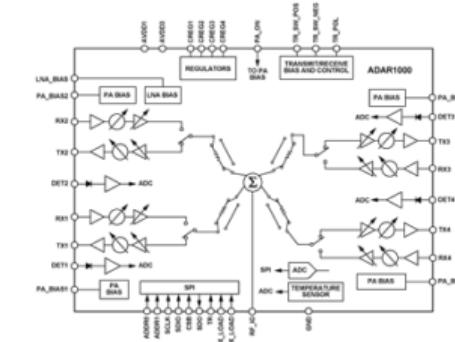
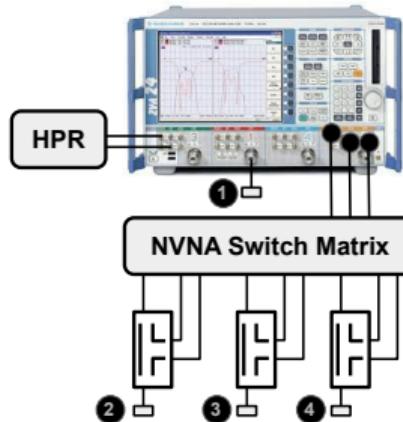
## Multiport NVNA for MIMO systems

- Direct receivers



*Dual Input Digital Doherty by XLIM (93<sup>rd</sup> ARFTG Conference)*

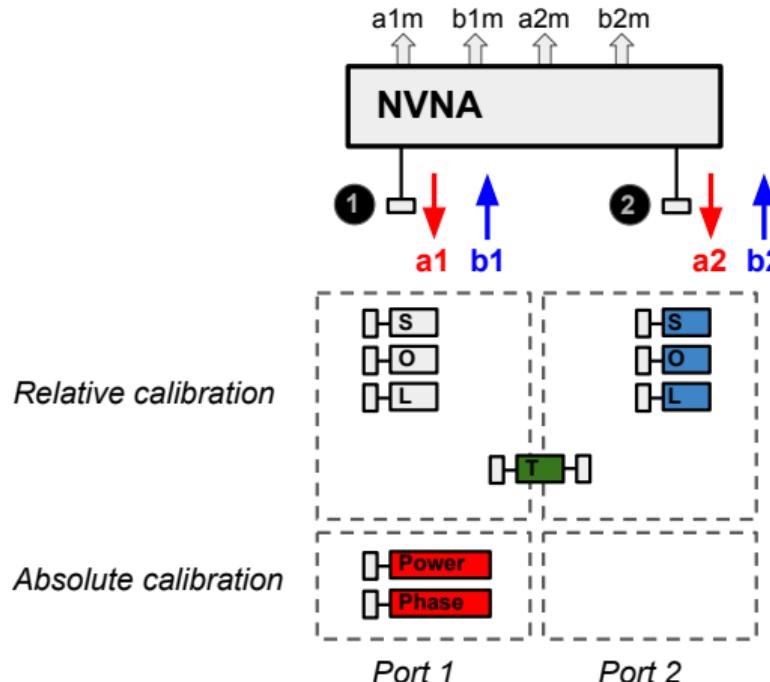
- Using a Switch Matrix



*Beamformer by Analog Devices (ADAR 1000)*

# Introduction

## Calibration of a 2-port NVNA



- Port 1

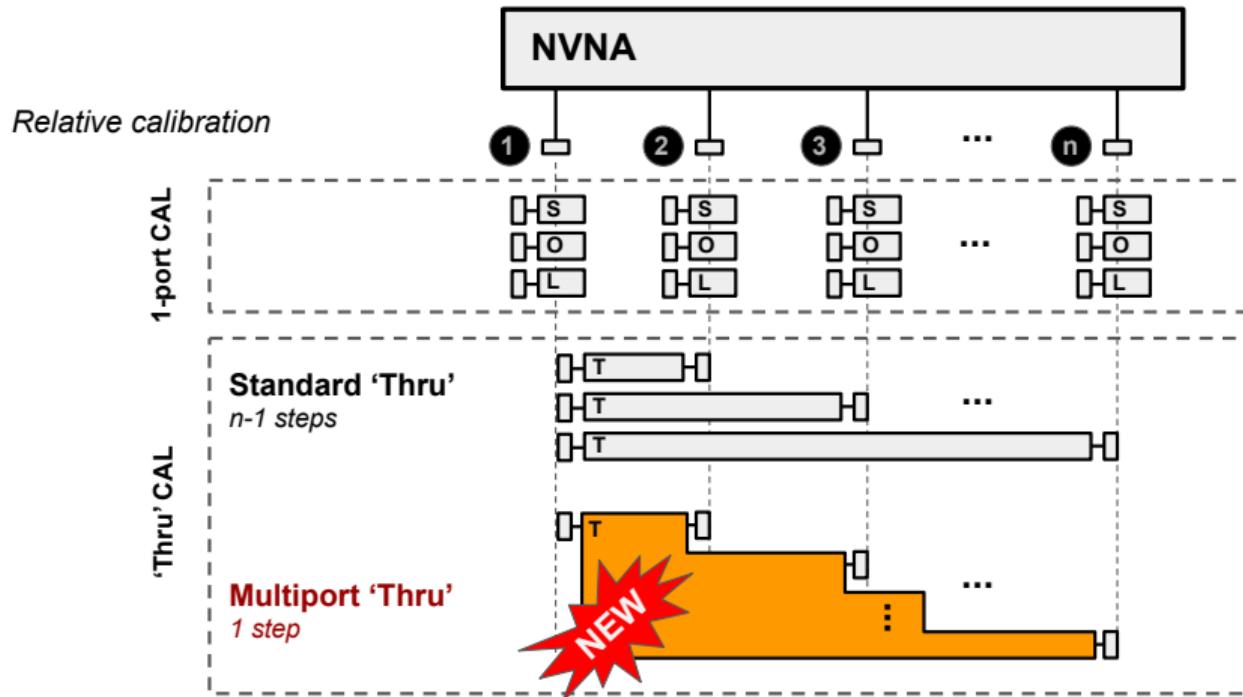
$$\begin{pmatrix} a_1 \\ b_1 \end{pmatrix} = \alpha_1 \begin{bmatrix} 1 & \beta'_1 \\ \gamma'_1 & \delta'_1 \end{bmatrix} \cdot \begin{pmatrix} a_{1m} \\ b_{1m} \end{pmatrix}$$

- Port 2

$$\begin{pmatrix} a_2 \\ b_2 \end{pmatrix} = \alpha_2 \begin{bmatrix} 1 & \beta'_2 \\ \gamma'_2 & \delta'_2 \end{bmatrix} \cdot \begin{pmatrix} a_{2m} \\ b_{2m} \end{pmatrix}$$

