Application of De-embedding Methods to Characterise a Mode Transformer

Adam Swiatko

Department of Electrical, Electronic and Computer Engineering,
University of Pretoria, South Africa.
Tel: +27 72 204 5157
Email: swiatko@gmail.com

***Abstract* – De-embedding is the process whereby the transmission properties of a section of microwave circuit are characterised. In this paper it is proposed that a new analysis mechanism be developed by applying a de-embedding method implemented in a numerical computational software package. The analysis mechanism can then be applied to a horn antenna to separate the transmission properties of the horn structure from the transmission properties of the mode transformer that is used to feed the system.**

***Index Terms* – De-embedding, Mason's Rule, Mode Transformer, Scattering parameters**

I. Introduction

Characterisation of a section of a microwave circuit, of which the transmission properties are not known, necessitates the isolation of that section from the rest of the system. This can be achieved by using de-embedding methods [1], [2].

The research undertaken was to develop an analysis mechanism to determine the transmission properties of a device indirectly, via the use of a mode transformer. Mode transformers are used, for instance, to adapt between coaxial lines and waveguides. The presence of the mode transformer obscures the electrical properties of the waveguide circuit when viewed from the coaxial input. In practice, the method is to be applied to obtain the properties of a Device Under Test (DUT) which has a waveguide input, when evaluated from a coaxial input port, such as evaluating, for instance, the properties of a horn antenna with a ridged waveguide feed. By applying de-embedding methods the desired device characteristics can be extracted from the overall system characteristics.

This analysis mechanism can be utilised in both the research environment to develop more efficient systems as well as in design and implementation processes as a verification tool.

II. De-embedding Methods and Methodology

Several different de-embedding methods have been reported [3]-[17] which can be categorised into two distinct classes. In both of these classes electrical standards, with known electrical characteristics, are used in place of the DUT, in order to characterise the properties of the system in which the DUT will be located.

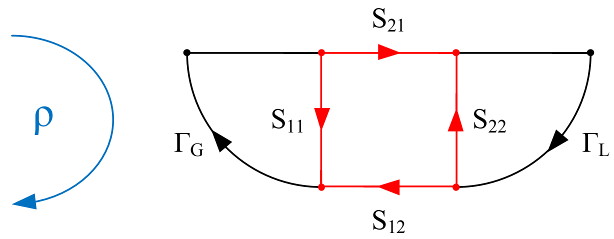

Fig. 1. Signal flow diagram to describe a section of microwave circuit.

A. De-embedding by Matrices or Signal Flow Diagrams

The one class of de-embedding methods makes use of both reflective and delay electrical standards and allows for the network to be in a one- or two-port configuration. This allows the network to be described as a cascade of matrices

$$[T_{\text{Total}}] = [T_{\text{Error Box A}}][T_{\text{DUT}}][T_{\text{Error Box B}}], \tag{1}$$

where

$[T_{Total}]$ = *Total network transmission matrix*
$[T_{Error\ Box\ N}]$ = *Error network N transmission matrix*
$[T_{DUT}]$ = *DUT transmission matrix.*

It should be noted that the matrices to the left and right of the DUT, also referred to as error boxes, can be as simple as just a mode transformer or can be more complex, comprising many components in the general sense. In this case, the interest is to characterise a mode transformer.

Examples of this class of de-embedding methods are the Through-Reflect-Line (TRL) [4], [5] and the Delay-and-Multiple-Length-Delay (L-NL) [7], [8] de-embedding methods.

Thereafter, by applying simple matrix manipulations to (1) the transmission properties of the desired section of the system can be isolated

$$[T_{\text{DUT}}] = [T_{\text{Error Box A}}]^{-1}[T_{\text{Total}}][T_{\text{Error Box B}}]^{-1} \tag{2}$$

These matrices can be of the form of an ABCD matrix, T matrix, or S-parameter matrix.

