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NEW DEVELOPMENTS IN THE NUMERICAL SIMULATION OF RF AND MICROWAVE CIRCUITS USING THE TLM METHOD

Vladica Trenkić, Christos Christopoulos and Trevor M. Benson

Abstract. Developments in the transmission-line modelling (TLM) method, to increase spatial resolution using multigrid techniques, and to reduce run-time using efficient formulations of the scattering algorithm are described. It is shown that these result in very substantial improvements in the efficiency of computation and thus to the suitability of the technique as a general solver in design software.

1. Introduction

The design of modern microwave circuits requires advanced computer based tools. Traditionally such tools are based on lumped representations of lines and discontinuities such as those found in microstrip lines. The development of more sophisticated field codes in recent years has made it possible to study such circuits using a rigorous self-consistent field approach. This development will improve accuracy and confidence in design by significant amounts. Although simple problems can be solved using a full field solution, it is undeniably true that the computational efficiency of these methods must be significantly enhanced so that more complex and realistic problems can be tackled and, more importantly, faster solution times are achieved. This is

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The authors are with Department of Electrical and Electronic Engineering, University of Nottingham, Nottingham NG7 2RD, UK.

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important in the design office environment where a faster response is necessary to allow an interactive environment for achieving design optimisation.

An important aspect in the development of field simulation software is the optimisation of existing computer codes and further development in numerical models to make the best use of available computational resources.

Several methods are available to study microwave circuits. Of the methods offering a full field solution which is general and versatile enough to be used as a general design tool the finite element, finite difference and transmission-line modelling (TLM) methods are those almost exclusively used for this type of work. Of these three methods only the last two have been applied extensively in the time-domain and thus offer a solution in a single computation over a wide frequency range.

In this paper some recent developments to TLM which enhance its capabilities as a general numerical simulation tool are described.

2. Improvements in Spatial Resolution

Improvement in spatial resolution may be achieved by increasing the number of nodes used to model a fixed block of space. The symmetrical condensed node shown in Figure 1. is used extensively in TLM. Reducing the basic space step Δl increases resolution to any desired value. In practice, however, such increases result in an increase to the computer storage required and hence practical limits are imposed to indiscriminate increase in resolution across the entire problem space. A more acceptable practice is to increase the spatial resolution where it is required e.g. where fields vary rapidly, whilst keeping a modest resolution elsewhere. In order to achieve this a fine mesh must be used in selected parts of the problem with a coarser mesh elsewhere. The techniques to achieve this are referred to as multigrid or subgrid techniques and are currently of major research interest. Work in this area has been reported recently both in connection with the finite difference time-domain method [1,2] and with TLM [3,4].

In the case of TLM resolution ratios as high as 9:1 have been used successfully with small loss in accuracy. Careful studies have shown that a compromises must be sought when developing pulse conversion strategies across the interface between a fine and a coarse mesh. These developments have allowed increasingly more complex problems to be treated which were outside the capabilities of techniques based on a uniform mesh. The multigrid technique is also superior to others methods which use a graded mesh to increase resolution. Taking the uniform mesh case as the reference requiring

1 unit of storage and 1 unit of CPU time then a graded technique requires 0.04 and 10^{-3}, and a multigrid technique 8×10^{-3} and 10^{-4} respectively. Although these figures are problem dependent they nevertheless illustrate the amount of computational savings that can be made.

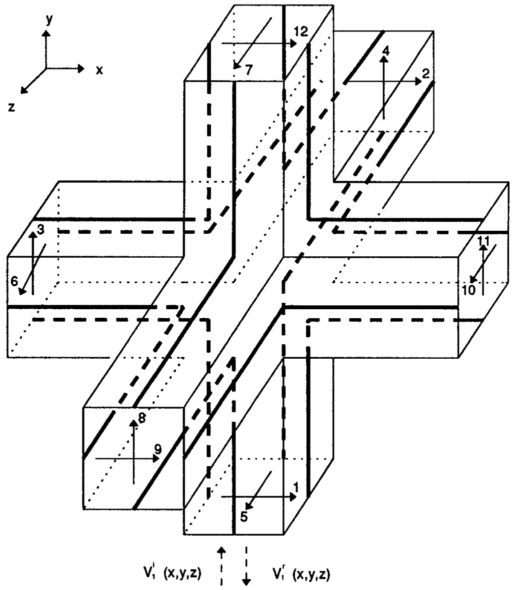

Fig. 1. Symmetrical condensed node (SCN)

3. Improvements in Run-Time Efficiency

The scattering matrix for the TLM node shown in Figure 1. was originally obtained by Johns [5] by enforcing energy and charge conservation laws for the incident and scattered voltage pulses at the node. This allows all scattering coefficients to be determined. For a 12-port symmetrical condensed node (SCN) expressions for calculating reflected voltages are of the form

$$V_3^r = \frac{1}{2}(V_4^i + V_8^i + V_1^i - V_{12}^i) \tag{1}$$

where the original numbering scheme introduced by Johns [5] is used. It can be easily found that 36 additions/subtractions and 12 multiplications by a constant must be performed in order to calculate all 12 reflected voltages in a single node for one time step.

