Developments in the Transmission-Line Modelling (TLM) of Microwave Components

Jonathan L. Herring and Wolfgang J. R. Hoefer

NSERC/MPR Teltech Research Chair in RF Engineering
Department of Electrical & Computer Engineering
University of Victoria
Victoria, British Columbia, Canada

Abstract

Developments in the TLM modelling of microwave components are described. The accuracy of TLM is considered and efficient methods of correcting coarseness error are presented. Absorbing boundary conditions, a hybrid TLM/mode-matching method and models for general materials are also featured. Typical results are shown.

Introduction

The transmission-line modelling (TLM) method is an approach to numerical modelling in which a continuous system is approximated by a network of transmission-lines and this discrete network is then solved exactly. The origins of TLM date back to 1944 and the work of Kron and others who noticed the similarity between circuit concepts and Maxwell's equations [1]. The TLM method, as a practical tool for solving electromagnetic field problems was introduced by Johns and Beurle in 1971 [2]. The method has since been used to model diffusion and acoustic systems in both two and three dimensions, but it is perhaps most widely used to obtain full-wave electromagnetic field solutions directly in the time domain.

Some recent advances in the TLM method were reported by Christopoulos in the October 1995 issue of the Informer [3]. In this paper, work done by the research group of the NSERC/MPR Teltech Research Chair in RF Engineering at the University of Victoria, British Columbia, Canada is reported. The group concentrates on numerical modelling of microwave components. Numerical modelling allows components to be tested without the need for physical realization and, through visualisation of the fields, can enhance understanding of how the component operates.

Time domain TLM is most appropriate when output is required over a wide frequency range and where the geometry is too complex for other solution methods. Inhomogeneous materials, non-linearities and time variations can all be easily included. The method is very similar to the finite difference time domain (FDTD) technique as proposed by Yee in 1966 [4] and indeed some TLM formulations produce identical results to FDTD. The most common node used for three-dimensional work, the symmetrical condensed node (SCN) [5], does however possess some unique features and there is no simple FDTD equivalent [6].

Accuracy of TLM

TLM is a discrete system in which the results tend to the solution of the continuous system as the discretization steps tends to zero. Practical simulations must necessarily employ a finite discretization and this introduces numerical dispersion [7], which varies with frequency and direction of propagation. To keep the dispersion error within acceptable limits the maximum frequency at which results are taken as valid is typically limited to 10 nodes per wavelength. Dispersion analysis gives the behaviour of the TLM model of free-space. For systems in which discontinuities are present, the discrete solution can converge more slowly to the continuous one, resulting in coarseness error. This behaviour can be studied by analytically solving the difference equation of the numerical scheme, subject to the actual boundary conditions of the problem [8]. The closed form solution can only be obtained in certain cases but conclusions can be drawn about the propagation behaviour of modes in the general case. For example, the accuracy of the field for a capacitive diaphragm in a TEM waveguide modelled with two-dimensional TLM is reduced from second to first order with the introduction of the discontinuity.

Correction of Coarseness Error

Coarseness error will typically result in a shift in frequency domain characteristics. This error is often unacceptable when analysing narrowband devices such as filters. One solution is mesh refinement but this is particularly unattractive for discontinuities which only have first order convergence. It is more efficient to make only a simple local mesh modification around the discontinuity leaving nodes in the remaining space unchanged. Previously, for the two-dimensional case, inductive stubs have been added to the nodes adjacent to the discontinuity to increase the local energy storage [9]. A new more vigorous approach is based on the quasi-static approximation of the analytical Green's function for the discontinuity under study [10]. Here, the field distribution is represented in terms of an equivalent circuit. When expressed as a Z matrix, this circuit can be implemented easily and efficiently in TLM.

