# Line Network Network (LNN): An Alternative In-Fixture Calibration Procedure

Holger Heuermann, *Member, IEEE* and Burkhard Schiek, *Member, IEEE*

***Abstract*—An alternative method for a network analyzer calibration is evaluated. This line network network (LNN) method avoids de-embedding of the device under test (DUT) and it allows the characterization of an unknown two-port inserted between an arbitrary number of cascaded unknown two-ports. An unknown obstacle must be moved on a transmission line into three positions. The LNN calibration technique delivers the electrical wavelength or the relative dielectric constant of the transmission line and the scattering parameters of the obstacle. Since the connectors do not have to be exchanged, nonreproducibilities of the connectors are only a minor problem. Additionally, a double-calibration technique is presented. The double-calibration technique is used to employ the LNN method on both sides of the two-port DUT in order to perform an error-corrected measurement. Experimental results compare the LNN method with the tru-reflect-line (TRL) method particularly for an in-fixture calibration.**

***Index Terms*— Calibration of a network analyzer, de-embedding, in-fixture measurements, microwave device.**

## I. Introduction

In ORDER TO measure the scattering parameters of a device under test (DUT), the chip or wafer must be mounted in a contacting fixture, which transforms the actual chip or wafer parameters.

Fig. 1 shows the block diagram of a double reflectometer with a test-fixture.

$[\mathbf{A}]$ and $[\mathbf{B}]^{-1}$ are virtual, linear-error networks interfacing the DUT and the fixture networks $[\mathbf{G}]$ and $[\mathbf{H}]^{-1}$ to an error-free double reflectometer (network analyzer with four measurement ports, e.g., HP8510, Wiltron 360).

There are two ways to obtain the unknown DUT parameters with high precision.

The first way to get the corrected parameters is as follows. The network analyzer is calibrated inserting standards at the site of the DUT [1]. One directly calculates the combination $[\mathbf{D}]$ and $[\mathbf{E}]^{-1}$ of the error networks $[\mathbf{A}]$ and $[\mathbf{B}]^{-1}$ and the fixture networks $[\mathbf{G}]$ and $[\mathbf{H}]^{-1}$.

The DUT is implemented in a transmission line, (e.g., microstrip or coplanar line). This is termed an in-fixture calibration [2] or one-tier de-embedding [3]. This method of calibration is well suited for the Txx self-calibration procedures [4]–[6], as well as the tru-reflect-line (TRL) method [7] (a special case of Txx). All of these conventional calibrating methods exhibit the common drawback that during the calibrating process the individual calibrating standards must successively be inserted and taken out again, which poses a problem with the reproducibility of the contacts.

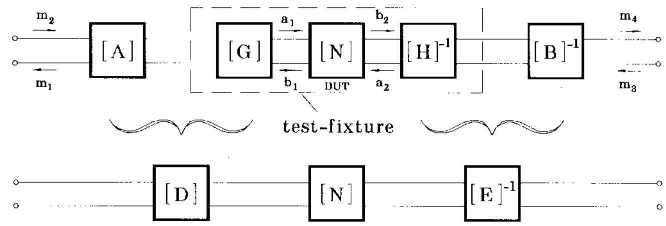


Fig. 1. Error model of a network analyzer with four measurement channels (double reflectometer) interfacing a test-fixture.

The second way to get the corrected parameters is as follows. The reflectometer is calibrated in either a coaxial-type or another type of a waveguide, then the calibrated network analyzer is used to characterize the fixture networks $[\mathbf{G}]$ and $[\mathbf{H}]^{-1}$. This is termed a de-embedding [2] or two-tier de-embedding [3] and is used in the frequency- [8] and time-domain [9] options.

When in-fixture standards of a similar quality are available, an in-fixture calibration should give more accurate results than a de-embedding, since the evolution of measurement errors is reduced.[1]

In this paper, the authors present a simple and robust self-calibration method, where the calibration constants are evaluated via closed-form analytical equations.

A further advantage of this new method is the fact that one can perform a calibrated free-field measurement without moving the antennas. Therefore, this procedure allows calibrated measurements with antennas for high frequencies.

