A general method for mode selection in mode matching analysis of complex waveguide structures

M. Dionigi, L. Tarricone, R. Sorrentino
Istituto di Elettronica, S. Lucia-Canetola, I-06131 Perugia, Italy

Abstract

The time and accuracy performances of a 3D rectangular waveguide Mode-Matching (MM) simulator are strictly dependent on the appropriate selection of the basis functions used for the modal expansion of the fields. The number of selected modes determines the size of a linear system of equations whose solution is the computational core of the MM analysis. Moreover, the use of modes not suitable to the studied structures increases the risk of numerical instability.

We present a new method, based on graph theory, to detect automatically the minimum number of modes guaranteeing a fixed spatial resolution for whatever considered structure. The method is general, and does not require any considerations on the geometric properties of the structure.

Results prove that a substantial speed-up is obtained with the use of the optimal modal set.

1 Introduction

The Mode-Matching (MM) technique has been proved to be among the most efficient and reliable methods for the analysis of waveguide structures. Its quick response and accuracy make it appropriate for the development of waveguide

circuit CAD tools. In MM the field propagating inside a structure is expanded into a sum of basis functions called modes which depend on the cross section of the guiding structure. With the generalized admittance matrix (GAM) [1-3], the structure is segmented into simple cells, where the EM field is expanded in terms of appropriate Green's functions. At the openings between adjacent cells, the field is expressed in terms of two-dimensional modal sets. By, connecting all the GAMs the structure can be modelled by circuit theory. The accuracy and spatial resolution of the analytical description of the fields depends on the number of modes taken into account. It should be recalled that MM solutions are affected by the relative convergence phenomenon. The most accurate results are obtained by selecting the maximum mode orders in such a way that the same spatial resolution is obtained in adjacent regions. We call here *modal set* (MS) the set of all modes used to expand the field at all internal ports that connect the different cells.

The core of the MM solver is the solution of a linear system of equations (we call "solution system" SS) brought out by the combination of the GAMs of the different cells. Each variable in the SS represents the amplitude of a certain mode belonging to the chosen MS,whilst the impressed excitation represents the SS right-hand side.The size of the system matrix depends both on the complexity of the circuit (number of cells) and on the number of modes in the MS. Depending on symmetry properties of the entire circuit or some of its parts, and on the excitation of the circuit, certain subsets of modes may not be excited and should therefore be eliminated from the entire MS. The selection of the minimum MS (MMS) guaranteeing the required spatial resolution in the whole structure, is of fundamental importance in order to reduce the computation time and extend the MM method to the study of complex networks of waveguide structures.

Moreover, the selection of an MMS, reduces the risk of a numerical excitation of modes which are not physically present in the structure, or of ill conditioning of the problem, with a consequent degradation of the accuracy.

A pre-processing module, devoted to the automatic selection of the MMS is therefore a necessary part of the MM code.

A solution could be the implementation of an algorithm which, starting from a description of the topology and geometry of the circuit, automatically finds out the symmetry properties of the structure, and exploits them to cut away any redundant mode initially included in the MS. This solution is feasible, but

highly complex. The main difficulty is the implementation of a really flexible code, able to deal with complex structures.

An alternative solution, less flexible but much more viable, is to perform an analytical preliminary study of the MMS of a given structure and excitation. The resulting code is unavoidably "goal oriented", i.e. specifically devoted to a particular structure.

Both methods are clearly unsatisfactory. The former is hard to be followed, the latter compells the user to write down different codes for different circuits. Moreover in both methods the user is required to identify the right MMS depending both on the structure symmetries and the different external excitation, and this can be a hard task when the complexity of the structure grows up.

2 Mode selection module

We propose here a general method for the automatic selection of the MMS for a given spatial resolution and excitation. It applies to a whatever complex network, and does not require to the user any study on the symmetry properties of the structure. The method is based on graph theory and is described next.

The MS of a given structure can be divided into two parts: a subset of MS carrying power from the input ports to the output, and a subset of MS not excited by the input excitation. The existence of a set of modes not involved in the power propagation inside the structure can be recognized by an analysis of the network response to different excitations at different ports. Remembering that a variable in SS corresponds to a mode amplitude in MS, this means grouping the variables of the SS into a certain number of independent sets, where only the variables belonging to the same set are linked one another by equations included in the SS. One of these independent sets is composed of all the modes carrying power from the input to the output ports for a given excitation. This set is the MMS we are looking for.

The fundamental idea of the method is to translate in a graph form[4] the relationships among the variables in the SS. The graph nodes represent the SS variables (mode amplitudes), and a variable V_i is connected to a variable V_j if the coefficient a_{ij} (A is the system matrix in SS) is greater than a certain threshold value, and this corresponds to an edge connecting nodes i and j.

