Calibration of Test Fixtures Using at Least Two Standards

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Abstract —**A study is made of the determination of the error networks in the measurements of microwave circuits with arbitrary test fixtures. A general-purpose de-embedding method for known standards is shown. Also a method for symmetrical test fixtures is described. The method uses only two fixture standards, of which one must be a two-port standard with a transmission not equal to zero. A computer simulation is used to compare the error sensitivities of the different calibration algorithms.**

I. Introduction

Microstrip and stripline circuits, semiconductor devices, etc. are difficult to measure because they usually cannot be connected directly to the network analyzer. Some kind of test fixture with a pair of coaxial-to-microstrip launchers is needed.

The fixture produces in the signal path a discontinuity that affects the measurement greatly. The S parameters measured with the fixture have to be corrected in order to get acceptable results. Precise knowledge of the electrical characteristics of the fixture is essential to compensate the errors.

The fixture–coaxial transition is sometimes modeled approximately with transmission lines and lumped components. The models are based on the S parameters measured with a "thru" line standard. In the optimization the fixture is often assumed to be symmetrical [1], [2]. Usually at least three reference measurements with different standards are made to calibrate the fixture–analyzer system (one-tier calibration). If the analyzer is precalibrated alone at its coaxial terminals, additional calibration measurements are made with the standards on the fixture (two-tier calibration).

Many calibration procedures have been published in the literature [1], [3]–[9]. Most of them use transmission line and short circuit or open circuit standards. Three or more standards are needed to accurately determine the error networks.

In this paper new general-purpose calibration procedures will be shown using at least two fixture standards. The method makes it possible to use transmission lines (not only 50 Ω), microstrip open ends, gaps, etc. as calibration standards if their S parameters can be calculated. Also, the dispersion of the transmission lines can be taken into account. The automatic network analyzer must be calibrated first with its own standards. In the three-standard case the method can be considered a simplification of the super TSD method [4]. The two-standard case is applicable only with symmetrical test fixtures, which, however, are the most common type. The only restriction is that at least one of the standards must have a transmission path. Furthermore, the method is not very sensitive to the slight asymmetry inevitable in practice. The symmetry of the test fixture at different frequencies can easily be tested by comparing the measured reflection coefficients S_{11} and S_{22} of the fixture–standard combination. In fact, total symmetry is not necessarily needed. It is only required that the ratio of the S_{21}'s of each half of the fixture (error network) be approximately equal to 1 or be precisely known.

The symmetry assumption has also been used in references [10]–[13], but they are all restricted to 50 Ω transmission line standards. In [14] the error networks are assumed to be both symmetric and matched. The widely used TRL/LRL method assumes only the reflection standard to be symmetric. A method to calculate the leakage and the fringing capacitances of the fixture is outlined in [15]. The crosstalk problem has not been treated in this paper.

There exist a number of different solutions for the calibration equations. Although the results are mathematically correct, they differ from each other as a consequence of measurement and other errors. The existence of more than one solution comes from the fact that in the measurements of two or more calibration standards we often have more information than strictly needed to calculate the error networks. Different equations ($2 \cdots 4$/measured standard) use different S parameters from the incorrect input data. The calculated results are thus dependent of the choice of the equations. Possible data reduction techniques are described in, e.g., [11].

When the error networks are known, the device is measured and its S parameters can be de-embedded explicitly as shown, e.g., in [4], [11], [16], and [17].

II. De-embedding with an Arbitrary Test Fixture

A. Asymmetrical Case

The measurement network in Fig. 1 is assumed to be connected to a calibrated network analyzer. To determine the left and right error networks $\boldsymbol{L}$ and $\boldsymbol{R}$ at least three calibration measurements, $\boldsymbol{M}_A$, $\boldsymbol{M}_B$, and $\boldsymbol{M}_C$, are normally made successively with standards $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$. For convenience two-port $\boldsymbol{R}$ is cascaded here in the opposite direction to the other two-ports (port one on the right-hand side).