Additionally, the authors present an alternative method of calibration, the so-called double-calibration technique which employs the line network network (LNN) calibration method before and after the DUT to perform an error-corrected in-fixture measurement. With the double-calibration technique one can determine the corrected scattering parameters of a DUT without the direct connection (thru or line) of the test-ports of the network analyzer. It should be mentioned that any two-port calibration method for double reflectometers [e.g., TAN, TRL, thru-match-reflect (TMR)], is equally well suited for the double-calibration technique, if applied before and after

Manuscript received June 12, 1996; revised November 21, 1996.

H. Heuermann is with the Development Department, Rosenberger HF-Technik GmbH & Company, 84526 Tittmoning, Germany.

B. Schiek is with the Institut für Hochfrequenztechnik, Ruhr-Universität Bochum, 44780 Bochum, Germany.

Publisher Item Identifier S 0018-9480(97)01710-9.

[1] Furthermore, the fixture networks ($[\mathbf{G}]$, $[\mathbf{H}]^{-1}$) must normally be reciprocal for a de-embedding, whereas nonreciprocal elements are allowed by an in-fixture calibration.

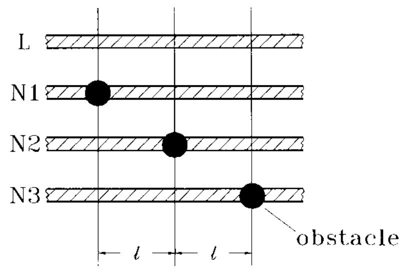


Fig. 2. The four calibration measurements of the LNN calibration procedure with a circular obstacle on a planar microstrip substrate.

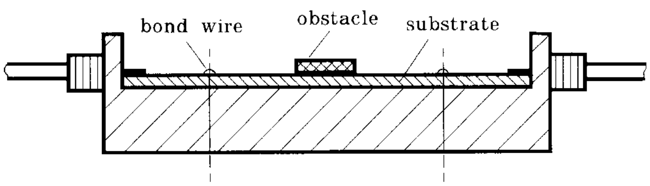


Fig. 3. LNN calibration with an unknown obstacle on a planar microwave substrate.

the DUT. Therefore, this alternative calibration method allows calibrated measurements even when it is impossible to remove the DUT (e.g., mixer measurements).

## II. THE NECESSARY CALIBRATION STANDARDS

The LNN procedure requires the calibration measurement of a line-standard and two or three measurements of the line together with an object to be calibrated (called "obstacle"), as is seen in Fig. 2.

The mechanical length of the line and step-width $\ell$ must be known. The characteristic impedance $Z_0$ of the line establishes the reference impedance of the measurements ($S_{L11} = S_{L22} = 0$). The system impedance is defined to be the same as $Z_0$ of the line.

The otherwise unknown obstacle is required to be reciprocal ($S_{Q21} = S_{Q12}$), to have identical reflection coefficients on either side ($S_{Q11} = S_{Q22}$), and its electrical properties must not change when it is moved.

The scattering parameters of the obstacle will be determined in the self-calibration part of the algorithm. Furthermore, the self-calibration delivers the generally complex propagation constant $\gamma$ of the transmission line. However, the algorithm needs prior rough information regarding the propagation or phase constant in order to resolve a sign ambiguity.

Fig. 3 is a cross section showing the application of the LNN procedure in a network analyzer with a test-fixture in a stripline technique on a substrate.

## III. THEORY

### A. The LNN Self-Calibration Technique

Represented as transmission or chain-transfer parameters, the vector equations of the mutually independent measuring values $m'_1$, $m'_2$, $m'_3$, and $m'_4$ for the first position of the switch [5] and $m''_1$, $m''_2$, $m''_3$, $m''_4$ for the second position of the switch are combined in accordance with the so-called four-port to two-port reduction to form a matrix equation:

$$\begin{pmatrix} m'_1 & m''_1 \\ m'_2 & m''_2 \end{pmatrix} = [\mathbf{D}][\mathbf{N}][\mathbf{E}]^{-1} \begin{pmatrix} m'_3 & m''_3 \\ m'_4 & m''_4 \end{pmatrix} \quad (1)$$

$$\Longrightarrow \qquad [\mathbf{M}] = [\mathbf{D}][\mathbf{N}][\mathbf{E}]^{-1} \quad (2)$$

with the measurements matrix

$$[\mathbf{M}] = \begin{pmatrix} m'_1 & m''_1 \\ m'_2 & m''_2 \end{pmatrix} \begin{pmatrix} m'_3 & m''_3 \\ m'_4 & m''_4 \end{pmatrix}^{-1} \quad (3)$$

and the abbreviations

$$[\mathbf{D}] = [\mathbf{A}][\mathbf{G}]$$

and

$$[\mathbf{E}]^{-1} = [\mathbf{H}]^{-1}[\mathbf{B}]^{-1}. \quad (4)$$

The $D_{ij}$- and $E_{ij}$-coefficients of the 2 × 2 matrices $[\mathbf{D}]$ and $[\mathbf{E}]$ are the eight unknown-correction quantities which may be reduced to seven by fixing one of them to unity [5].