# Introduction

## Multiport NVNA Calibration





# The presentation outline

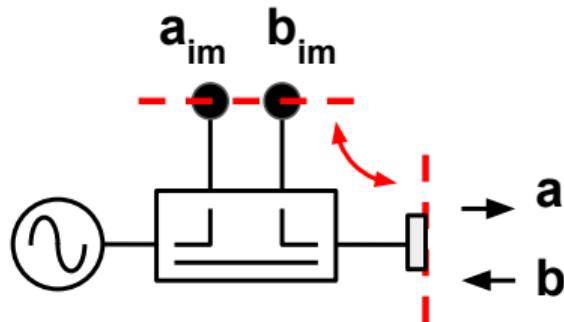
## Calibration algorithms for a multiport NVNA

- ① SOL
- ② SOLT
- ③ SOLR
- ④ Calibration comparison
- ⑤ Multiport NVNA in LabVIEW
- ⑥ GSOLT conversion

# SOL Calibration

## Short-Open-Load method for port i

$$\Gamma_{\langle std \rangle} = \frac{b_i}{a_i} \quad \text{and} \quad \Gamma_{m\langle std \rangle} = \frac{b_{im}}{a_{im}} \quad \text{with} \quad \langle std \rangle = \text{Short ; Open ; Load}$$



$$\begin{pmatrix} a_i \\ b_i \end{pmatrix} = \alpha_i \cdot \begin{pmatrix} 1 & \beta'_i \\ \gamma'_i & \delta'_i \end{pmatrix} \cdot \begin{pmatrix} a_{im} \\ b_{im} \end{pmatrix}$$

$$\Gamma_{\langle std \rangle} = \beta'_i \cdot \Gamma_{\langle std \rangle} \cdot \Gamma_{m\langle std \rangle} + \gamma'_i + \delta'_i \cdot \Gamma_{m\langle std \rangle}$$

