Incomplete 2-Port Vector Network Analyzer Calibration Methods

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***Abstract*— Different types of incomplete 2-port vector network analyzer (VNA) calibration methods are explained. All of them are particular cases of the 12-term error model and a comparison, including advantages and disadvantages, between them and a Full 2-Port method, such as TOSM, is made.**

***Resumen*— En el presente informe se explican los distintos tipos de calibración incompleta de un VNA de 2 puertos. Todos ellos son casos particulares del modelo de 12 términos de error, y se realiza una comparación, incluyendo ventajas y desventajas, entre ellos respecto a un método Full 2-Port como el método TOSM.**

I. Introduction

When calibrating a 2-Port VNA, Full 2-Port calibration is usually employed [1]. There are different types of methods depending on the error model to be considered. The most common calibration method used for coaxial systems is TOSM (also known as SOLT) which uses the 12-term error model [2]. However, this method requires an 8-step procedure to get both ports calibrated.

When is not necessary to measure all four scattering parameters (i.e. S_{11}, S_{12}, S_{21} and S_{22}) of the Device Under Test (DUT) or uncertainties are not necessary to be as small as possible, alternative calibration methods may be employed. Advantages and disadvantages must be previously considered in order to determine which one will be the best option for each particular case.

II. TOSM Calibration

Before measuring any DUT S-parameters, both VNA's ports must be first calibrated in order to calculate system errors. Most common employed method is TOSM. It consists in calculating 6 forward (F) and 6 reverse (R) error terms as shown in figures 1 and 2.

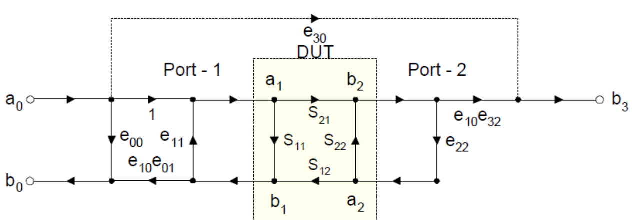

Fig. 1 Forward 12-term error model flow chart

where forward error terms are

e_{00} :	Directivity (F)
e_{11} :	Port-1 Source Match (F)
$e_{10}e_{01}$:	Reflection Tracking (F)
$e_{10}e_{32}$:	Transmission Tracking (F)
e_{30} :	Leakage (Crosstalk)(F)
e_{22} :	Port-2 Load Match (F)

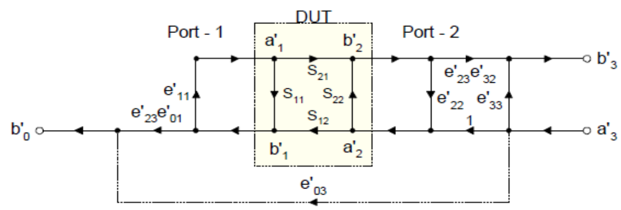

Fig. 2 Reverse 12-term error model flow chart

where reverse error terms are

e'_{33} :	Directivity (R)
e'_{11} :	Port-1 Load Match (R)
$e'_{23}e'_{32}$:	Reflection Tracking (R)
$e'_{23}e'_{01}$:	Transmission Tracking (R)
e'_{03} :	Leakage (Crosstalk) (R)
e'_{22} :	Port-2 Source Match (R)

Solving measured S-parameters from figures 1 and 2 [2]

$$S_{11\mathrm{M}} = \frac{b_0}{a_0} = e_{00} + \frac{e_{10}e_{01}\cdot(S_{11} - e_{22}\Delta_S)}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta_S} \quad (1)$$

$$S_{21\mathrm{M}} = \frac{b_3}{a_0} = e_{30} + \frac{e_{10}e_{32}\cdot S_{21}}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta_S} \quad (2)$$

$$S_{22\mathrm{M}} = \frac{b'_3}{a'_3} = e'_{33} + \frac{e'_{23}\,e'_{32}\cdot(S_{22} - e'_{11}\,\Delta_S)}{1 - e'_{11}\,S_{11} - e'_{22}\,S_{22} + e'_{11}\,e'_{22}\,\Delta_S} \quad (3)$$

$$S_{12\mathrm{M}} = \frac{b'_0}{a'_3} = e'_{03} + \frac{e'_{23}\,e'_{01}\cdot S_{12}}{1 - e'_{11}\,S_{11} - e'_{22}\,S_{22} + e'_{11}\,e'_{22}\,\Delta_S} \quad (4)$$