Considering in Fig. 2 the left-hand and the right-hand reference planes for deriving the so-called self-calibration, one obtains with the line through connection ($[\mathbf{L}]$ $[\mathbf{L}]$) for the first calibrating measurement

$$[\mathbf{M_L}] = [\mathbf{D}][\mathbf{L}][\mathbf{L}][\mathbf{E}]^{-1} \quad (5)$$

in which

$$[\mathbf{L}] = \begin{pmatrix} \exp -\gamma\ell & 0 \\ 0 & \exp \gamma\ell \end{pmatrix}. \quad (6)$$

The Greek letter $\gamma$ represents the complex propagation constant and $\ell$ is the length of the line system. The transmission parameter matrix of the object to be calibrated, the obstacle, is $[\mathbf{Q}]$.

For the second calibrating measurement the obstacle is in the first position and the measurements matrix is written as

$$[\mathbf{M_{N1}}] = [\mathbf{D}][\mathbf{Q}][\mathbf{L}][\mathbf{L}][\mathbf{E}]^{-1} \quad (7)$$

in which

$$[\mathbf{Q}] = \begin{pmatrix} q_{11} & q_{12} \\ q_{21} & q_{22} \end{pmatrix}. \quad (8)$$

When substituting (5) in (7) it follows:

$$[\mathbf{M_{N1}}][\mathbf{M_L}]^{-1} = [\mathbf{D}][\mathbf{Q}][\mathbf{D}]^{-1}. \quad (9)$$

Using a theorem for similar matrices[2] one obtains

$$\underbrace{\mathrm{trace}\,([\mathbf{M_{N1}}][\mathbf{M_L}]^{-1})}_{\beta_1} = \mathrm{trace}\,([\mathbf{Q}]) \quad (10)$$

[2] According to a theorem of the linear-mapping theory the following holds: Square matrices $[\mathbf{X}]$ and $[\mathbf{Y}]$ for which:

$$[\mathbf{X}] = [\mathbf{K}]^{-1}[\mathbf{Y}][\mathbf{K}].$$

($[\mathbf{K}]$: regular matrix) are similar matrices. Similar matrices have the following properties:

$$\mathrm{trace}\,([\mathbf{X}]) = \mathrm{trace}\,([\mathbf{Y}])$$
$$\det\,([\mathbf{X}]) = \det\,([\mathbf{Y}]).$$

from which there results the first self-calibration equation for determining the unknown obstacle two-port $[\mathbf{Q}]$

$$\beta_1 = q_{11} + q_{22}. \quad (11)$$

For the third LNN calibration measurement the obstacle is in the second position and it follows:

$$[\mathbf{M_{N2}}] = [\mathbf{D}][\mathbf{L}][\mathbf{Q}][\mathbf{L}][\mathbf{E}]^{-1}. \quad (12)$$

Combining the second and third calibration measurements, the evaluation of

$$\underbrace{\mathrm{trace}\,([\mathbf{M_{N1}}][\mathbf{M_{N2}}]^{-1})}_{\beta_2} = \mathrm{trace}\,([\mathbf{Q}][\mathbf{L}][\mathbf{Q}]^{-1}[\mathbf{L}]^{-1}) \quad (13)$$

results in the second required equation

$$2 - \beta_2 = q_{12}q_{21}[2\cosh(2\gamma\ell) - 2]. \quad (14)$$

Here use has been made of the postulated property that $\mathbf{Q}$ is the matrix of a reciprocal two-port:

$$1 = q_{11}q_{22} - q_{12}q_{21}. \quad (15)$$

The fourth calibration measurement yields, with the obstacle in the third position

$$[\mathbf{M_{N3}}] = [\mathbf{D}][\mathbf{L}][\mathbf{L}][\mathbf{Q}][\mathbf{E}]^{-1}. \quad (16)$$