$$\begin{pmatrix} \Gamma_S \\ \Gamma_O \\ \Gamma_L \end{pmatrix} = \begin{pmatrix} \beta'_i \\ \gamma'_i \\ \delta'_i \end{pmatrix} \cdot \begin{bmatrix} -\Gamma_{mS} \cdot \Gamma_S & 1 & \Gamma_{mS} \\ -\Gamma_{mO} \cdot \Gamma_O & 1 & \Gamma_{mO} \\ -\Gamma_{mL} \cdot \Gamma_L & 1 & \Gamma_{mL} \end{bmatrix}$$

$$\begin{pmatrix} \beta'_i \\ \gamma'_i \\ \delta'_i \end{pmatrix} = \begin{bmatrix} -\Gamma_{mS} \cdot \Gamma_S & 1 & \Gamma_{mS} \\ -\Gamma_{mO} \cdot \Gamma_O & 1 & \Gamma_{mO} \\ -\Gamma_{mL} \cdot \Gamma_L & 1 & \Gamma_{mL} \end{bmatrix}^{-1} \cdot \begin{pmatrix} \Gamma_S \\ \Gamma_O \\ \Gamma_L \end{pmatrix}$$

# SOL Calibration

Partially calibrated NVNA after a SOL on port i

- Fully calibrated system

$$\begin{pmatrix} a_i \\ b_i \end{pmatrix} = \alpha_i \cdot \begin{bmatrix} 1 & \beta'_i \\ \gamma'_i & \delta'_i \end{bmatrix} \cdot \begin{pmatrix} a_{im} \\ b_{im} \end{pmatrix}$$

$$\begin{pmatrix} a_i \\ b_i \end{pmatrix} = \alpha_i \cdot \begin{pmatrix} \bar{a}_i \\ \bar{b}_i \end{pmatrix}$$

- Partially calibrated system

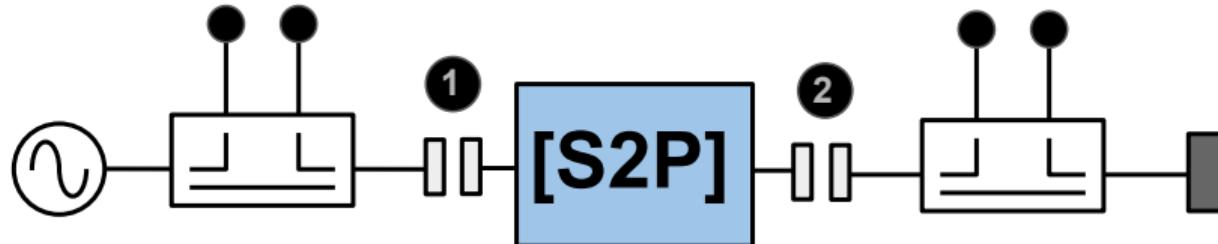
$$\begin{pmatrix} \bar{a}_i \\ \bar{b}_i \end{pmatrix} = \begin{bmatrix} 1 & \beta'_i \\ \gamma'_i & \delta'_i \end{bmatrix} \cdot \begin{pmatrix} a_{im} \\ b_{im} \end{pmatrix}$$

$\alpha_1$  is extracted from an absolute calibration on port 1.

$\alpha_2$  to  $\alpha_n$  are extracted from a “Thru” calibration. This “Thru” may be known (SOLT) or unknown but reciprocal (SOLR).

# SOLT Calibration

“Thru” calibration on a 2-port NVNA with an active source on port 1

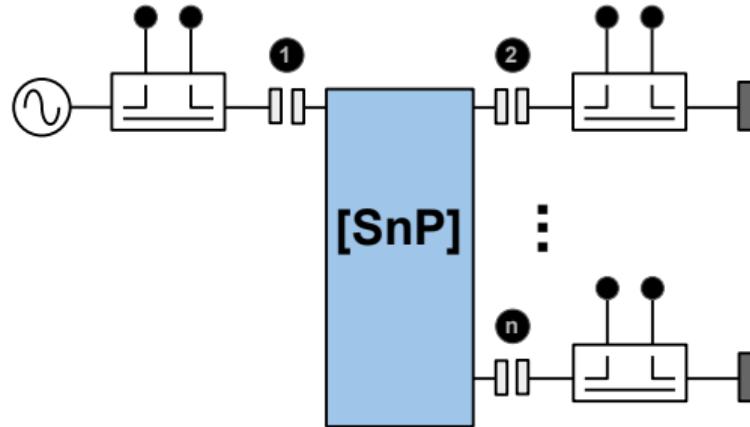


$$b_2 = S_{21} \cdot \bar{a}_1 + S_{22} \cdot a_2$$

$$\alpha_2 = \left( \bar{b}_2 - S_{22} \cdot \bar{a}_2 \right)^{-1} \cdot \bar{a}_1 \cdot S_{21}$$