where

S_{xxM}:	Measured, i.e. uncorrected, S-parameters
S_{xx}:	Corrected S-parameters

$$\Delta_S = S_{11}S_{22} - S_{12}S_{21} \quad (5)$$

A. VNA Calibration

Calibration procedure consists in measuring 7 different reference standards (2 Opens, 2 Shorts, 2 Matches and a Thru) with known reflection and/or transmission values from a TOSM calibration kit. In this paper reference standards are considered to have ideal values as follows

$$\Gamma_{OPEN} = 1 \tag{6}$$

$$\Gamma_{SHORT} = -1 \tag{7}$$

$$\Gamma_{MATCH} = 0 \tag{8}$$

$$S_{THRU} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \tag{9}$$

To perform a complete 2-Port calibration, an 8-step procedure must be done as follows

Step 1: Connect $Open_1$ to Port 1
Step 2: Connect $Short_1$ to Port 1
Step 3: Connect $Match_1$ to Port 1
Step 4: Connect $Open_2$ to Port 2
Step 5: Connect $Short_2$ to Port 2
Step 6: Connect $Match_2$ to Port 2
Step 7: Connect $Match_1$ Port 1 / $Match_2$ Port 2
Step 8: Connect Thru between Port 1 and Port 2

1) Port 1 Calibration: Making steps 1 to 3, an OSM calibration [2] to Port 1 is performed and the following forward error terms are calculated from (1)

$$e_{00} = S_{11M}\left(match_1\right) \tag{10}$$

$$e_{11} = \frac{S_{11M}(open_1) + S_{11M}(short_1) - 2 \cdot e_{00}}{S_{11M}(open_1) - S_{11M}(short_1)} \tag{11}$$

$$e_{10}e_{01} = \frac{-2 \cdot \left[S_{11M}(open_1) - e_{00}\right] \cdot \left[S_{11M}(short_1) - e_{00}\right]}{S_{11M}(open_1) - S_{11M}(short_1)} \tag{12}$$

TABLE I
PORT 1 CALIBRATION SUMMARY

Reference	Error to be corrected	Description
$Open_1$	e_{11}	Source Match (F)
$Short_1$	$e_{10}e_{01}$	Reflection Tracking (F)
$Match_1$	e_{00}	Directivity (F)

2) Port 2 Calibration: Making steps 4 to 6, an OSM calibration to Port 2 is performed and the following reverse error terms are calculated from (3)

$$e'_{33} = S_{22M}\left(match_2\right) \tag{13}$$

$$e'_{11} = \frac{S_{22M}(open_2) + S_{22M}(short_2) - 2 \cdot e'_{33}}{S_{22M}(open_2) - S_{22M}(short_2)} \tag{14}$$

$$e'_{23}e'_{32} = \frac{-2 \cdot \left[S_{22M}(open_2) - e'_{33}\right] \cdot \left[S_{22M}(short_2) - e'_{33}\right]}{S_{22M}(open_2) - S_{22M}(short_2)} \tag{15}$$

TABLE II
PORT 2 CALIBRATION SUMMARY

Reference	Error to be corrected	Description
$Open_2$	e'_{11}	Source Match (R)
$Short_2$	$e'_{23}e'_{32}$	Reflection Tracking (R)
$Match_2$	e'_{33}	Directivity (R)

3) Isolation Ports Calibration: Step 7 is optionally made only when very low transmission parameters must be measured. In most cases this error term is neglected.

$$e_{30} = S_{21M}\left(match_{1,2}\right) \tag{16}$$

$$e'_{03} = S_{12M}\left(match_{1,2}\right) \tag{17}$$

TABLE III
ISOLATION PORTS CALIBRATION SUMMARY

Reference	Error to be corrected	Description
$Match_1$	e_{30}	Crosstalk (F)
$Match_2$	e'_{03}	Crosstalk (R)