Combining (7) and (16), one obtains

$$\underbrace{\mathrm{trace}\,([\mathbf{M_{N1}}][\mathbf{M_{N3}}]^{-1})}_{\beta_3} = \mathrm{trace}\,([\mathbf{Q}][\mathbf{L}][\mathbf{L}][\mathbf{Q}]^{-1}[\mathbf{L}]^{-1}[\mathbf{L}]^{-1}) \quad (17)$$

delivering the last of the required equations to determine the self-calibration parameters

$$2 - \beta_3 = q_{12}q_{21}[2\cosh(4\gamma\ell) - 2]. \quad (18)$$

Dividing (14) by (18) one obtains an equation for the determination of either the complex phase constant $\gamma\ell$ or the complex propagation constant $\gamma$ with the mechanical length $\ell$ being known:

$$\cosh(2\gamma\ell) = \frac{1}{2}\,\frac{2-\beta_3}{2-\beta_2} - 1. \quad (19)$$

If the propagation constant $\gamma$ is known *a priori*, the fourth calibration measurement and consequently the calculating steps from (16) to (19) can be omitted.

If the mechanical length $\ell$ is given incorrectly, the result for $\gamma$ is likewise incorrect, but the product $\gamma\ell$ still is exact.

As both parameters $\gamma$ and $\ell$ subsequently only occur in the form of this product, the incorrectly given mechanical length $\ell$ does not affect the calibration accuracy.

Considering the initially required property that the obstacle should be reflection-symmetrical, the following holds in transmission parameters

$$q_{12} = -q_{21} \quad (20)$$

which substituted in (14) results in

$$q_{21} = \pm\sqrt{\frac{\beta_2 - 2}{2\cosh(2\gamma\ell) - 2}}. \quad (21)$$

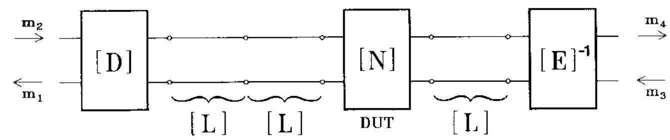


Fig. 4. Error model of a network analyzer (double reflectometer) interfacing a double-LNN test-fixture.

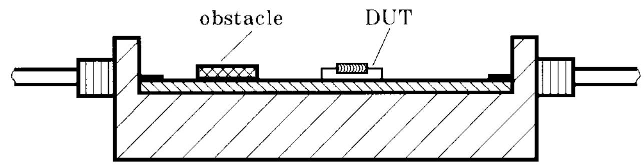


Fig. 5. Double-LNN calibration with an implemented DUT and an unknown obstacle on a microwave substrate.

Substituting (11) in (15) one obtains after a short computation the equation for the other $q_{ij}$-quantities

$$q_{11} = \frac{\beta_1}{2} \pm \sqrt{\frac{\beta_1^2}{4} + q_{21}^2 - 1} \quad (22)$$

and $q_{22}$ follows directly from (11).

Transforming the problem to scattering parameters, the sign decisions are reduced to the evaluation of the passivity of the obstacle. Furthermore the phase of the reflection characteristic of the obstacle must be known to 180°, similar to the previous calibrating methods.

Once the $q_{ij}$ coefficients and the product $\gamma\ell$ are known, the so-called self-calibration is complete. Thus, four calibration measurements with completely known standards are available.

However, for the computation of the $D_{ij}$ and $E_{ij}$ error-correction coefficients one only requires three calibration measurements with known standards. Hence, there is sufficient information available to determine the correction values in a conventional way [6].

Note that in this theory the obstacle with the transmission parameters $q_{ij}$ has been treated as a nonphysical two-port with zero dimensions implemented between the lines with the transmission matrix $[\mathbf{L}]$. One can obtain the physical transmission parameters $r_{ij}$ of the obstacle with the mechanical length $2\ell_r$ via

$$\begin{pmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{pmatrix} = \begin{pmatrix} \exp -\gamma\ell_r & 0 \\ 0 & \exp\gamma\ell_r \end{pmatrix} \cdot \begin{pmatrix} q_{11} & q_{12} \\ q_{21} & q_{22} \end{pmatrix} \begin{pmatrix} \exp -\gamma\ell_r & 0 \\ 0 & \exp\gamma\ell_r \end{pmatrix}. \quad (23)$$

Notice that the sign decisions rely on the nonphysical parameters $q_{ij}$.