# SOLT Calibration

"Thru" calibration on a n-port NVNA with an active source on port 1



$$\begin{pmatrix} \alpha_2 \\ \vdots \\ \alpha_n \end{pmatrix} = \left[ \text{diag} \begin{pmatrix} \bar{b}_2 \\ \vdots \\ \bar{b}_n \end{pmatrix} - \begin{bmatrix} S_{22} & \dots & S_{2n} \\ \vdots & \ddots & \vdots \\ S_{n2} & \dots & S_{nn} \end{bmatrix} \cdot \text{diag} \begin{pmatrix} \bar{a}_2 \\ \vdots \\ \bar{a}_n \end{pmatrix} \right]^{-1} \cdot \bar{a}_1 \cdot \begin{pmatrix} S_{21} \\ \vdots \\ S_{n1} \end{pmatrix}$$

# SOLR: SHORT-OPEN-LOAD-RECIPROCAL

## Origins



Andrea Ferrero

IEEE MICROWAVE AND GUIDED WAVE LETTERS, VOL. 2, NO. 12, DECEMBER 1992

505

## Two-Port Network Analyzer Calibration Using an Unknown "Thru"

Andrea Ferrero, *Member, IEEE*, and Umberto Pisani

**Abstract**—A procedure performed by using a generic two port reciprocal network instead of a standard *thru* in a full two-port error correction of an automatic network analyzer is presented. Although it can be applied to any type of waveguide system the proposed technique is particularly useful with noninsertable coaxial or on-wafer devices. Experimental comparisons show that the suggested procedure provides a great degree of accuracy.

### I. INTRODUCTION

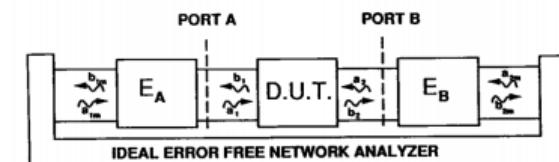
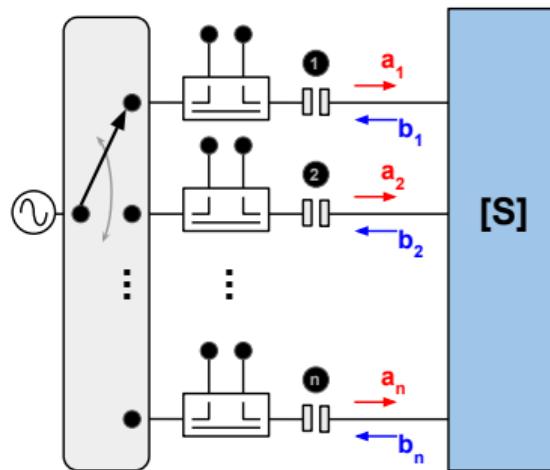


Fig. 1. Error box NWA model.

A. Ferrero, U. Pisani,  
"Two-port network analyzer calibration using an unknown 'thru'"  
IEEE Microwave and Guided Wave Letters, Vol. 2, No. 12, 1992, pp. 505-507

# SOLR: SHORT-OPEN-LOAD-RECIPROCAL

## Method for multiport NVNAs



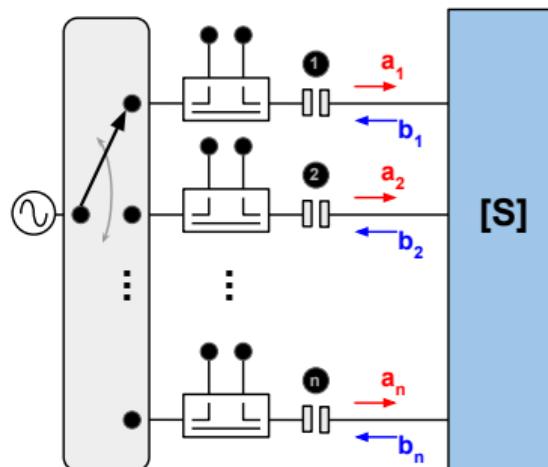
- The “Thru” standard ( $[S]$ ) is unknown but reciprocal ( $S_{ij} = S_{ji}$ ) ;
- The active source is swept from 1 to n
- By definition, we have:

$$[S] = \begin{bmatrix} b_{11} & \dots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{n1} & \dots & b_{nn} \end{bmatrix} \begin{bmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \dots & a_{nn} \end{bmatrix}^{-1}$$

where  $a_{ij}$  and  $b_{ij}$  are respectively the incident and reflected waves measured at port  $i$  when the RF source is active on port  $j$ .