Naylor and Ait-Saidi [6] have found that the scattering procedure can be implemented by first calculating the total voltages (V_x, V_y, V_z) and the total currents (I_x, I_y, I_z) from the incident pulses. The reflected voltages pulses then can be found from expressions of the form

$$V_L^r = V_n + I_n Z_L - V_R^i. \tag{2}$$

This method requires 42 additions/subtractions and 6 multiplications by a constant for scattering in a 12-port SCN. It gives the same total number of operations as for the original method, 48, but 6 multiplications are being replaced by 6 additions. The relative efficiency of these methods depends on machine architecture, i.e. how the additions and multiplications are implemented and on whether floating-point or fixed-point arithmetic is used.

Recently an alternative method for deriving the scattering matrix was suggested by Herring and Christopoulos [7], where scattering equations were obtained from the principles of conservations of charge and magnetic flux and continuity of electric and magnetic field. In [8] this method was applied on a general node introduced by German [9] where the impedances of the link-lines vary and a modified equation similar to (2) was found to be valid on a variety of TLM nodes.

The scattering equations obtained from the principles suggested by Herring and Christo-poulos [7] for a 12-port SCN are of the same form as the scattering matrix given by Johns [5]. For a clarity we write them using the notation of reference [7], as shown in Figure 2. In this scheme, each port is assigned a three-character name: the first character gives the direction parallel to the link line, the second is n or p indicating the port on the negative or positive side of the node and the third gives the polarization. The following expressions for the scattered pulses are found:

$$\begin{aligned}
V_{ynx}^r &= \frac{1}{2}(V_{znx}^i + V_{zpx}^i + V_{xny}^i - V_{xpy}^i),\\
V_{ypx}^r &= \frac{1}{2}(V_{znx}^i + V_{zpx}^i + V_{xpy}^i - V_{xny}^i),\\
V_{znx}^r &= \frac{1}{2}(V_{ynx}^i + V_{ypx}^i + V_{xnz}^i - V_{xpz}^i),\\
V_{zpx}^r &= \frac{1}{2}(V_{ynx}^i + V_{ypx}^i + V_{xpz}^i - V_{xnz}^i),\\
V_{zny}^r &= \frac{1}{2}(V_{xny}^i + V_{xpy}^i + V_{ynz}^i - V_{ypz}^i),
\end{aligned}$$

$$V^r_{zpy} = \frac{1}{2}(V^i_{xny} + V^i_{xpy} + V^i_{ypz} - V^i_{ynz}),$$
$$V^r_{xny} = \frac{1}{2}(V^i_{zny} + V^i_{zpy} + V^i_{ynx} - V^i_{ypx}),$$
$$V^r_{xpy} = \frac{1}{2}(V^i_{zny} + V^i_{zpy} + V^i_{ypx} - V^i_{ynx}),$$
$$V^r_{xnz} = \frac{1}{2}(V^i_{ynz} + V^i_{ypz} + V^i_{znx} - V^i_{zpx}),$$
$$V^r_{xpz} = \frac{1}{2}(V^i_{ynz} + V^i_{ypz} + V^i_{zpx} - V^i_{znx}),$$
$$V^r_{ynz} = \frac{1}{2}(V^i_{xnz} + V^i_{xpz} + V^i_{zny} - V^i_{zpy}),$$
$$V^r_{ypz} = \frac{1}{2}(V^i_{xnz} + V^i_{xpz} + V^i_{zpy} - V^i_{zny}).$$

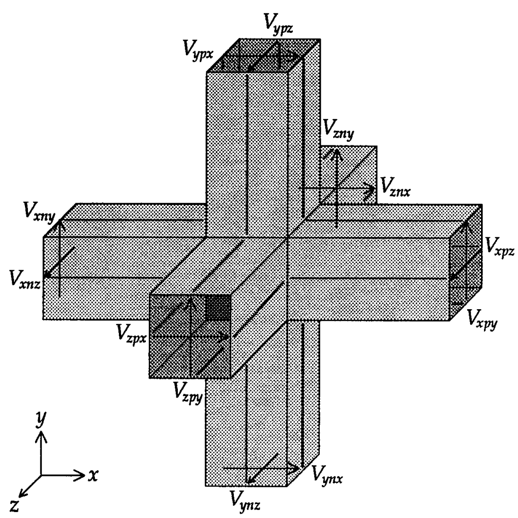

Fig. 2. An alternative notation of SCN ports from reference [7]

This form requires 36 additions/subtractions and 12 multiplications by a constant in order to calculate 12 reflected pulses.