### B. The Double-LNN Self-Calibration Technique

In order to derive the double-LNN self-calibration technique, Fig. 4 describes the actual calibration scheme. $[\mathbf{D}]$ and $[\mathbf{E}]^{-1}$ are error networks interfacing the DUT with the transmission matrix $[\mathbf{N}]$ to an ideal network analyzer.

Fig. 5 is a cross section showing the application of the double-LNN technique in a test-fixture with stripline technique on a substrate.

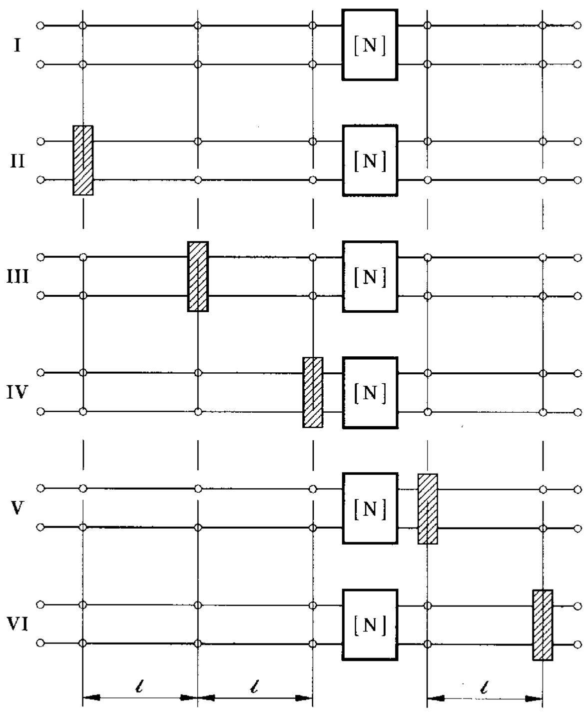


Fig. 6. The six calibration measurements of the double-LNN calibration process.

Dealing with these two-ports, one obtains in reference to (2) the double reflectometer equation:

$$[\mathbf{M}] = [\mathbf{D}][\mathbf{L}][\mathbf{L}][\mathbf{N}][\mathbf{L}][\mathbf{E}]^{-1} \tag{24}$$

with the measurement matrix $[\mathbf{M}]$.

During the double-LNN calibration process the connectors do not have to be exchanged, only the scattering obstacle must be moved on the transmission line before and behind the DUT (Fig. 6).

The LNN calibration on the left side of the DUT delivers the error-corrected coefficients, with $\tilde{D}_{22}$ set to unity

$$\begin{aligned}[\mathbf{D}] &= \alpha \begin{pmatrix} \tilde{D}_{11} & \tilde{D}_{12} \\ \tilde{D}_{21} & 1 \end{pmatrix} \\ &= \alpha[\widetilde{\mathbf{D}}] \end{aligned} \tag{25}$$

except for a common complex factor $\alpha$.

Similarly, the LNN calibration on the right side of the DUT delivers the correction values

$$\begin{aligned}[\mathbf{E}] &= \beta \begin{pmatrix} \tilde{E}_{11} & \tilde{E}_{12} \\ \tilde{E}_{21} & 1 \end{pmatrix} \\ &= \beta[\widetilde{\mathbf{E}}] \end{aligned} \tag{26}$$

with $\tilde{E}_{22}$ set to unity. The error box $[\widetilde{\mathbf{E}}]$ is the same as the error box $[\mathbf{E}]$ except for a common factor $\beta$.

Inserting $[\widetilde{\mathbf{D}}]$ and $[\widetilde{\mathbf{E}}]$ into (24) one obtains

$$[\mathbf{M}] = \frac{\alpha}{\beta}[\widetilde{\mathbf{D}}][\mathbf{L}][\mathbf{L}][\mathbf{N}][\mathbf{L}][\widetilde{\mathbf{E}}]^{-1}. \tag{27}$$

Here, use can be made of the postulated property that $[\mathbf{N}]$ is the matrix of a reciprocal two-port $\{\det([\mathbf{N}]) = 1\}$. Taking the determinant on both sides one can resolve for $\alpha/\beta$:

$$\left(\frac{\alpha}{\beta}\right)^2 = \frac{\det([\mathbf{M}])\det([\widetilde{\mathbf{E}}])}{\det([\widetilde{\mathbf{D}}])}. \tag{28}$$

In order to make the sign decision it is necessary to have a preliminary information about the DUT, but this does not constitute a practical problem.