# SOLR: SHORT-OPEN-LOAD-RECIPROCAL

Method for multiport NVNAs



- Fully calibrated system:  $[S] = [b_{ij}]. [a_{ij}]^{-1}$
- Partially calibrated system:  $\bar{[S]} = [\bar{b}_{ij}]. [\bar{a}_{ij}]^{-1}$

$$[S] = [\text{diag}(\alpha_1, \dots, \alpha_n)] \bar{[S]} [\text{diag}(\alpha_1, \dots, \alpha_n)]^{-1}$$

$$S_{ij} = \frac{\alpha_i}{\alpha_j} \bar{S}_{ij}$$

- Reciprocity:  $S_{ij} = S_{ji}$

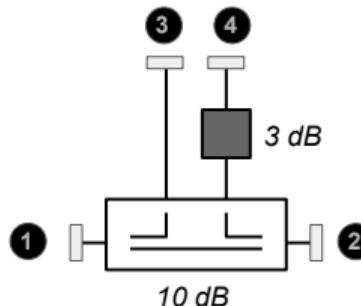
$$\alpha_j = \pm \alpha_i \cdot \sqrt{\frac{\bar{S}_{ij}}{\bar{S}_{ji}}}$$

The correct solution is selected according an estimation of  $\text{Arg}\{S_{ij}\}$   
 We start from  $\alpha_1 = 1$  and then calculate  $\alpha_i$  for  $i = 2..n$

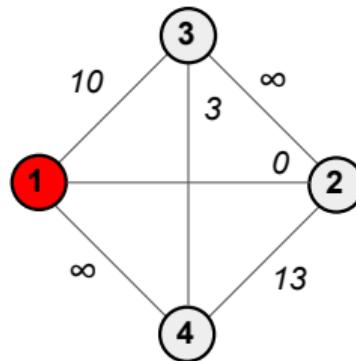


# Multiport SOLR

The Dijkstra Algorithm on a nonideal multiport “thru” standard



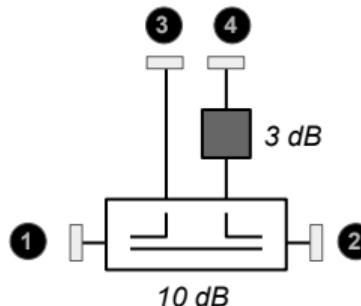
$$\alpha_1 = 1$$



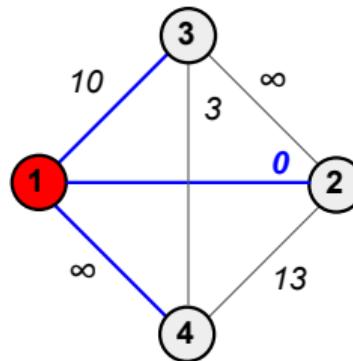


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The Dijkstra Algorithm on a nonideal multiport “thru” standard