The following equations in terms of the S parameters can be found for the measurement network shown in Fig. 1 using the wave scattering matrices, flow graph analysis, or related

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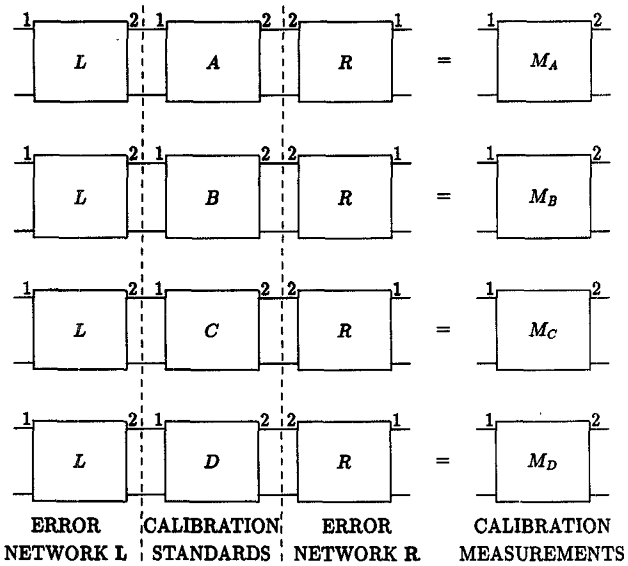

Fig. 1. Block diagram for the calibration of the test fixture.

techniques [4]:

$$(1-L_{22}A_{11})M_{A11}-R_{22}\frac{L_{21}}{R_{21}}A_{21}M_{A12}=L_{11}-\Delta LA_{11} \quad (1)$$

$$-L_{22}A_{12}M_{A11}+(1-R_{22}A_{22})\frac{L_{21}}{R_{21}}M_{A12}=-\Delta LA_{12} \quad (2)$$

$$(1-L_{22}A_{11})M_{A21}-R_{22}\frac{L_{21}}{R_{21}}A_{21}M_{A22}=-\Delta R\frac{L_{21}}{R_{21}}A_{21} \quad (3)$$

$$-L_{22}A_{12}M_{A21}+(1-R_{22}A_{22})\frac{L_{21}}{R_{21}}M_{A22}=(R_{11}-\Delta RA_{22})\frac{L_{21}}{R_{21}} \quad (4)$$

where $\Delta L=L_{11}L_{22}-L_{12}L_{21}$ and $\Delta R=R_{11}R_{22}-R_{12}R_{21}$.

The error networks can be identified in the general case with no symmetry assumption by using e.g. equations (1_A), (2_A) or (3_A), (4_A), (1_B), (4_B), (1_C), (4_C), where 1_A = equation (1) with standard $\boldsymbol{A}$. The equations needed can be chosen from (1)–(4) in some other ways, too. They form a set of seven linear equations for L_{11}, L_{22}, ΔL, kR_{11}, kR_{22}, $k\Delta R$, and $k=L_{21}/R_{21}$, from which the unknown two-ports $\boldsymbol{L}$ and $\boldsymbol{R}$ can be solved.

The measurements with two different standards are not totally independent, because, for any reciprocal error two-ports $\boldsymbol{L}$ and $\boldsymbol{R}$, $M_{A12}A_{21}=M_{A21}A_{12}$, $M_{B12}B_{21}=M_{B21}B_{12}$, and

$$\begin{aligned}(M_{A22}-M_{B22})A_{21}B_{12}*\\ [(\Delta A+\Delta B-A_{11}B_{22}-B_{11}A_{22})M_{A12}M_{B21}\\ -(\Delta M_A+\Delta M_B-M_{A11}M_{B22}\\ -M_{B11}M_{A22})A_{12}B_{21}]=0.\end{aligned} \quad (5)$$

This means that after we have got three independent equations from the measurement of the first two-port standard, every new standard gives only two independent equations more. It does not matter, whether they are one-ports or two-ports. Formula (5) is the determinant of the matrix containing equations (1), (2), (3), and (4) of standard $\boldsymbol{A}$ and equations (2), (3), and (4) of standard $\boldsymbol{B}$. The relation is characteristic of this type of flow graph. It is also valid, if standards $\boldsymbol{A}$ and $\boldsymbol{B}$ are nonreciprocal.

Thus two measurements $\boldsymbol{M}_A$ and $\boldsymbol{M}_B$ do not allow the determination of all six unknown parameters (excluding the leakage) in the error networks of the asymmetrical test fixtures.

B. Nearly Symmetrical Case, $L_{21}=R_{21}$

If the ratio L_{21}/R_{21} is known or assumed to be equal to 1, as in symmetrical test fixtures, only two standards, $\boldsymbol{A}$ and $\boldsymbol{B}$, are needed to solve the unknowns. One of the standards has to be a two-port. If $L_{12}/R_{12}=L_{21}/R_{21}=1$, the solution is automatically such that

$$L_{12}L_{21}=L_{11}L_{22}-\Delta L=R_{11}R_{22}-\Delta R=R_{12}R_{21} \quad (6)$$

because in fact we have only five unknowns. If standard $\boldsymbol{B}$ is a "dual one-port" standard, equations (1_A), (2_A), (3_A), (4_A), (1_B), and (4_B) have to be used, because (2_B) and (3_B) are no longer available. The solution is not singular, although in (1)–(4) there are only three independent equations (reciprocity). If both of the standards are two-ports, some other equation combinations also are applicable.