Inserting the result of $\alpha/\beta$ from (28) into (27) it follows for the DUT parameters:

$$[\mathbf{N}] = \frac{\beta}{\alpha}[\mathbf{L}]^{-1}[\mathbf{L}]^{-1}[\widetilde{\mathbf{D}}]^{-1}[\mathbf{M}][\widetilde{\mathbf{E}}][\mathbf{L}]^{-1}. \tag{29}$$

For the measurement of the scattering parameters of a nonreciprocal device like a transistor it may be advisable to turn off the dc-voltages of the transistor to guarantee reciprocity during the calibration part. If necessary, the transmission may be enhanced by a coupling bridge during the calibration part.

For the actual measurement the transistor may be operated actively. Notice that the transistor must not be removed for a through connection as it is necessary for most other methods.

However, any two-port calibration method for double reflectometers (e.g., TAN, TRL, TMR), is equally well suited for the double-calibration technique, if applied before and after the DUT. In general, the double-calibration technique is useful for a variety of coaxial and noncoaxial environments and may find further application (e.g., in the field of free-space measurements).

## IV. Experimental Comparison: The LNN with the TRL-Calibration Procedure

One can find in [10] very useful numerical simulations of the LNN calibration procedure. One can additionally find in this paper the first LNN-error-corrected measurements up to 4 GHz.

It has been shown in [10] numerically and in [11] experimentally that the LNN self-calibration part is a good way to evaluate the propagation constant. Verification measurements of the double-LNN calibration procedure has been published in [12]. One automatic method of movement of the obstacle before and after the DUT for the double-LNN process is given in [13].

For the comparison of the LNN correction process with the TRL-calibration process, the resulting equations were applied to measurements values. The following measurement have been carried out on a HP 8510 C with a self-made test-fixture over a frequency range of 2–10 GHz. The raw measurement data have been read out and processed on a personal computer. For the LNN calibration the step-width $\ell$ of the movement of the obstacle was 0.75 cm and the microwave substrate was TMM3 ($\epsilon_r = 3.25$).

We have used a cylindrical block out of metal (diameter: 3.6 mm, height: 2 mm) and fixed it in plastic to realize the obstacle. Additionally, we have produced a simple and robust fixture with slots in a distance of 0.75 mm to move the obstacle without changing its electrical parameters.

Fig. 7 shows the measurement values of the reflection of the used obstacle evaluated via the LNN self-calibration process

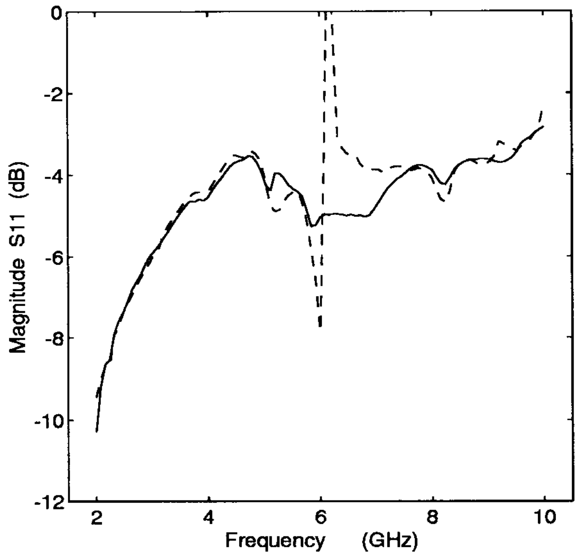


Fig. 7. Measurement of the magnitude of the obstacle evaluated via the LNN-self-calibration process (solid line) and via a LNN calibration (dashed line) versus frequency.

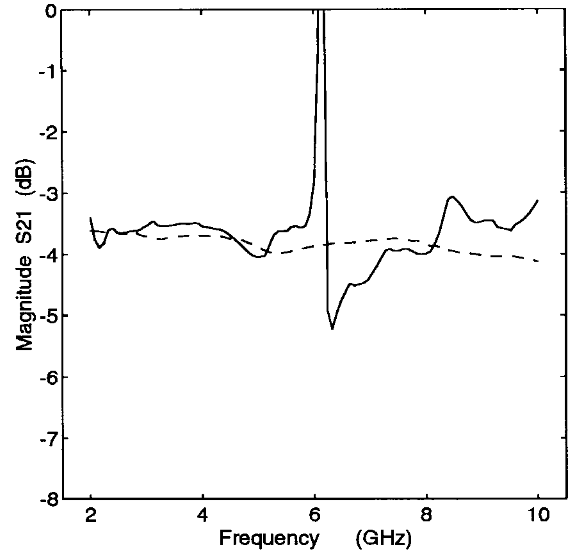


Fig. 9. Magnitude of the transmission of a 50 Ω-series resistor error-corrected with the LNN-procedure (solid line) and the TRL-procedure (dashed line).