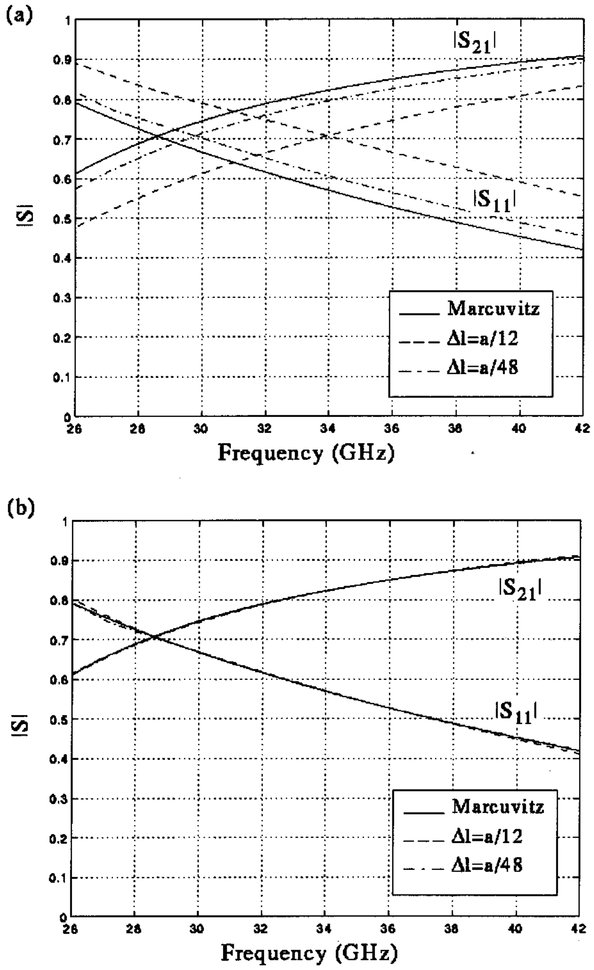

Fig. 1. S-parameters for a thin iris in WR28 waveguide: (a) without corner correction, (b) with corner correction

The method is illustrated for a thin iris in Fig 1. The S-parameters are shown for two different discretizations and are compared with the formulae by Marcuvitz [11].For the three-dimensional case, a method has been proposed in which the velocity of the voltage pulses around the discontinuity is adjusted to minimize the coarseness error [12]. This produces good results but there are currently no analytical formulae available for determining the parameters to be used in the correction.

Local mesh modification methods such as these allow the discretization to be determined by the dispersion error rather than the coarseness error and this is essential if complex structures are to be solved within a reasonable time.

Absorbing Boundary Conditions

In TLM, the entire problem space must be discretized. For open systems a suitable termination must be applied to the edge of the mesh. Such terminations are termed "absorbing boundary conditions" (ABC) since they are expected to completely absorb any incident wave and produce no reflection. If the wave impedance is independent of frequency and the angle of incidence is known then the ABC is trivial and is implemented by terminating the transmission-lines on the edge of the mesh with an appropriate impedance. In other cases a more sophisticated boundary condition must be applied, for example, the one-way equation ABC proposed by Higdon [13]. A major problem associated with this type of ABC is instability resulting from round-off errors. However, by using appropriate coefficients and by applying the ABC directly to the TLM voltage pulses rather than the fields, stable and efficient ABC's can be obtained [14].

An ABC that has been receiving considerable attention recently is Berenger's perfectly matched layer (PML) for FDTD [15]. A direct TLM equivalent of the PML has not yet been reported. However, the FDTD formulation can be incorporated into TLM by introducing a TLM/FDTD interface on the edge of the TLM mesh [16]. This approach allows features that have been developed for FDTD to be used in TLM without first forming an equivalent network model. The typical performance of second order Higdon and Berenger ABC's when used to terminate a waveguide is shown in Fig. 2. The Berenger ABC clearly gives much better performance but it does require a certain thickness to be included in the PML, 20 nodes in this case.