4) Calibration between Ports: When making step 8 both Load Match and Transmission Tracking error terms are calculated from (1), (2), (3) and (4) as follows

$$e_{22} = \frac{S_{11M}(Thru) - e_{00}}{S_{11M}(Thru) \cdot e_{11} - \Delta e} \tag{18}$$

$$e_{10}e_{32} = \left[S_{21M}(Thru) - e_{30}\right] \cdot (1 - e_{11}e_{22}) \tag{19}$$

$$e'_{11} = \frac{S_{22M}(Thru) - e'_{33}}{S_{22M}(Thru) - \Delta e'} \tag{20}$$

$$e'_{23}e'_{32} = \left[S_{12M}(Thru) - e'_{03}\right] \cdot (1 - e'_{33}e'_{11}) \tag{21}$$

where

$$\Delta e = e_{00}.e_{11} - e_{01}e_{10} \tag{22}$$

$$\Delta e' = e'_{33}.e'_{22} - e'_{23}e'_{32} \tag{23}$$

TABLE IV
CALIBRATION BETWEEN PORTS SUMMARY

Reference	Error to be corrected	Description
Thru	e_{22}	Load Match (F)
	e'_{11}	Load Match (R)
	$e_{10}e_{32}$	Transmission Tracking (F)
	$e'_{23}e'_{01}$	Transmission Tracking (R)

Equations (10) to (21) represent the 12 error terms to be calculated.

B. DUT S-Parameters Measurement

Solving equations (1) to (4), corrected S-parameters of the DUT can be expressed as follows [1]–[4]

$$S_{11} = \frac{A_{11} \cdot (1 + A_{22} \cdot e'_{22}) - e_{22} \cdot A_{21} \cdot A_{12}}{D} \tag{24}$$

$$S_{21} = \frac{A_{21} \cdot [1 + A_{22} \cdot (e'_{22} - e_{22})]}{D} \tag{25}$$

$$S_{22} = \frac{A_{22} \cdot (1 + A_{11} \cdot e_{11}) - e'_{11} \cdot A_{21} \cdot A_{12}}{D} \tag{26}$$

$$S_{12} = \frac{A_{12} \cdot [1 + A_{11} \cdot (e_{11} - e'_{11})]}{D} \tag{27}$$

where

$$N_{11} = \frac{S_{11M} - e_{00}}{e_{10} e_{01}} \tag{28}$$

$$N_{12} = \frac{S_{12M} - e'_{03}}{e'_{23} e'_{01}} \tag{29}$$

$$N_{21} = \frac{S_{21M} - e_{30}}{e_{10} e_{32}} \tag{30}$$

$$N_{22} = \frac{S_{22M} - e'_{33}}{e'_{23} e'_{32}} \tag{31}$$

$$D = (1 + A_{11} \cdot e_{11}) \cdot (1 + A_{22} \cdot e'_{22}) - A_{21} \cdot A_{12} \cdot e_{22} \cdot e'_{11} \tag{32}$$

where N_{xx} are normalized S-parameters [4].

C. Full 2-Port: Advantages and Disadvantages

1) Advantages: Provides low uncertainties as all 12 error terms are calculated and all four DUT S-parameters are measured.

2) Disadvantages: Needs an 8-step procedure calibration. It is always necessary to measure all four DUT S-parameters even if only one is needed to be corrected.

III. Incomplete 2-Port VNA Calibration

In the past, VNAs had only a transmission/reflection (T/R) test set. This allowed only forward parameters to be measured, since Port 1 acted as a source and Port 2 as a load. Then, calibration methods used were:

- Transmission Response (TR)
- 1-Port + Normalization (1-P+N)
- Enhanced Response(ER)
- One-Path 2-Port (1-P 2-P)

Nowadays, most VNAs have a full S-parameter test set. This allows the source to be switched to both ports, hence it is able to measure all four S-parameters and a TOSM, i.e. complete, calibration can be done.

However, when it is not necessary (or convenient for some reason) to measure all four DUT S-parameters or, uncertainties are not necessary to be as small as possible, above mentioned incomplete calibration methods can be used [5]. All of them are partial calibrations based on TOSM method described in section II.

To simplify mathematical expressions, crosstalk error terms will be considered null valued for all cases

$$e_{30} = 0 \tag{33}$$

$$e'_{03} = 0 \tag{34}$$

IV. Transmission Response

It is the simplest 2-Port calibration method and is used when only S_{21} (or S_{12}) parameter is of interest. A Thru reference element is connected between ports for the calibration, so only transmission tracking error term is partially calculated. This causes the highest uncertainties in transmission S-parameter measurements.