An alternative way of describing a system within this class of de-embedding methods is by using basic circuit theory and modelling the network by its signal flow diagram using Mason's Rule, applied to Fig. 1 [18].

$$T = \frac{\sum_k T_k \Delta_k}{\Delta}, \tag{3}$$

where

T_k = *path gain of the k^{th} forward path*
Δ = *1 – Σ(all individual loop gains)*
+ Σ(loop gain products of all possible… combinations of two non-touching loops)
– Σ(loop gain products of all possible… combinations of three non-touching loops)
+ …
Δ_k = *the value of Δ not touching the k^{th} forward path.*

The use of signal flow diagrams allows for the network properties to be described by S-parameters.

$$\rho = S_{11} + \frac{S_{21}S_{12}\Gamma_L}{1 - S_{22}\Gamma_L} \tag{4}$$

B. De-embedding by Numerical Methods

The second class of de-embedding methods make use of reflection measurements which then require the use of numerical computational methods such as Method of Moments (MoM) [16] or Finite-Difference Time-Domain (FDTD) [17] to perform the de-embedding process. These methods are computationally demanding and due to the use of only reflection measurements, they are better suited to one-port networks.

III. Development of an Analysis Tool

The aim is to obtain the transmission properties of just the horn structure shown in Fig. 2. To do this it is necessary to first isolate the transmission properties of the mode transformer used to feed the system.

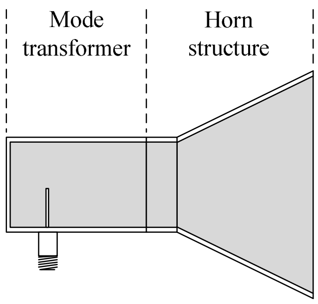

Fig. 2. Mode transformer with a horn structure attached as the load.

It is possible to characterise a mode transformer, in this case a 50 Ω coaxial feed to a X-band rectangular waveguide, but measuring both the reflection and transmission S-parameters. This requires two mode transformers to be placed back-to-back as shown in Fig. 3, effectively creating a two-port network.

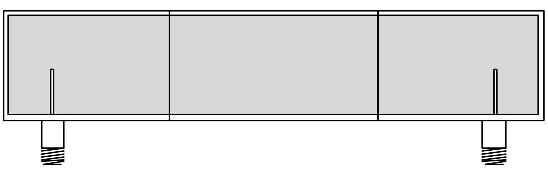

Fig. 3. Back-to-back configuration of two mode transformers with a phase delay between them.

By applying a combination of the TRL and L-NL de-embedding methods the transmission properties of the mode transformer section can be extracted. The TRL and L-NL de-embedding methods have been identified to deliver a high degree of accuracy while maintaining a low degree of structural complexity.

Finally by applying simple matrix manipulations, such as those described by (2), the transmission properties of just the mode transformer can be determined.

While this allows for both the reflection and transmission S-parameters to be calculated it also means that an a-priori knowledge of the mode transformers transmission properties are required when the cascaded matrices de-embedding method is applied. This defeats the purpose of the de-embedding method for this type of configuration.

An alternative approach is to describe the back-to-back configuration by its signal flow diagrams and then apply Mason's Rule (3) to characterise the mode transformer. This however presents its own challenges as the equations derived for the back-to-back configuration are complex and easily allow for an input error to be introduced.

It was subsequently found that the de-embedding of the waveguide structure can be satisfactorily performed using only a combination of three different offset shorts as terminations to the mode transformer [19]. The equations presented in [19] are derived from Mason's Rule and require that only the reflection measurements of the three different mode transformer and termination configurations be obtained to perform the de-embedding of the error network. This setup is shown in Fig. 4 [19],

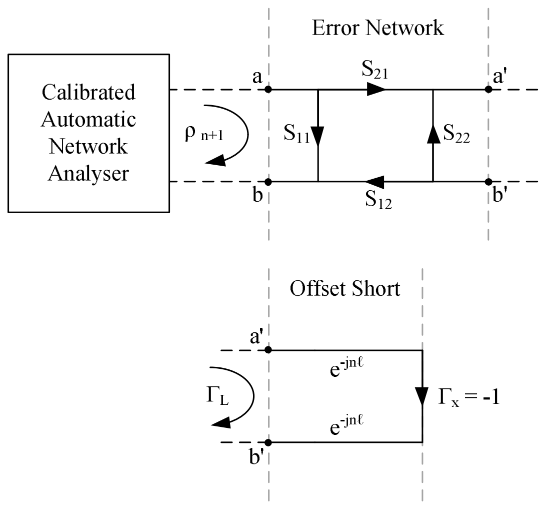

Fig. 4. Graphical representation of the three different offset short configuration for de-embedding. Adapted from [19].

where

n = 0, 1, 2.
ℓ = electrical length of the offset short.