C. Symmetrical Case

The symmetrical case means that matrices $\boldsymbol{L}$ and $\boldsymbol{R}$ are identical, which is a valid assumption in many practical test fixtures [1], [2], [9], [11]:

$$R_{11}=L_{11} \qquad R_{12}=L_{12} \qquad R_{21}=L_{21} \qquad R_{22}=L_{22}.$$

Equations (1)–(4) then form a set of four linear equations for the unknowns L_{11}, L_{22}, and ΔL:

$$L_{11}+L_{22}(A_{11}M_{A11}+A_{21}M_{A12})-\Delta LA_{11}=M_{A11} \quad (7)$$

$$L_{22}(A_{12}M_{A11}+A_{22}M_{A12})-\Delta LA_{12}=M_{A12} \quad (8)$$

$$L_{22}(A_{11}M_{A21}+A_{21}M_{A22})-\Delta LA_{21}=M_{A21} \quad (9)$$

$$L_{11}+L_{22}(A_{12}M_{A21}+A_{22}M_{A22})-\Delta LA_{22}=M_{A22}. \quad (10)$$

It can be shown that two measurements, $\boldsymbol{M}_A$ and $\boldsymbol{M}_B$, are needed to solve the unknown parameters. One measurement would not be enough, even if the calibration standard were asymmetrical and nonreciprocal. This is because the measured S parameters M_{Aii} and M_{Aij} are related to each other in the symmetrical case by the following equations:

$$(M_{A11}-M_{A22})A_{12}=(A_{11}-A_{22})M_{A12} \quad (11)$$

$$M_{A12}A_{21}=M_{A21}A_{12} \quad (12)$$

which means that in (7)–(10) there are only two linearly independent equations. Three equations from the measurements of at least two standards have to be chosen to solve the unknowns. In accordance with inaccurate input data (measurement error, inaccurately known standards) the solutions differ at least slightly. If standard $\boldsymbol{B}$ has a nearly zero transmission, as with, for example, practical open or short circuit standards, (8_B) and (9_B) become identically zero. The nonsingular solutions are then (7_A, 8_A or 9_A, 7_B), (7_A, 8_A or 9_A, 10_B), (8_A or 9_A, 10_A, 7_B), (8_A or 9_A, 10_A, 10_B). These equation combinations also give the best results with "thru" and delay line standards.

D. TD Method

A special case of (5) is used in the TSD and LRL methods [3], [5] to find the difference in phase and loss of the two lines. If $A_{11} = A_{22} = B_{11} = B_{22} = 0$, (5) can be written

$$2\cosh(\gamma_A s_A - \gamma_B s_B) = \frac{A_{21}}{B_{21}} + \frac{B_{12}}{A_{12}} = \frac{M_{A11}M_{B22} + M_{B11}M_{A22} - \Delta M_A - \Delta M_B}{M_{A12}M_{B21}} \tag{13}$$

where γ_A, γ_B = propagation constants of the transmission lines, and s_A, s_B = line lengths.

In the LRL method an unknown reflection standard can be used if the length and the attenuation of one line is known. In the thru-delay-method (TD) (1)–(4) can be solved for 50 Ω transmission line standards assuming $k = 1$ as in [10]–[13]:

$$L_{11} = \frac{M_{A11}M_{B12} - \dfrac{A_{21}}{B_{21}}M_{A12}M_{B11}}{M_{B12} - \dfrac{A_{21}}{B_{21}}M_{A12}} \tag{14}$$

$$R_{11} = \frac{M_{A22}M_{B21} - \dfrac{A_{12}}{B_{12}}M_{A21}M_{B22}}{M_{B21} - \dfrac{A_{12}}{B_{12}}M_{A21}} \tag{15}$$

$$L_{22} = \frac{M_{A12} - \dfrac{A_{21}}{B_{21}}M_{B12}}{A_{12}(M_{A11} - M_{B11})} \tag{16}$$

$$R_{22} = \frac{M_{A21} - \dfrac{A_{12}}{B_{12}}M_{B21}}{A_{21}(M_{A22} - M_{B22})} \tag{17}$$

$$\Delta L = \frac{M_{A12}M_{B11} - \dfrac{A_{21}}{B_{21}}M_{A11}M_{B12}}{A_{12}(M_{A11} - M_{B11})} \tag{18}$$

$$\Delta R = \frac{M_{A21}M_{B22} - \dfrac{A_{12}}{B_{12}}M_{A22}M_{B21}}{A_{21}(M_{A22} - M_{B22})} \tag{19}$$

where $A_{12} = A_{21} = e^{-\gamma_A s_A}$ and ratio $A_{12}/B_{12} = A_{21}/B_{21}$ can be calculated from (13). In addition to the measurement data only $e^{-\gamma_A s_A}$ should be known. For a zero-length line $A_{21} = 1$.