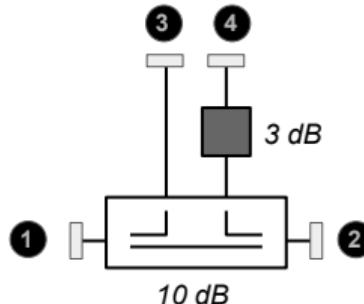
$$\alpha_1 = 1$$





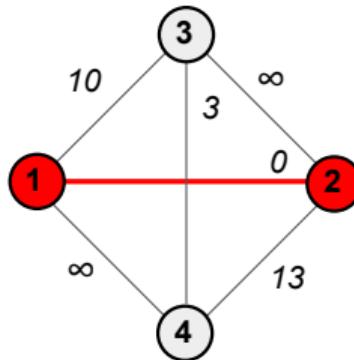
# Multiport SOLR

The Dijkstra Algorithm on a nonideal multiport “thru” standard



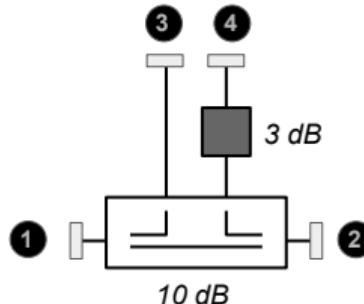
$$\alpha_1 = 1$$

$$\alpha_2 = \pm \alpha_1 \cdot \sqrt{\frac{\bar{S}_{12}}{\bar{S}_{21}}}$$



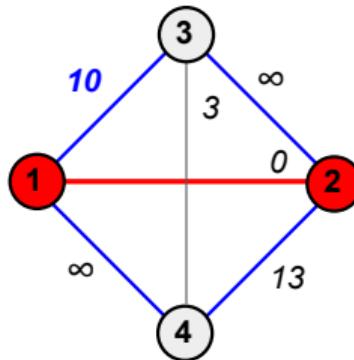
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The Dijkstra Algorithm on a nonideal multiport “thru” standard



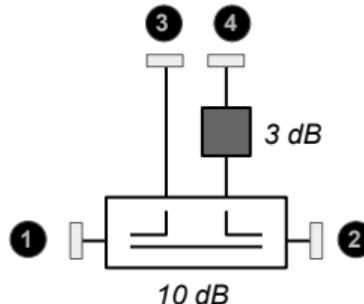
$$\alpha_1 = 1$$

$$\alpha_2 = \pm \alpha_1 \cdot \sqrt{\frac{\bar{S}_{12}}{\bar{S}_{21}}}$$



# Multiport SOLR

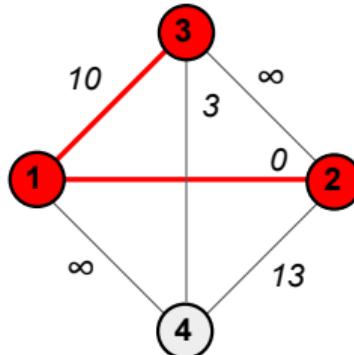
The Dijkstra Algorithm on a nonideal multiport “thru” standard



$$\alpha_1 = 1$$

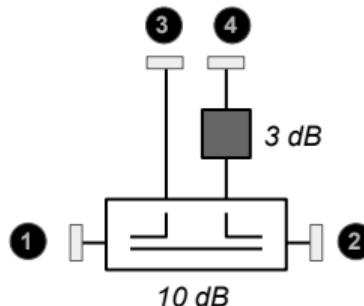
$$\alpha_2 = \pm \alpha_1 \cdot \sqrt{\frac{\bar{S}_{12}}{\bar{S}_{21}}}$$

$$\alpha_3 = \pm \alpha_1 \cdot \sqrt{\frac{\bar{S}_{13}}{\bar{S}_{31}}}$$



# Multiport SOLR

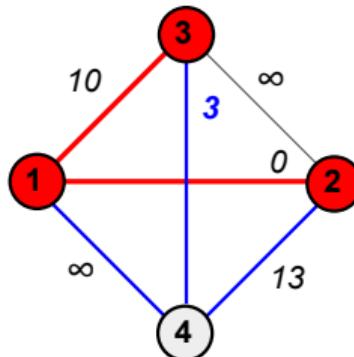
The Dijkstra Algorithm on a nonideal multiport “thru” standard



$$\alpha_1 = 1$$

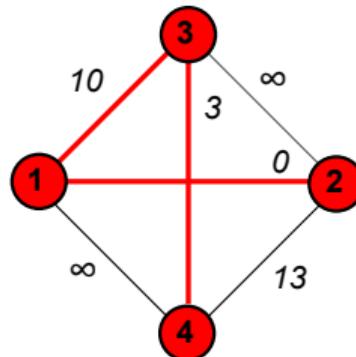
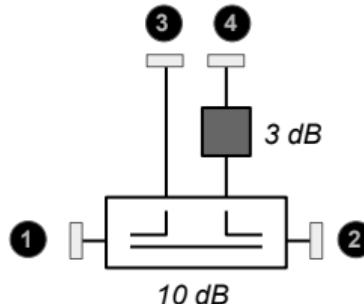
$$\alpha_2 = \pm \alpha_1 \cdot \sqrt{\frac{\bar{S}_{12}}{\bar{S}_{21}}}$$