From the above expressions it can be noted that incident pulses with the same direction and polarization, arriving from the negative and positive sides of the node (e.g. V^i_{znx} and V^i_{zpx}), might be grouped in appropriate partial sums and differences. These terms, representing the sums and differences of the pulses, can then be used twice in a subset of two consecutive equations.

Let the indices a and b determine the direction and polarization of an incident pulse, respectively, i.e. $a, b \in (x, y, z) \wedge a \neq b$. A sum and a difference of incident pulses than can be written as:

$$\begin{aligned} V_{asb} =& V^i_{anb} + V^i_{apb}, \\ V_{adb} =& V^i_{anb} - V^i_{apb} \end{aligned}$$

where the indices s and d stand for a sum and a difference, respectively. Using this notation, the set of 12 scattering equations given above can be rewritten in the following form:

$$\begin{aligned} V^r_{ynx} =& \frac{1}{2}(V_{zsx} + V_{xdy}), \\ V^r_{ypx} =& \frac{1}{2}(V_{zsx} - V_{xdy}), \\ V^r_{znx} =& \frac{1}{2}(V_{ysx} + V_{xdz}), \\ V^r_{zpx} =& \frac{1}{2}(V_{ysx} - V_{xdz}), \\ V^r_{zny} =& \frac{1}{2}(V_{xsy} + V_{ydz}), \\ V^r_{zpy} =& \frac{1}{2}(V_{xsy} - V_{ydz}), \\ V^r_{xny} =& \frac{1}{2}(V_{zsy} + V_{ydx}), \\ V^r_{xpy} =& \frac{1}{2}(V_{zsy} - V_{ydx}), \\ V^r_{xnz} =& \frac{1}{2}(V_{ysz} + V_{zdx}), \\ V^r_{xpz} =& \frac{1}{2}(V_{ysz} - V_{zdx}), \\ V^r_{ynz} =& \frac{1}{2}(V_{xsz} + V_{zdy}), \\ V^r_{ypz} =& \frac{1}{2}(V_{xsz} - V_{zdy}). \end{aligned}$$

This new form requires less operations than the previous ones. For each subset of two equations only one partial sum and one partial difference of incident pulses may be used in both equations. Accordingly, 4 additions/subtractions and 2 multiplications by a constant are required for a subset of two reflected pulses, giving in total 24 additions/subtractions and 12 multiplications by a constant required for a complete set of scattered pulses to be obtained.

A further reduction in the number of operations required can also be made. Using the identity

$$\frac{1}{2}(a-b) = \frac{1}{2}(a+b) - b,$$

the second expression in each subset can be rewritten in terms of the first expression, thus saving a multiplication per subset. Finally, the complete set of scattering equations is written as:

$$\begin{aligned}
V^r_{ynx} &= \frac{1}{2}(V_{zsx} + V_{xdy}), \\
V^r_{ypx} &= V^r_{ynx} - V_{xdy}, \\
V^r_{znx} &= \frac{1}{2}(V_{ysx} + V_{xdz}), \\
V^r_{zpx} &= V^r_{znx} - V_{xdz}, \\
V^r_{zny} &= \frac{1}{2}(V_{xsy} + V_{ydz}), \\
V^r_{zpy} &= V^r_{zny} - V_{ydz}, \\
V^r_{xny} &= \frac{1}{2}(V_{zsy} + V_{ydx}), \\
V^r_{xpy} &= V^r_{xny} - V_{ydx}, \\
V^r_{xnz} &= \frac{1}{2}(V_{ysz} + V_{zdx}), \\
V^r_{xpz} &= V^r_{xnz} - V_{zdx}, \\
V^r_{ynz} &= \frac{1}{2}(V_{xsz} + V_{zdy}), \\
V^r_{ypz} &= V^r_{ynz} - V_{zdy}.
\end{aligned}$$

The required number of operations is now 24 additions/subtractions and 6 multiplications by a constant, or total of 30 operations per node for a scattering iteration, which is considerably less than in previous methods [5,6]. A comparison of required number of operations per node for different methods is shown in Table 1.

Table 1. Number of operations per node for scattering procedure in TLM

Method	Johns [5]	Naylor [6]	New method
ADD/SUB	36	42	24
MUL by 1/2	12	6	6
Total	48	48	30

4. Conclusion

Substantial improvements in storage spatial resolution and run-time in connection with the TLM method have been achieved recently. It is possible that further improvements will be achieved in the future and that other more radical approaches such as hybridisation of TLM with other techniques will be introduced. It is not unrealistic to expect that in the near future field-based computational tools will be used extensively and will eventually replace approximate methods in everyday design practice.

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