E. Identification of the Phase of L_{21}

In most calibration methods L_{11}, L_{22}, and ΔL are solved. Normally we cannot identify L_{12} and L_{21} separately. However, if matrix $\boldsymbol{L}(\boldsymbol{R})$ is reciprocal as usual,

$$L_{12} = L_{21} = \pm\sqrt{L_{11}L_{22} - \Delta L}\,. \tag{20}$$

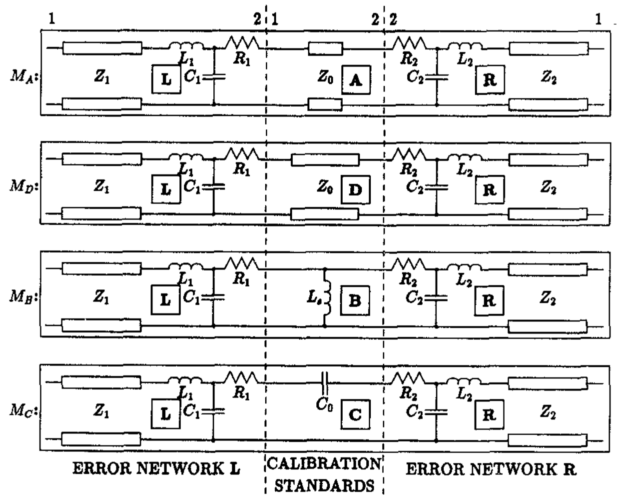

Fig. 2. Example networks used in the error simulation.

TABLE I
NOMINAL COMPONENT VALUES OF THE *RLC* NETWORKS

R_1 [Ω]	L_1 [nH]	C_1 [pF]	R_2 [Ω]	L_2 [nH]	C_2 [pF]
0.5	0.015	0.075	0.5	0.015	0.075

In the symmetrical case the choice of the sign does not affect the de-embedding, but the same sign has to be used for both error networks. Generally the phase (sign) of L_{12} and L_{21} can be found on the basis of the mechanical measures of the error networks or based on the measurements made at a comparatively low frequency. Because the question is only to choose one of the two angles separated by 180°, a rather crude method will do. A good way is to compare the phase of L_{21} with the phase of a similar length (s) of transmission line. If the characteristic impedance of the line is approximately equal to the normalization impedance, then $\arg[S_{21}] \approx -\beta s$ (β = phase constant).

III. Simulation

A computer simulation was done for the networks in Fig 2. The S parameters of the calibration standards and the artificial measurement data were produced by the circuit design program APLAC [18]. The S parameters were used as the input data for the general-purpose calibration and de-embedding program CADEP [19]. A simple *RLC* network (Table I) was assumed to represent the connection discontinuities between the standards and the test fixture. The *RLC* networks were included in the error two-ports. To simulate some of the different errors appearing in practice the element values of these networks were randomly changed at each frequency during the calibration measurements. The variation in each of the six lumped components was within ±50% of their nominal values with even distribution. The *RLC* networks have so little effect on the overall S parameters that even a ±50% variation of the values do not destroy the de-embedding process. The random values of R_1, L_1, C_1, R_2, L_2, and C_2 simulate errors of the S parameters of the standards and their contact leads.

For simplicity, error networks $\boldsymbol{L}$ and $\boldsymbol{R}$ are transmission lines with the *RLC* network connected to one end. The slight asymmetry of the test fixture was caused by a 1%

TABLE II
TRANSMISSION LINE PARAMETERS

Line	Impedance Z [Ω]	Delay [ns]	Attenuation [dB]	Name
L	55	0.134	0.2	Left error network
R	55.55	0.13534	0.2	Right error network
A	50	0.025	0.1	(Nonzero-length) "thru"
D	50	0.050	0.2	Delay