Once the transmission properties of the error network are calculated the horn structure can be isolated by applying a reworked form of Mason's Rule where the reflection coefficient at reference plane *a'-b'* is made the subject of the formula.

$$\Gamma_L = \frac{\rho - S_{11}}{S_{22}\rho + S_{21}S_{12} - S_{11}S_{22}} \tag{5}$$

IV. RESULTS AND DISCUSSION

The de-embedding is performed via a network which has a certain response, ultimately the coaxial to waveguide mode transformer. The nature of the proposed approach, to perform the de-embedding, is based on the signal flow diagram of the microwave network and is therefore independent of the physical properties of the structure allowing it to be arbitrary, a "black box". For this reason a test microwave network was used as a verification tool to ensure there was no error in the implementation of the de-embedding equations. The structure chosen was a third-order Chebyshev low pass filter with a 0.5 dB pass band ripple and a cut-off frequency of 2.4 GHz. The response of this network is shown in Fig. 5.

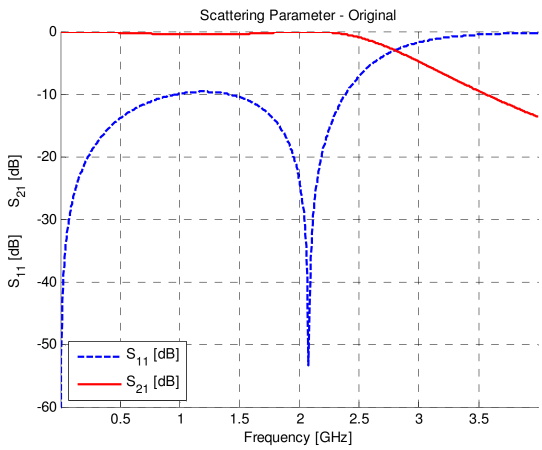

Fig. 5. Third order Chebyshev low pass filter with a 0.5 dB ripple and cut-off frequency of 2.4 GHz.

The structure was then terminated in three different offset shorts with offset lengths of 0 λ, 0.25 λ and 0.50 λ, respectively, and λ calculated at the cut-off frequency. The calculated reflection coefficients of the three short terminations are shown in Fig. 6, Fig. 7 and Fig. 8, respectively. The transmission coefficient was calculated from the reflection coefficient by assuming the network is lossless and using the conservation of energy equation.

$$|S_{11}|^2 + |S_{21}|^2 = 1 \quad (6)$$

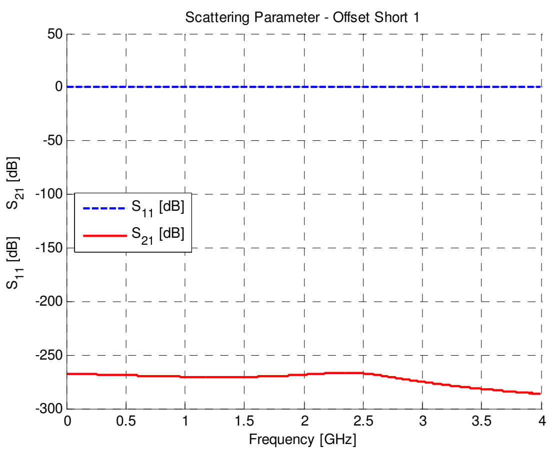

Fig. 6. Calculated reflection coefficient with first short termination of 0 λ.

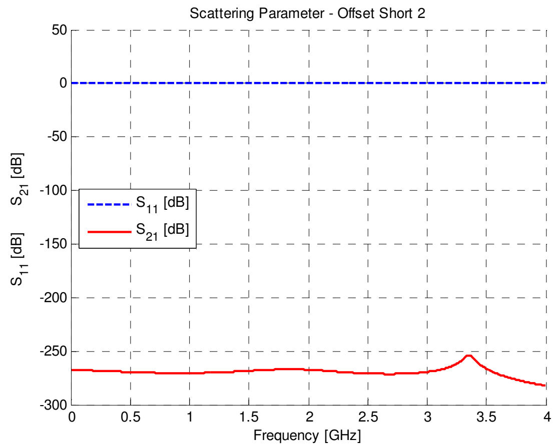

Fig. 7. Calculated reflection coefficient with second short termination of 0.25 λ.