A. VNA Calibration (between Ports)

From (2) and (33):

$$S_{21\mathrm{M}} = \frac{e_{10} e_{32} \cdot S_{21}(Thru)}{1 - e_{11} S_{11}(Thru) - e_{22} S_{22}(Thru) + e_{11} e_{22} \Delta_S (Thru)} \tag{35}$$

Applying (9) in (30)

$$S_{21\mathrm{M}} = e_{10} e_{32} \cdot \frac{1}{1 - e_{11} e_{22}} \tag{36}$$

As neither e_{11} nor e_{22} are calculated, the correction term related to them is considered null valued.

$$e_{11} e_{22} = 0 \tag{37}$$

Replacing (37) in (36)

$$e_{10} e_{32} = S_{21\mathrm{M}} \tag{38}$$

Similar considerations are applied for the reverse transmission tracking term

$$e'_{01} e'_{23} = S_{12\mathrm{M}} \tag{39}$$

B. DUT S_{21} (or S_{12}) Measurement

As only S_{21} parameter is measured and $e_{10}e_{32}$ error term is calculated, equation (25) is reduced to

$$S_{21} = \frac{S_{21M}(DUT)}{e_{10} e_{32}} \tag{40}$$

Similar considerations can be applied for S_{12}

$$S_{12} = \frac{S_{12\mathrm{M}}(DUT)}{e'_{23} e'_{01}} \tag{41}$$

C. *Transmission Response: Advantages and Disadvantages*

1) Advantages: Very fast one-step calibration procedure. Only S_{21} needs to be measured in order to get its corrected value, so a good option for unidirectional devices.

2) Disadvantages: Only for transmission (S_{21} or S_{12}) parameters. As Transmission Tracking error term is not calculated correctly, this method is not very accurate with lossy DUTs. On the other hand, it is recommended only for insertable devices as in practice this method always considers ideal Thru values as in (9).

V. 1-PORT + NORMALIZATION

This method performs a 1-Port calibration (at Port 1 or Port 2) and, separately, a transmission response. This is usually employed when only forward parameters (S_{11} and S_{21}) or reverse parameters (S_{22} and S_{12}) are required.

A. *VNA Calibration*

1) Port 1 (or Port 2) Calibration: Procedure is applied in the same manner as in Section II A.1 (or section II A.2).

2) Calibration between Ports: Procedure is applied in the same manner as in Section IV A.

B. *DUT Forward (or Reverse) Parameters Measurement*

As DUT reverse parameters are not measured, e_{22} and all reverse error terms are not calculated, hence all correction terms related to them in (24) and (25) are considered null valued. S_{11} can be expressed as follows

$$S_{11}=\frac{S_{11\mathrm{M}}(DUT)-e_{00}}{S_{11\mathrm{M}}(DUT)\cdot e_{11}-\Delta e} \tag{42}$$

As OSM and transmission normalization calibrations are performed separately, S_{21} corrected value remains the same as in section IV B.

$$S_{21}=\frac{S_{21M}(DUT)}{e_{10}e_{32}} \tag{43}$$

Similar considerations are applied for reverse parameters

$$S_{22}=\frac{S_{22\mathrm{M}}(DUT)-e'_{33}}{S_{22\mathrm{M}}(DUT)\cdot e'_{22}-\Delta e'} \tag{44}$$

$$S_{12}=\frac{S_{12M}(DUT)}{e'_{23}e'_{01}} \tag{45}$$

C. *1-Port + Normalization: Advantages and Disadvantages*

1) Advantages: Corrects directivity, reflection tracking and source match of Port 1 (or Port 2).

2) Disadvantages: Similar as in Transmission Response method.

VI. ENHANCED RESPONSE

It is an improvement of the 1-P+N method for measuring Forward (or Reverse) S-parameters. It needs the same four steps as before to calibrate the VNA but, in this case, it also calculates Load Match error term. This allows Transmission Tracking error term to be correctly calculated.

A. *VNA Calibration*

1) Port 1 (or Port 2) Calibration: Procedure is applied in the same manner as in Section II A.1 (or section II A.2).

2) Calibration between Ports: Procedure is applied in the same manner as in Section II A.4.

B. *DUT Forward (or Reverse) Parameters Measurement*

Although e_{22} is calculated in this case, DUT reverse parameters are not measured and none of the reverse error terms is calculated. Hence, all correction terms related to them in (24) and (25) are considered null valued and S_{11} and S_{21} can be derived as follows

$$S_{11}=\frac{S_{11\mathrm{M}}(DUT)-e_{00}}{S_{11\mathrm{M}}(DUT)\cdot e_{11}-\Delta e} \tag{46}$$

$$S_{21}=\frac{S_{21\mathrm{M}}(DUT)}{e_{10}e_{32}}\cdot\left[\frac{e_{01}e_{10}}{e_{11}S_{11\mathrm{M}}(DUT)-\Delta e}\right] \tag{47}$$