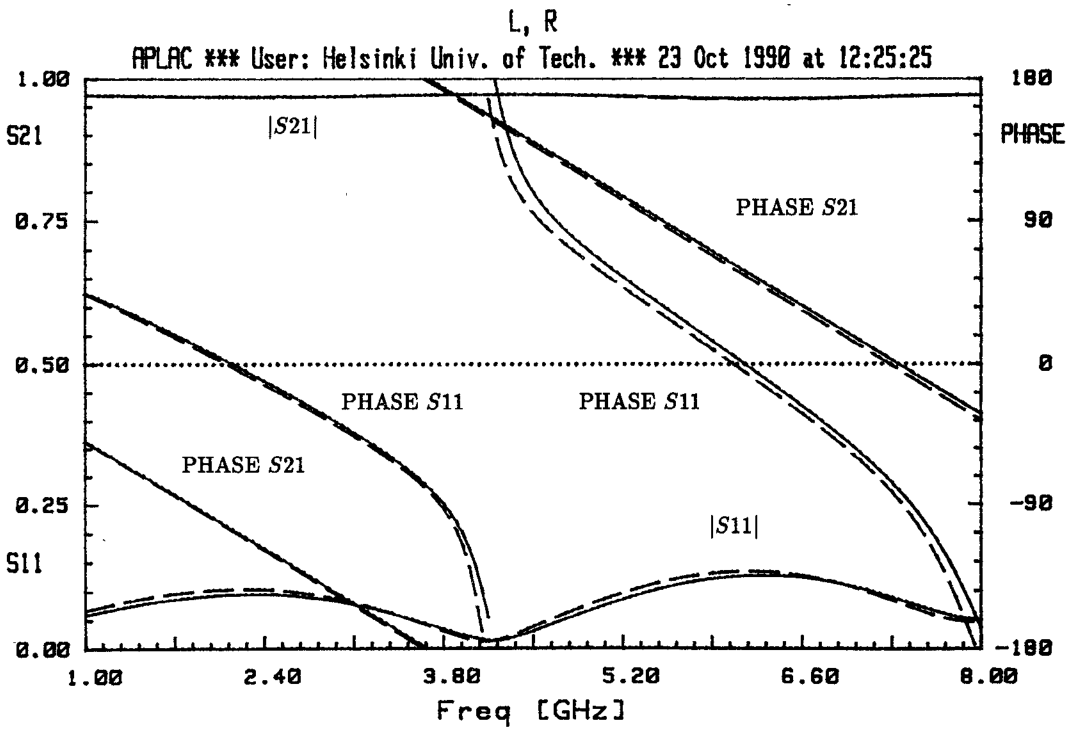

Fig. 3. Correct S parameters of the error networks. Solid line: $\boldsymbol{L}$. Dashed line: $\boldsymbol{R}$.

difference in the transmission line parameters (see Table II). Also the left and right RLC networks have randomly different values.

The standards used were two transmission lines, an open and a short circuit thus allowing a comparison with the TSD (thru-short-delay), LRL (line-reflect-line), and TSO (thru-short-open) methods [3], [5], [6], [7]. The parameters of the transmission lines were as in Table II. The shorter line, $\boldsymbol{A}$, is named thru and the longer one, $\boldsymbol{D}$, delay. The short circuit ($\boldsymbol{B}$) was modeled simply with a shunt inductance $L_s = 0.02$ nH and the open circuit ($\boldsymbol{C}$) with a small series capacitance $C_o = 0.01$ pF.

IV. Discussion and Comparison with the Earlier Methods

The calibration was performed with the normal TSD, LRL, and TSO methods using the appropriate standards. The TSD method was modified slightly to include as input data the S parameters of the reflection standard [19]. So it was not restricted to the short circuit termination. Also, the calculations both with the super TSD-method [4] and with (1)–(4) (solution: (1_A), (2_A), (4_A), (1_B), (4_B), (1_C), (4_C)) for the same combinations of standards were done.

In the symmetrical case all eight nonsingular solutions mentioned in subsection II-C of both the thru-short (TS) and the thru-open (TO) methods were calculated. The same solutions were also chosen in the thru-delay (TD) method. The simulation results with some other solutions are essentially less accurate with the thru- and delay-line standards than the eight chosen ones. According to the simulations, the situation is not necessarily the same with other transmission line standards (e.g. the same length, but different impedance). The calculations with two standards were repeated using the assumption $L_{21} = R_{21}$ (solution: (1_A), (2_A), (3_A), (4_A), (1_B), (4_B)).