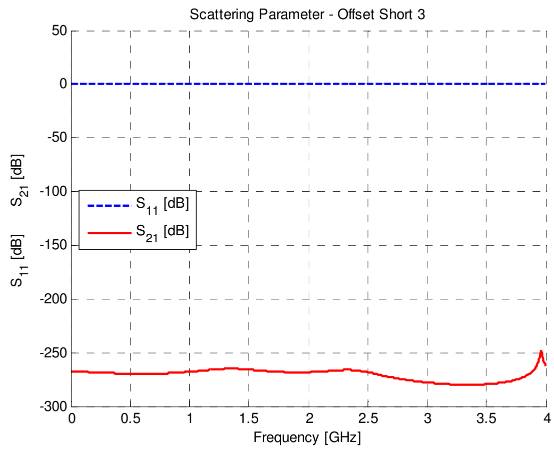

Fig. 8. Calculated reflection coefficient with third short termination of 0.50 λ.

From the offset short figures it is evident that the input signal is reflected back to the source and only a phase shift, caused by the offset lengths, is observed.

The three calculated reflection coefficients were then imported into the de-embedding equations from [19] and the initial network response, shown in Fig. 9, was extracted.

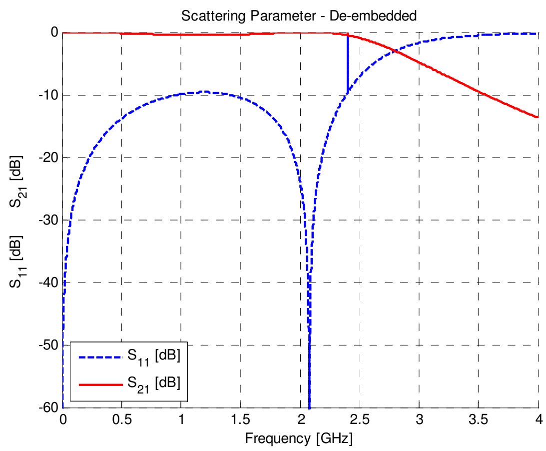

Fig. 9. De-embedded response of the initial third order Chebyshev low pass filter.

The de-embedded network response is almost identical to the initial network response with the exception of the anomaly that occurs at 2.4 GHz. This is caused by the offset lengths behaving like quarter-wave transformers at 2.4 GHz. Changing the length of the offsets causes the anomaly to shift along the frequency band relative to the specified length. The difference between the two networks was calculated and is shown in Fig. 10.

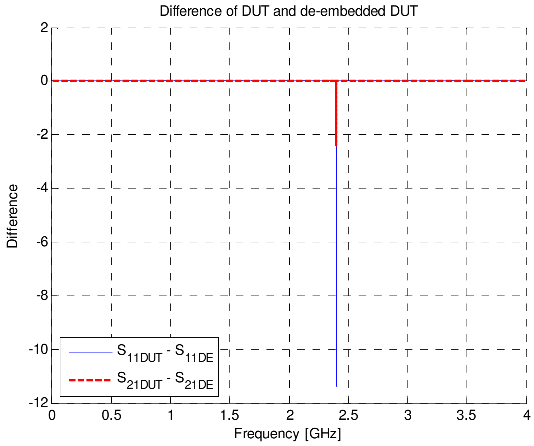

Fig. 10. Calculated difference between initial and de-embedded network.

The responses of the initial and de-embedded networks are to all intents and purposes identical.

V. Conclusion

It is concluded from the above results that an arbitrary microwave network can be characterised through obtaining three different termination measurements instead of having to obtain both the reflection and transmission properties; thus characterisation of the network is performed by the use of only a single parameter.

VI. Contribution

A method has been proposed to develop an analysis mechanism, which is based on basic circuit theory and requires only three different termination measurements in order to function. It characterises the properties of a microwave network and can thereafter be applied to determine the properties of any network attached onto the initial microwave network. The developed process has been verified by using a test network and the results have been found to be satisfactory.

Currently no such analysis tool is available.

References

[1] R.F. Bauer and P. Penfield Jr., "De-Embedding and Unterminating," *IEEE Trans. Microw. Theory Tech.*, vol. 22, no. 3, pp. 282- 288, Mar. 1974.

[2] R. Lane, "De-embedding device scattering parameters," *Microw. J.*, vol. 27, no., pp. 149-156, Aug. 1984.

[3] N.R. Franzen and R.A. Speciale, "A New Procedure for System Calibration and Error Removal in Automated S-Parameter Measurements," *5th Euro. Microw. Conf., 1975.*, vol., no., pp. 69-73, Sept. 1-4, 1975.