Similar considerations are applied for reverse parameters

$$S_{22}=\frac{S_{22M}(DUT)-e'_{33}}{S_{22\mathrm{M}}(DUT)\cdot e'_{22}-\Delta e'} \tag{48}$$

$$S_{12}=\frac{S_{12\mathrm{M}}(DUT)}{e'_{23}e'_{01}}\cdot\left[\frac{e'_{23}e'_{32}}{e'_{22}S_{22\mathrm{M}}(DUT)-\Delta e'}\right] \tag{49}$$

C. *Enhanced Response: Advantages and Disadvantages*

1) Advantages: Calculates Transmission Tracking error term correctly.

2) Disadvantages: As only Forward (or Reverse) S-parameters are measured, Load Match value can not be used for correcting DUT S-parameters.

VII. ONE-PATH 2-PORT

Originally named One-Path Full 2-Port, was introduced to T/R VNAs in order to measure all four S-parameters. However, DUT must be manually reversed to measure Reverse S-parameters .

At present most VNAs have this calibration option, but special care must be taken as some manufactures consider ER method as 1-P 2-P.

A. VNA Calibration

This method considers Forward and Reverse models the same as follows

$$e_{00} = e'_{33} \tag{50}$$
$$e_{11} = e'_{22} \tag{51}$$
$$e_{10}e_{01} = e'_{23}e'_{32} \tag{52}$$
$$e_{10}e_{32} = e'_{01}e'_{23} \tag{53}$$
$$e_{22} = e'_{11} \tag{54}$$
$$e_{30} = e'_{03} \tag{55}$$

Hence, it needs the same four steps as in the previous methods to calibrate the VNA and only 6 forward error terms are needed to be calculated using (10), (11), (12), (16), (18) and (19).

B. DUT Parameters Measurement

When measuring DUT device, forward parameters are measured first, and then DUT is connected backwards and reverse parameters are measured. This allows equations (24) to (27) to be used with no correction terms null valued.

C. One Path 2-Port: Advantages and Disadvantages

1) Advantages: All four DUT S-parameters can be measured. As Forward and Reverse error terms have same values, only a four-step procedure is needed to calibrate the VNA.

2) Disadvantages: Not recommended for VNAs using any combination of coaxial sexed port connectors due to the necessity of adapters. A series of single sweep and DUT manually change procedure must be performed in order to get all four S-parameters. In practice, uncertainties may be higher that Full 2-Port due to connector mechanical repeatability or cable flexibility.

VIII. SIMULATIONS

A series of comparisons between incomplete calibrations methods respect to TOSM were carried out. S_{11} and S_{21} measurements were simulated and maximal deviation results are shown in figures 3 to 6.

A. S_{11} Deviation Results

Different maximal deviations of $|S_{11}|$ for 1-P+N and ER methods respect to TOSM are shown in figure 3. As in both incomplete methods, S_{11} has the same value (see equations (42) and (46)), such deviations respect to TOSM are the same. These deviations depend on Port 2 Load Match, i.e. e_{22} value, and DUT´s attenuation, i.e. S_{21} value.

For example, if the DUT consists of a 6-dB attenuator and $|e_{22}|$ = 0.1, then maximal deviation respect to TOSM method will be 0.026.

If now the DUT consists of a coaxial cable with nominal 0 dB attenuation value, and $|e_{22}|$ remains in 0.1, then maximal deviation respect to TOSM method arises to 0.100.

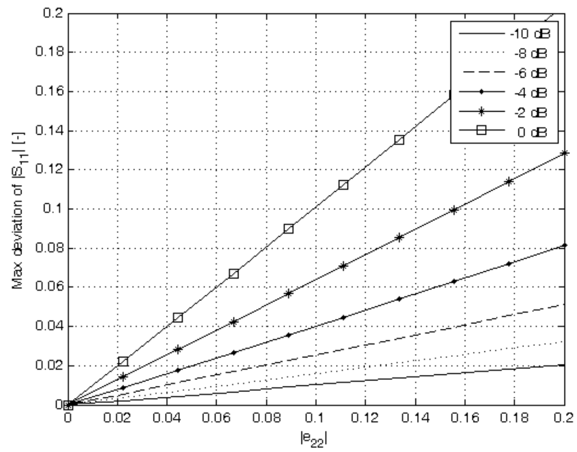

Fig. 3 $|S_{11}|$ maximal deviation for 1-Port + Normalization and Enhanced Response with respect to TOSM method.