Some of the achieved results for L_{11} and $L_{12} = L_{21}$ are shown as dashed lines in Figs. 3–6, the sloping straight lines representing the phase of L_{21} and the sloping curved lines the phase of L_{11}. The correct values are shown as solid lines. The frequency band was restricted to 1–8 GHz (0.05 GHz step), because the TSO method has proved to be very inaccurate near the frequency in which the length of the "thru" line is $\lambda/4$. The super TSD method becomes singular at $\lambda/2$ line lengths. Thus the delay line was chosen to be only 72° longer than the "thru" line at 8 GHz. A difference of 180° would lead to singularities with the TD, TSD, and LRL methods. In the TS and TO methods the "thru" line length

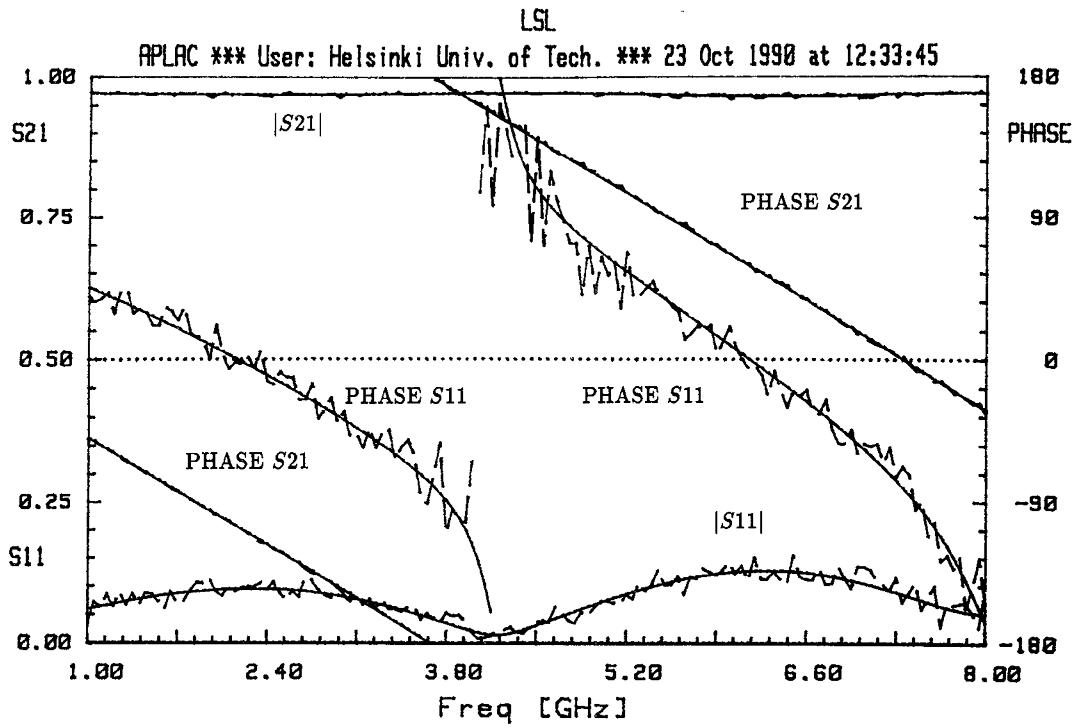

Fig. 4. Dashed line: LRL solution of the left error network L using the thru-short-delay standards. Solid line: correct L.