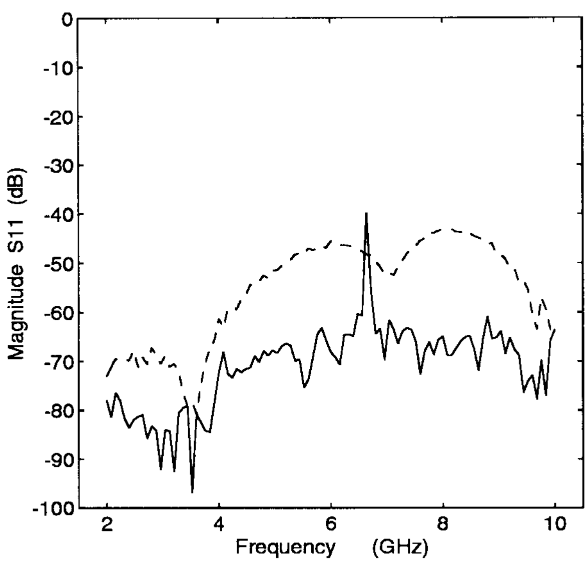


Fig. 8. LNN-error-corrected (dashed line) reflection measurement of a calibration-line standard versus frequency.

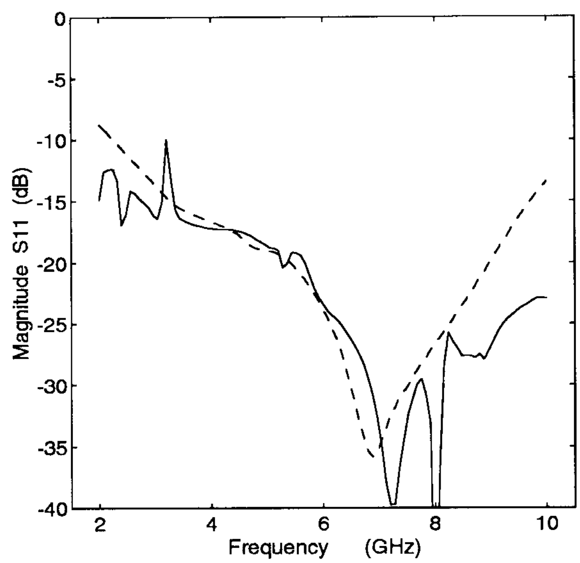


Fig. 10. Magnitude of the reflection of a 2.2-pF series capacitor error-corrected with the LNN-procedure (solid line) and the TRL-procedure (dashed line).

and via the LNN calibration. In the latter case (i.e., the LNN calibration) the obstacle is treated as a normal DUT. This figure proves that the self-calibration process does not have a range of unreliable calibration (here at 6.2 GHz).

The following TRL-error-corrected measurements do not break down because the step-width $\ell$ was so short that the first multiple of half a wavelength was outside the considered frequency range.

Since for the LNN calibration measurements nonreproducibilities of the connectors are only a minor problem, the LNN-corrected measurement of the line-standard shows superior results in comparison with the TRL-corrected measurement (Fig. 8).

However, for a high-quality error correction of the measurement of a common DUT it is necessary that one provides over well-matched *and* high-reflective calibration standards. The numerical results of [10] prove that it is disadvantageous to use an obstacle with a high-reflection value for the LNN self-calibration process.

This matter of fact is the main reason that the LNN-corrected results of common DUT's are not as good as the TRL-corrected results (Figs. 9 and 10).

Aside from these aspects of high-precision measurements, these measurements results show that with this new LNN method one can perform useful error-corrected measurements.

## V. Conclusion

A simple and robust in-fixture calibration method has been described in close-form solutions. The LNN calibration technique delivers the electrical wavelength or the relative dielectric constant of the transmission line. Since the connectors do not have to be exchanged in the calibration process, nonreproducibilities are only a minor problem in the calibration process of the LNN procedure.