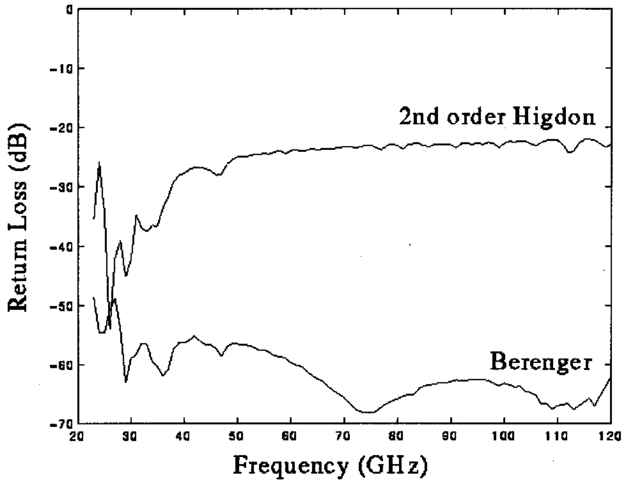

Fig. 2. Return loss for different absorbing boundary conditions in WR28 waveguide

Another type of ABC is the modal diakoptics boundary [17][18]. This can be used to terminate waveguides, where the modes are independent of frequency. The voltage pulses incident on the boundary at each timestep are decomposed into modes by multiplying with the expected spatial distribution of each mode. The resulting mode amplitudes are then convolved with the impulse responses of an infinite waveguide (obtained either analytically or from a separate TLM simulation) and the results are reinjected into the TLM mesh. For structures in which the modes are known, modal ABC's are efficient and give very good performance.

Hybrid Methods

Time-domain modal diakoptics is not restricted in application to ABC's; it can also be used to connect two sub-domains in which the more complicated part of the problem is modelled with TLM and the other part is modelled analytically. The packaged microstrip with via shown in Fig. 3 is particularly amenable to this approach [19]. The region above the plane AA' can be considered as a waveguide stub; the modes are simply obtained for the rectangular waveguide cross-section and there is no coupling between modes since the waveguide is uniform. The advantage of this approach is that the three-dimensional system above the interface is reduced to a number of one-dimensional problems. The number of modes which must be included in the decomposition is dependent on the height of the interface above the discontinuity; the higher it is the fewer the number of modes but the larger the volume modelled with TLM. Comparison with experiment [20] is shown in Fig. 4. The results from

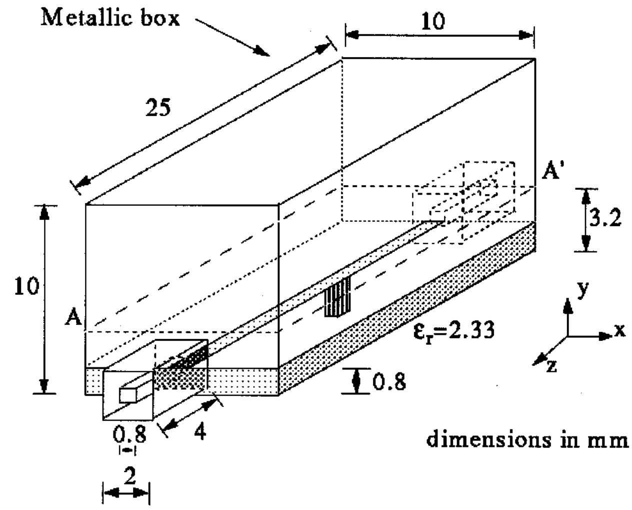

Fig. 3. Geometry of packaged microstrip via-hole

the hybrid analysis are essentially the same as those obtained from a full TLM simulation but the runtime was reduced from 157 to 62 minutes and the memory requirement was reduced from 13 to 6 Mbyte.

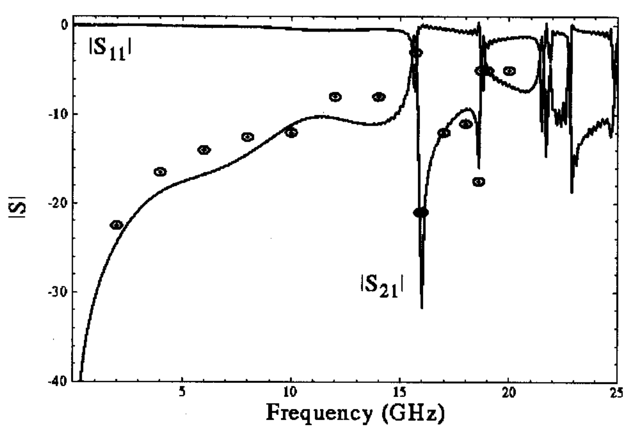

Fig. 4. S-parameters for the packaged microstrip (solid line - TLM, circles - experiment)