[4] G.F. Engen and C.A. Hoer, "Thru-Reflect-Line: An Improved Technique for Calibrating the Dual Six-Port Automatic Network Analyzer," *IEEE Trans. Microw. Theory Tech.*, vol. 27, no. 12, pp. 987- 993, Dec. 1979.

[5] J.E. Zuiga-Juarez, J.A. Reynoso-Hernandez, and M.C. Maya-Sanchez, "An improved multiline TRL method," *67th ARFTG Conf. 2006*, vol., no., pp. 139-142, June 16, 2006.

[6] E.S. Daniel, N.E. Harff, V. Sokolov, S.M. Schreiber, and B.K. Gilbert, "Network analyzer measurement de-embedding utilizing a distributed transmission matrix bisection of a single THRU structure," *63rd ARFTG Conf. Digest Spring, 2004*, vol., no., pp. 61- 68, June 11, 2004.

[7] J.C. Rautio, "A de-embedding algorithm for electromagnetic," *Int. J. Microw. Mill.*, vol. 1, no. 3, pp. 282-287, 1991.

[8] S.C. Leong, L. Fujiang, and X. Yong Ping, "An improved NL-L transmission line de-embedding technique for mm-wave applications," *IEEE Int. Symp. RF Integration Tech., 2009, RFIT 2009*, vol., no., pp. 133-136, Jan. 9 – Dec. 11, 2009.

[9] M.B. Steer, S.B. Goldberg, G. Rinne, P.D. Franzon, I. Turlik, and J.S. Kasten, "Introducing the through-line deembedding procedure," *IEEE MTT-S Int. Microw. Symp. Digest, 1992*, vol. 3, no., pp. 1455-1458, June 1-5, 1992.

[10] C. Wan, B. Nauwelears, W. De Raedt, and M. Van Rossum, ""1 Thru + 2.5 Reflects": A new technique for de-embedding MIC/MMIC device measurements in fixed-length fixtures," *26th Euro. Microw. Conf., 1996*, vol. 1, no., pp. 174-177, Sept. 6-13, 1996.

[11] M. Farina and T. Rozzi, "A short-open deembedding technique for method-of-moments-based electromagnetic analyses," *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 4, pp. 624-628, Apr. 2001.

[12] F.M. Ghannouchi, F. Beauregard, R. Hajji, and A. Brodeur, "A DE-embedding technique for reflection-based S-parameter measurements of HMICs and MMICs," *Microw. Opt. Techn. Let.*, vol. 10, no. 4, pp. 218-222, 1995.

[13] H. Heuermann and B. Schiek, "Line network network (LNN): an alternative in-fixture calibration procedure," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 3, pp. 408-413, Mar. 1997.

[14] G. Gronau and I. Wolff, "A simple broad-band device de-embedding method using an automatic network analyzer with time-domain option," *IEEE Trans. Microw. Theory Tech.*, vol. 37, no. 3, pp. 479-483, Mar. 1989.

[15] J. Song, F. Ling, W. Blood, E. Demircan, K. Sriram, K.-H. To, R. Tsai, Q. Li, T. Myers, and M. Petras, "De-embedding and EM simulations for microstrip over lossy silicon," *IEEE Antennas Propag. Society Int. Symp., 2003*, vol. 3, no., pp. 973-976, June 22-27, 2003.

[16] Lei Zhu, Ke Wu, "Comparative investigation on numerical de-embedding techniques for equivalent circuit modeling of lumped and distributed microstrip circuits," *IEEE Micorw. Wireless Compon. Lett.*, vol.12, no.2, pp.51-53, Feb. 2002.

[17] Q. Chen and V.F. Fusco, "Numerical electromagnetic simulator termination de-embedding technique," *Electron. Lett.*, vol. 30, no. 5, pp. 423-424, Mar. 3, 1994.

[18] S.J. Mason, "Feedback Theory-Further Properties of Signal Flow Graphs," *Proc. IRE* , vol. 44, no. 7, pp. 920-926, July 1956.

[19] E.F. da Silva, M.K. McPhun, "Calibration of microwave network analyser for computer-corrected S parameter measurements," *Electron. Lett.*, vol. 9, no. 6, pp. 126-128, 22 Mar. 1973.

Adam Swiatko received his BEng and his BEng (Hons) in 2009 and 2010, respectively, from the University of Pretoria and is presently studying towards his MEng at the same institution. His research interests include microwave filters, antenna structures as well as microwave circuit characterisation.