B. S_{21} Deviation Results

Different maximal deviations of $|S_{21}|$ for TR and ER methods respect to TOSM are shown in figures 4 and 5 respectively for a DUT having a nominal attenuation value of 0 dB.

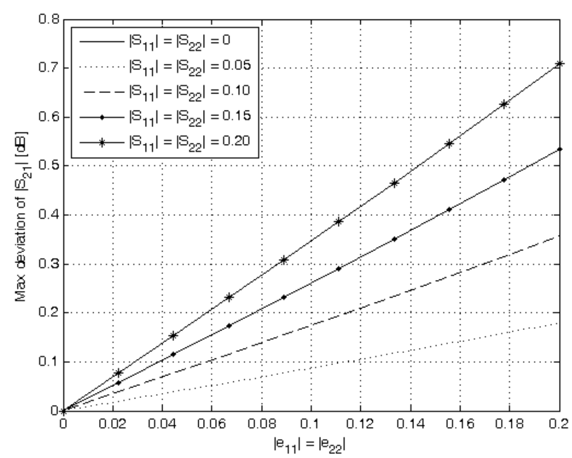

Fig. 4 $|S_{21}|_{dB}$ maximal deviation for Transmission Response with respect to TOSM method when measuring a S_{21} value of 0 dB.

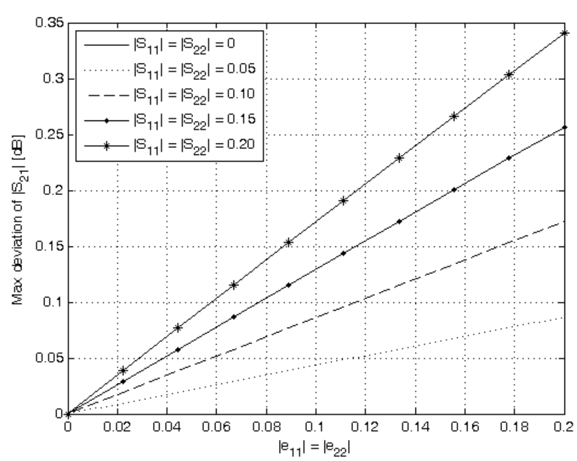

Fig. 5 $|S_{21}|_{dB}$ maximal deviation for Enhanced Response with respect to TOSM method when measuring a S_{21} value between 0 dB and 6 dB.

For example, if DUT´s parameters $|S_{11}| = |S_{22}| = 0.1$, and VNA´s error terms $|e_{11}| = |e_{22}| = 0.1$, then maximal deviation respect to TOSM method will be 0.17 dB for TR method and 0.09 dB for ER method.

According to figures 5 and 6, if now the same DUT has an attenuation value of 6 dB and all other values remain the same, then maximal deviation respect to TOSM method arises to 0.24 dB for TR method and remains in 0.09 dB for ER method.

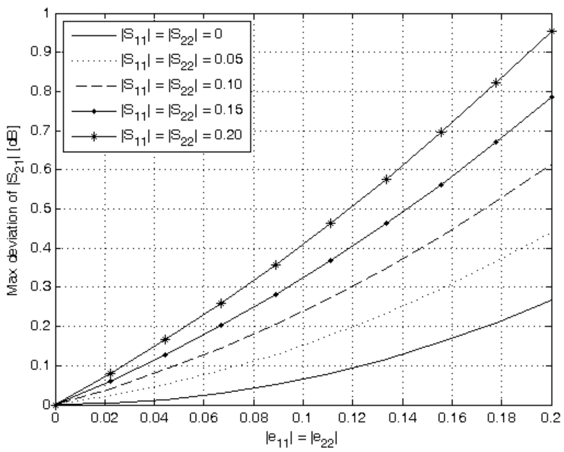

Fig. 6 $|S_{21}|_{dB}$ maximal deviation for Transmission Response with respect to TOSM method when measuring a S_{21} value of -6 dB.

IX. CONCLUSIONS

Different types of incomplete 2-Port VNA calibrations methods are explained in this paper. Each one of them has its own advantages and disadvantages respect to a complete 2-Port method as TOSM.

In practice, if VNA´s error terms and/or DUT´s mismatches are quite low, there will be no significant deviation between incomplete and complete calibration methods when measuring S_{11} or S_{21}. On the contrary, if VNA´s source and load match error term values are considerable and also DUT is lossy, then incomplete methods are not suitable due to the significant deviations they may have.

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