$$\alpha_3 = \pm \alpha_1 \cdot \sqrt{\frac{\bar{S}_{13}}{\bar{S}_{31}}}$$



# Multiport SOLR

The Dijkstra Algorithm on a nonideal multiport “thru” standard



$$\alpha_1 = 1$$

$$\alpha_2 = \pm \alpha_1 \cdot \sqrt{\frac{\bar{S}_{12}}{\bar{S}_{21}}}$$

$$\alpha_3 = \pm \alpha_1 \cdot \sqrt{\frac{\bar{S}_{13}}{\bar{S}_{31}}}$$

$$\alpha_4 = \pm \alpha_3 \cdot \sqrt{\frac{\bar{S}_{34}}{\bar{S}_{43}}}$$

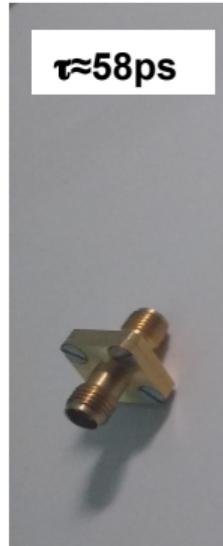
# Calibration comparison on a 4-port system

Multiport 'thru' standards for SOLT and SOLR

[A]

standard 'thru' Tees (minimal losses)

$\tau \approx 58\text{ps}$



[B]

standard 'thru' Tees (minimal losses)



[C]

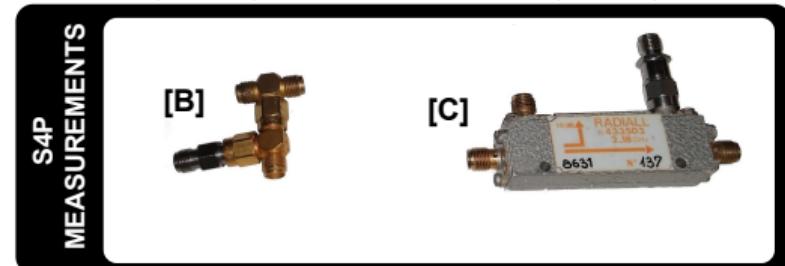
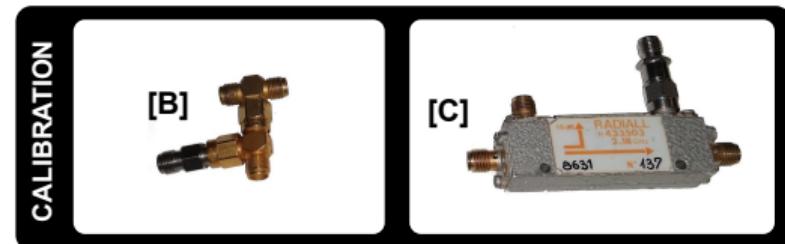
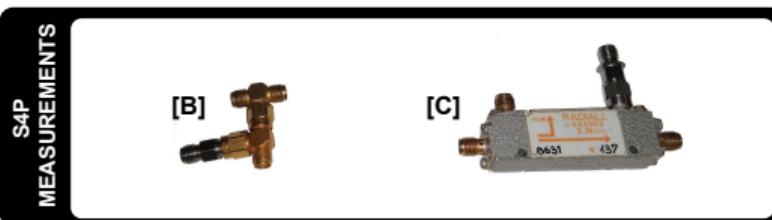
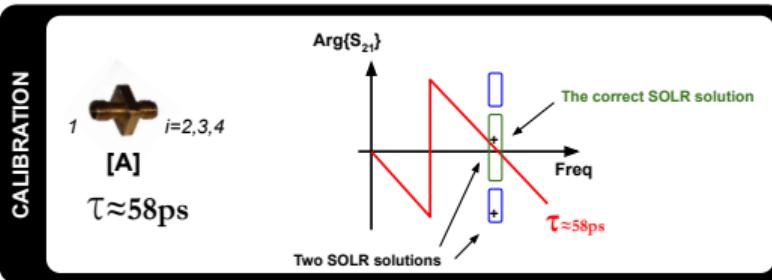
Coupler (high isolation)



# Calibration comparison on a 4-port system

The 2-port SOLR method is our reference to compare measurements

$$\alpha_i = \pm \alpha_1 \cdot \sqrt{\frac{\bar{S}_{1i}}{\bar{S}_{i1}}}$$



# Calibration comparison on a 4-port system

## S4P comparison results

	Calibrated with [B]		Calibrated with [C]	
	SOLT	SOLR	SOLT	SOLR
Measured [B]				
Measured [C]				



# Multiport NVNA in LabVIEW

## Unleash your NVNA



**INSTRUMENT**

FREQUENCY (GHz)