The experimental results show that the LNN calibration technique delivers better error-corrected results than the TRL calibration technique for well-matched DUT's. But in the case of a DUT with a high reflection coefficient the TRL procedure is the better choice.

## References


[1] "On-wafer measurements using the HP 8510 network analyzer and cascade microtech wafer probes," Hewlett Packard Prod. Note 8510-6, May 1986.

[2] "In-fixture microstrip device measurements using TRL* calibration," Hewlett Packard Prod. Note 8720-2, Aug. 1994.

[3] R. Lane, "De-embedding device scattering parameters," *Microwave J.*, pp. 149–156, Aug. 1984.

[4] H. J. Eul and B. Schiek, "Thru-match-reflect: One result of a rigorous theory for de-embedding and network analyzer calibration," in *Proc. 18th European Microwave Conf.,* Stockholm, Sweden, 1988, pp. 909–914.

[5] ——, "A generalized theory and new calibration procedures for network analyzer self-calibration," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 724–731, Apr. 1991.

[6] H. Heuermann and B. Schiek, "Robust algorithms for Txx network analyzer self-calibration procedures," *IEEE Trans. Instrum. Meas.*, pp. 18–23, Feb. 1994.

[7] G. F. Engen and C. A. Hoer, "Thru-reflect-line: An improved technique for calibrating the dual six port automatic network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 987–993, Dec. 1979.

[8] "Measurement and modeling of GaAs FET chips," Avantek Application Note, Oct. 1983.

[9] G. Gronau and I. Wolff, "A simple broad-band device de-embedding method using an automatic network analyzer with time-domain option," *IEEE Trans. Microwave Theory Tech.,* vol. 37, pp. 479–483, Mar. 1989.

[10] H. Heuermann and B. Schiek, "The in-fixture calibration procedure line-network-network-LNN," in *Proc. 23rd European Microwave Conf.,* Madrid, Spain, 1993, pp. 500–505.

[11] K.-H. Baek, H.-Y. Sung, and W. S. Park, "A 3-position transmission reflection method for measuring the permittivity of low loss materials," *IEEE Microwave Guided Wave Lett.,* vol. 5, pp. 3–5, Jan. 1995.

[12] H. Heuermann and B. Schiek, "The double-LNN calibration technique for scattering parameter measurements of micro-strip devices," in *25th European Microwave Conf.,* Bologna, Italy, 1995, pp. 343–347.

[13] ——, "Vorrichtung zur vollautomatischen Meßwertkorrektur für elektrische Bauelemente und Schaltungen auf planaren Mikrowellenleitungssystemen, Patent P 43 36 436.5, Oct. 26, 1993.



**Holger Heuermann** (S'92–M'95) was born in Wagenhoff, Niedersachsen, Germany, in 1964. He received the Dipl.-Ing. (FH) degree from the Fachhochschule Braunschweig-Wolfenbüttel, Germany, in 1988 and the degree Dipl.-Ing. from the University of Bochum, Bochum, Germany, in 1991, both in electrical engineering.

From 1991 to 1995, he was a Research Assistant at the Ruhr-Universität Bochum, Germany, working in the field of high-frequency measurement techniques and industrial applications of microwaves. Since 1995, he has been working at Rosenberger HF-Technik GmbH & Company, Development Department, Tittmoning, Germany, where he is engaged in the design of high-frequency equipment, especially for the calibration of network analyzers.



**Burkhard Schiek** (M'85) was born in Elbing, Germany, on October 14, 1938. He received the Dipl.-Ing. and Dr.-Ing. degrees in electrical engineering, both from the Technische Universität Braunschweig, Germany, in 1964 and 1966, respectively.

From 1964 to 1969, he was an Assistant at the Institut für Hochfrequenztechnik, Technische Universität Braunschweig, Germany, where he worked on frequency multipliers, parametric amplifiers, and varactor phase shifters. From 1966 to 1969, he was involved in MIS interface physics and in the development of MIS varactors. From 1969 to 1978, he was with the Microwave Application Group of the Philips Forschungslaboratorium Hamburg GmbH, Hamburg, Germany, where he was mainly concerned with the stabilization of solid-state oscillators, oscillator noise, microwave integration, and microwave systems. Since 1978, he has been a Professor in the Department of Electrical Engineering, Ruhr-Universität Bochum, Bochum, Germany, working on high-frequency measurement techniques and industrial applications of microwaves.