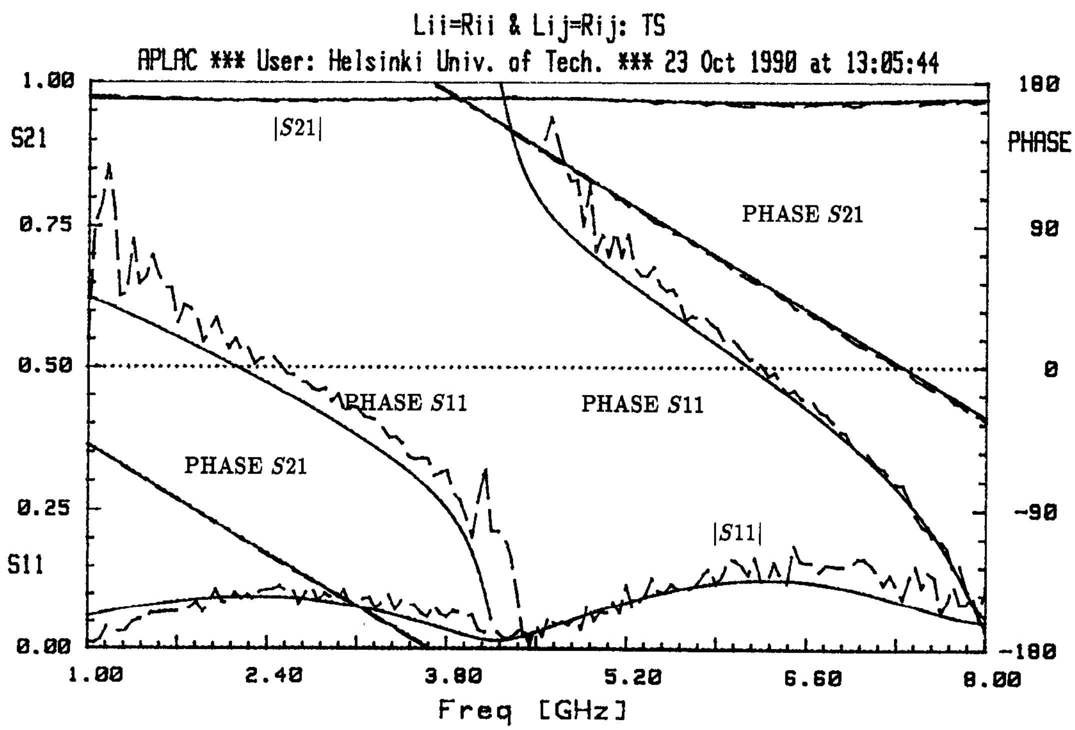

Fig. 5. Dashed line: S parameters of the left error network L achieved with the thru-short method (TS) assuming "total" symmetry; only one of the best solutions ($7_A, 8_A, 7_B$) is shown. Solid line: correct L.

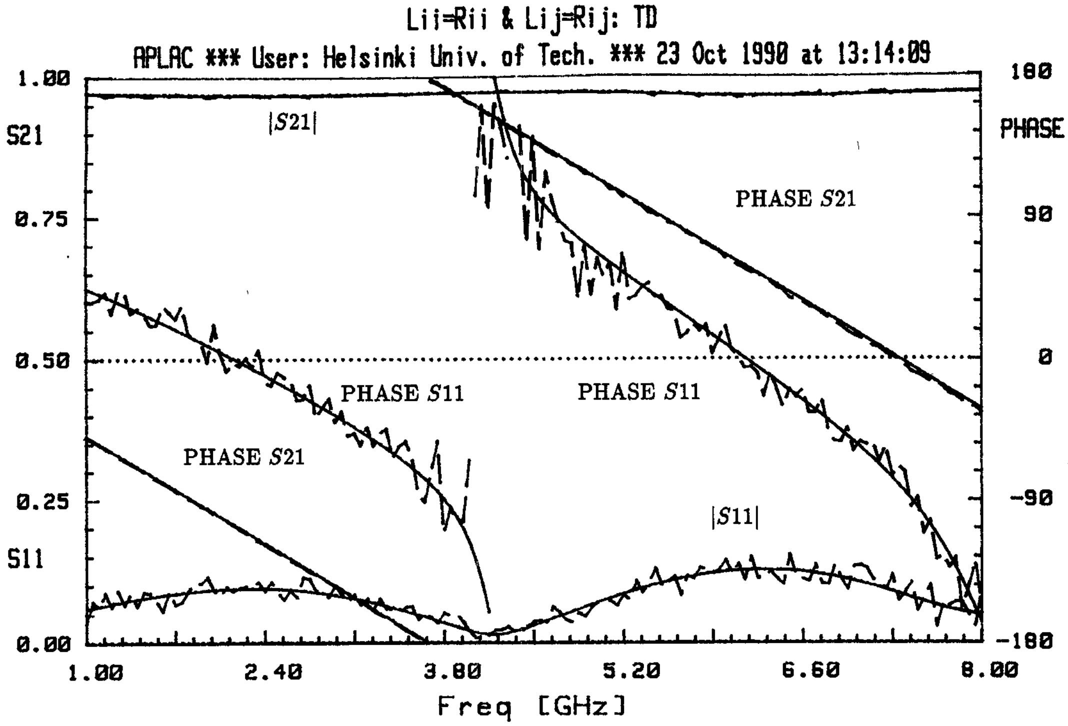

Fig. 6. Dashed line: S parameters of the left error network $\boldsymbol{L}$ achieved with the thru-delay method (TD) assuming "total" symmetry; only one of the best solutions $(7_A, 8_A, 7_B)$ is shown. Solid line: correct $\boldsymbol{L}$.

TABLE III
VALUES OF THE SIMILARITY INDEX OF THE ERROR NETWORKS COMPARED WITH THE CORRECT S PARAMETERS (M_A, M_B, M_C, M_D = MEASUREMENT DATA; $\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}, \boldsymbol{D}$ = S PARAMETERS OF THE STANDARDS