START: 1 STOP: 3 Points: 3 Phase Ref.: None OK

Name: my NVNA VISA: GPIB0::20 Driver: R&S ZVA 24

**POR**T

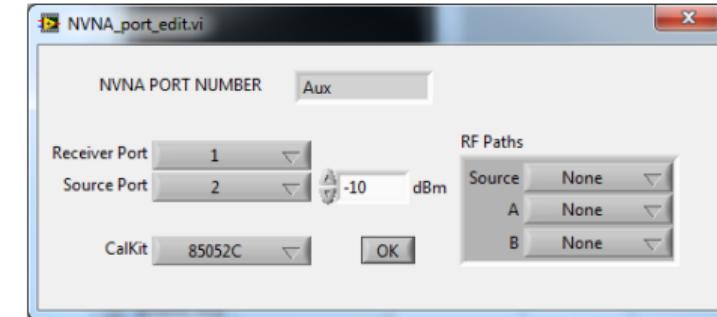
PORT	VNA Port	VNA Source	RF Path	S	O	L	Power	Phase	A
Aux.	1	2	---	Y	Y	Y	-	-	
1	1	1	---	Y	Y	Y	-	-	
2	2	2	---	Y	Y	Y	-	-	

**CALIBRATION**

Standard: LOAD: 85052C (Agilent) CALIBRATE X VIEW

THRU: Method: SOLT SnP Standard: 1

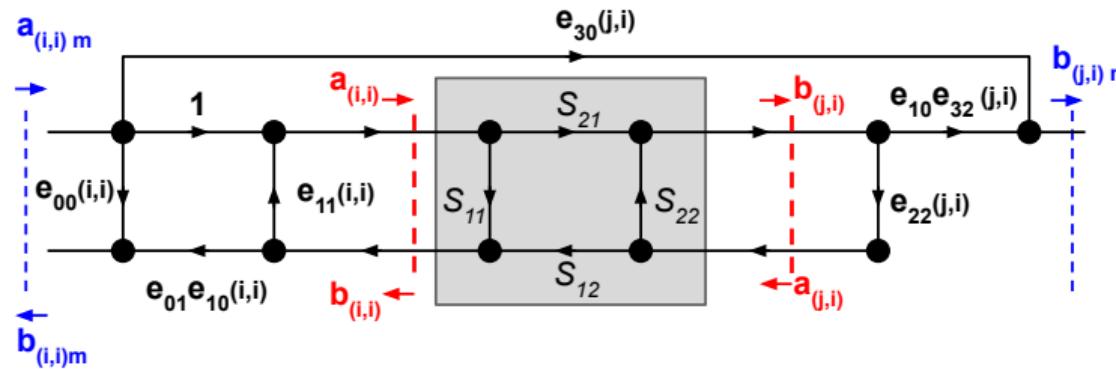
ADD EDIT DEL



- Each port include its CalKit, RF power for calibration, Switch matrix configuration and physical source and receiver ports ;
- A NVNA is a unlimited array of predefined ports ;
- Once each port is SOL calibrated, “Thru” calibration require a SnP file for SOLT and SOLR.

# GSOLT conversion

Export your error terms to a commercial VNA



## Diagonal Matrices

- Directivity:  $[e_{00}] = \text{diag}\left(-\frac{\gamma_i}{\delta_i}\right)$
- Reflection Tracking:  $[e_{11}] = \text{diag}\left(\frac{\beta_i}{\delta_i}\right)$
- Source Match:  $[e_{01}e_{10}] = \text{diag}\left(\frac{\alpha_i\delta_i - \beta_i\gamma_i}{(\delta_i)^2}\right)$

## Zero Diagonal Matrices

- Load Match:  $[e_{22}(j,i)] = \frac{\bar{a}(j,i)}{b(j,i)}$
- Transmission Tracking:  $[e_{10}e_{32}(j,i)] = \frac{\alpha_i\delta_i - \beta_i\gamma_i}{\delta_i\delta_j}$
- Crosstalk (Isolation):  $[e_{30}(j,i)] = \frac{b_{j,i} m}{a_{i,i} m}$



# Conclusion

## SOLT and SOLR calibration method using a single multiport “Thru”

- Theory, algorithm and validation have been presented ;
- Those methods are the fastest possible by reducing the number of “Thru” calibration steps ;
- Multiport NVNA error-terms can be exported to commercial multiport VNA ;
- Multiport NVNA structure is versatile.

## Domain of application

- Dual-input power amplifier analysis (Digital Doherty and LMBA) ;
- Behavioral modeling of beamformer circuits ;
- Large-signal measurements and validation for phased array antennas.