Modelling of General Materials

In the basic TLM formulation, regions of higher permittivity or permeability are modelled by adding open and short-circuit stubs to the node. For more general materials, where the constitutive parameters are frequency dispersive and non-linear, it is possible to represent the medium behaviour by equivalent sources placed at the node [21]. The sources are determined by the constitutive equations and the total voltages and currents at the node. The differential equations describing these relationships can be solved with state-variable techniques and an appropriate discretization scheme. The resulting system of difference equations is then solved at each TLM timestep. This method has the advantages that it is robust, it results in a TLM scattering matrix which is independent of the medium behaviour, and it can be integrated with conventional circuit analysis programs if an equivalent circuit of the medium behaviour is available.

The method is illustrated for an E-plane resonance isolator in a WR90 waveguide. A ferrite slab of width 0.5mm and length 24mm was placed 2.54mm from one of the inner waveguide walls, with a saturation magnetization of 1700 Gauss and a bias magnetic field of 2840 Oersteds. The results are shown in Fig. 5.

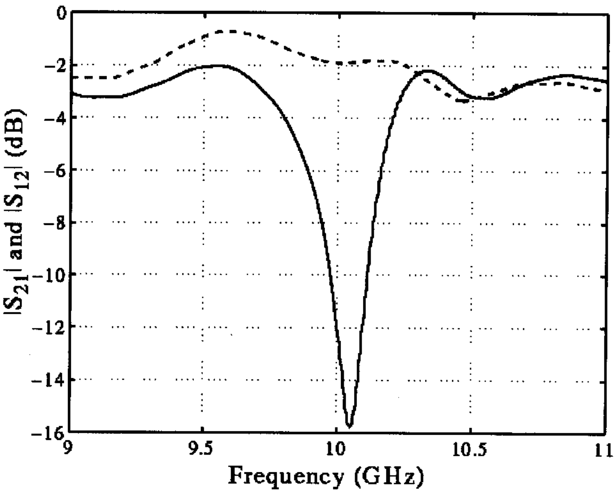

Fig. 5. Forward and reverse attenuation for E-plane resonance isolator

Conclusions

A thorough understanding of the errors inherent in a numeric scheme such as TLM is essential if confidence is to be placed in the results. Efficient methods of reducing these errors must be available if realistic problems are to be solved with reasonable computer resources. The combination of TLM with other methods and efficient absorbing boundary conditions also reduce the computational effort and the availability of models for general materials increases the range of problems that can be tackled.

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Jonathan L. Herring was born in Middlesbrough, England, in 1966. He received the M.Eng. degree in Electrical & Electronic Engineering from the University of Nottingham, UK in 1989 and received the Ph.D degree from the same university in 1993. From July 1989 to October 1993 he was employed as a Research Assistant at the University of Nottingham, where he worked on the modelling of EMC problems using the transmission-line modelling (TLM) technique. In November 1993 he joined the Department of Electrical & Computer Engineering, University of Victoria, Canada, as a Post-Doctoral Fellow and is continuing work on development of the TLM method.

Wolfgang J. R. Hoefer received the Dipl. Ing. degree in electrical engineering from the Technische Hochschule Aachen, Germany, in 1965, and the D. Ing. degree from the University of Grenoble, France, in 1968. During the academic year 1968/69 he was a Lecturer at the Institut Universitaire de Technologie de Grenoble and a Research Fellow at the Institut National Polytechnique de Grenoble, France. In 1969 he joined the Department of Electrical Engineering, the University of Ottawa, Canada where he was a Professor until March 1992. Since April 1992 he holds the NSERC/MPR Teltech Industrial Research Chair in RF Engineering in the Department of Electrical and Computer Engineering, the University of Victoria, Canada. His research interests include numerical techniques for modeling electromagnetic fields and waves, computer aided design of microwave and millimeter wave circuits, microwave measurement techniques, and engineering education. Dr. Hoefer is a fellow of the IEEE and of the Advanced Systems Institute (ASI) of British Columbia.