Calibration Method	Input Data	Standards	$\delta L * 10^3$	$\delta R * 10^3$
TSD	$M_A - M_B - M_D - B$	thru-short-delay	19	20
TSD (TOD)	$M_A - M_C - M_D - C$	thru-open-delay	28	26
LRL (LSL)	$M_A - M_B - M_D - A$	thru-short-delay	19	18
LRL (LOL)	$M_A - M_C - M_D - A$	thru-open-delay	24	24
Super TSD	$M_A - M_B - M_D - A - B - D$	thru-short-delay	37	35
Super TSD (TOD)	$M_A - M_C - M_D - A - C - D$	thru-open-delay	55	54
Super TSD (TSO)	$M_A - M_B - M_C - A - B - C$	thru-short-open	26	27
TSO	$M_A - M_B - M_C - A - B - C$	thru-short-open	25	26
TSO eqs. (1)–(4)	$M_A - M_B - M_C - A - B - C$	thru-short-open	25	29
TSD eqs. (1)–(4)	$M_A - M_B - M_D - A - B - D$	thru-short-delay	19	20
TOD eqs. (1)–(4)	$M_A - M_C - M_D - A - C - D$	thru-open-delay	28	34
TS $L_{21} = R_{21}$	$M_A - M_B - A - B$	thru-short	47	47
TO $L_{21} = R_{21}$	$M_A - M_C - A - C$	thru-open	47	48
TD $L_{21} = R_{21}$	$M_A - M_D - A - D$	thru-delay	22	22
TD eqs. (14)–(19)	$M_A - M_D - A$	thru-delay	22	21
TS $\boldsymbol{L} = \boldsymbol{R}$	$M_A - M_B - A - B$	thru-short	31 ··· 44	33 ··· 42
TO $\boldsymbol{L} = \boldsymbol{R}$	$M_A - M_C - A - C$	thru-open	44 ··· 46	44 ··· 47
TD $\boldsymbol{L} = \boldsymbol{R}$	$M_A - M_D - A - D$	thru-delay	22 ··· 27	22 ··· 27

should also be less than $\lambda/2$, but a zero-length line cannot be used.

A kind of similarity index has been used to compare the results:

$$\delta S = \sqrt{\frac{\sum_{\text{freq.}}\left(|\delta S_{11}|^2 + |\delta S_{12}|^2 + |\delta S_{21}|^2 + |\delta S_{22}|^2\right)}{4N_{\text{freq.}}}} \quad (21)$$

where δS_{ij} = the difference between the correct and the calculated S-parameter value. $N_{\text{freq.}} = 141$ = number of frequency points. So the index gives approximately the rms value of the complex error of each S parameter. In the TS, TO, and TD methods the results are dependent on the choice of the equations. The reason for this is the incorrect input data. The following index values were calculated according to the results (Table III).

The correct S parameters of $\boldsymbol{M_A}$, $\boldsymbol{M_B}$, $\boldsymbol{M_C}$, $\boldsymbol{M_D}$, $\boldsymbol{L}$, and $\boldsymbol{R}$ were calculated for a reference using the nominal component values in Tables I and II. The similarity index values between the input data and the correct S parameters are shown in Table IV. The index value between $\boldsymbol{L}$ and $\boldsymbol{R}$ is $\delta S * 10^3 = 29$, caused by the asymmetry (Table II).

The simulation results of both TD methods are nearly comparable to those of the TSD and LRL methods. With these input data, the TS and TO methods give less accurate results. The TO method is worst because of the increased

TABLE IV
VALUES OF THE SIMILARITY INDEX BETWEEN THE CADEP INPUT DATA AND THE CORRECT *S* PARAMETERS CALCULATED WITH THE NOMINAL *RLC* VALUES

Measurement	$\delta S * 10^3$
M_A ("thru")	20
M_B (short)	5
M_C (open)	45
M_D (delay)	24

error in the S parameters of measurement M_C (see Table IV). In the symmetrical case there are slight differences between the results of the eight solutions used. In practice the results are dependent on the structure of the fixture and on the existing errors. However, in other simulation examples the results have been very similar. Different error levels between the calibration procedures can be partly explained with different error levels in the S parameters of the input data, as shown in Table IV.

V. CONCLUSIONS

The main advantage of the methods described here is that the standards can be modeled freely and any idealization or restriction to certain special standards is not necessary. Any kind of standard can be used if the S parameters are known or if a circuit model for the standard can be determined. Also, the dispersion of the microstrip line standards can easily be taken into account. The characteristic impedance can be other than 50 Ω. If the test fixture is symmetrical, only two fixture standards are needed. Either one or both of the standards must have a nonzero transmission path to permit the solution.

With microstrip test fixtures, it is often difficult to use two different line lengths if the length of the fixture cannot be adjusted. This makes the use of the TSD or the LRL method impossible or at least inconvenient. In such a case only one transmission line in addition to a short or an open circuit standard can be used. If two different (length or impedance) lines can be used, the need for any reflection standard is eliminated. The new methods can also be used for checking the results achieved with any other procedure. However, when the highest possible accuracy is needed, at least three standards should be used.

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