The graph corresponding to a given A matrix can generally be composed of several *connected components*[4]. A connected component (CC) is a part of the graph characterized by the existence of a path leading from each node to any other node belonging to the same component. A CC can be identified by the knowledge of at least one of its nodes. The identification of the CCs in the graph is equivalent to finding the partitioning of the SS variables into independent sets, and is a trivial task. In order to single out the CC corresponding to the MMS, among all components in a graph, it is necessary to know at least one of the modes excited in the MS for the given excitation. This identifies a node in the graph, that ultimately identifies the CC corresponding to the MMS. A uniform waveguide section is supposed to connect each external port to the subsequent one (this assumption is not restrictive, as it just implies a phase shift of the scattering parameters). Under such an assumption, if we excite an outer port with the fundamental mode, the same mode will be present at the subsequent port which will be considered as the root of the MMS.

3 Results

We present three examples demonstrating how the mode selection module allows one to discard a huge percentage of modes initially taken into account. The initial MS was defined on the basis of the given spatial resolution and geometry of the structure.

The first (almost trivial) example refers to a 5-cavity H-plane iris filter in rectangular waveguide. At the beginning a modal expansion including TE_{m0} modes has been used. Without modal reduction a total of 204 modes were selected. Because of the symmetry in the structure, the optimal mode set is composed of $TE_{(2m+1)0}$ modes. The mode selection module, in fact, has reduced the used modes to 108, discarding all the modes with even first index. The good improvement in the computational performances due to the use of the module is evidenced in the comparison between the solution times. With the unoptimized mode set, the SS solution takes 0.91 s for a single frequency value on a PC 486-33 MHz. The optimal mode set allows the SS solution within 0.22 s, and the time required for the modal reduction is negligible, as it is accomplished on the fly during the first frequency iteration. In Fig. 1 the filter structure and its response are given. The results obtained with both mode sets are identical.

Observe that the same structure could be included in a multiplexer as a channel filter. In this case other modes in addition to the fundamental can be excited at the ports of the structure. Because of its simmetry, a large percentage of the MS can be discarded, and our method to single out the MMS can be efficiently applied. Similar observations hold also for the following two examples.

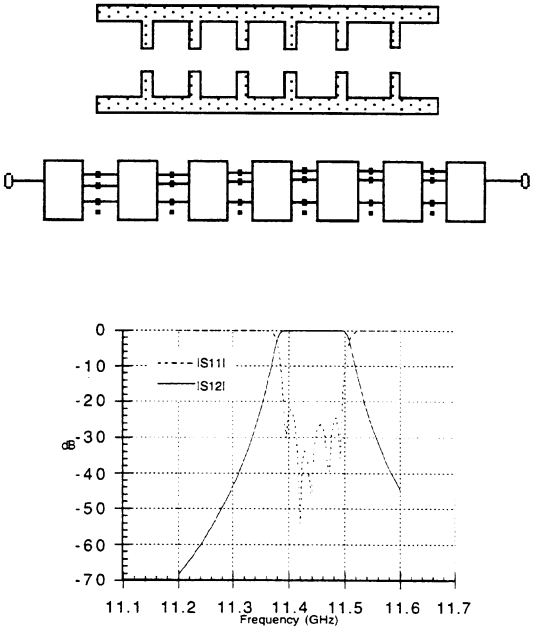


Fig. 1: H-Plane filter layout, schematic and scattering parameters.

The second example is the structure in Fig. 2, consisting of rectangular uniform waveguide sections coupled by double irises. The starting mode set, composed of 192 modes, was composed of TE_{mn} and TM_{mn} modes. Two symmetries can be immediately identified, one along an xz section and the other along an yz section. This means that only $TE_{(2m+1)2n}$ and $TM_{(2m+1)2n}$ modes should be considered. This is what the mode selection module does reducing the mode set from 192 to 40 modes. The starting set allows the SS solution in 1.4 s on a PC 486-33 MHz, whilst with the reduced mode set only 0.1 s are needed. Fig. 2 also shows the response of the structure, which is the same regardless of the used MS.

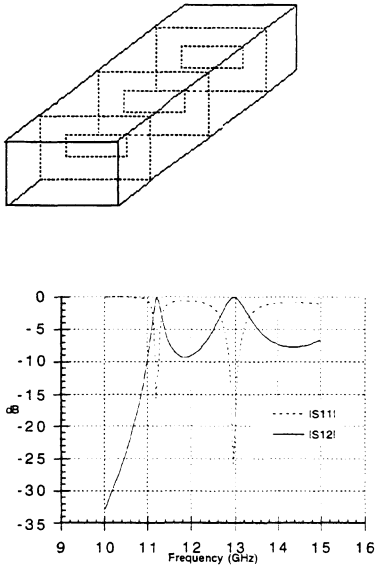


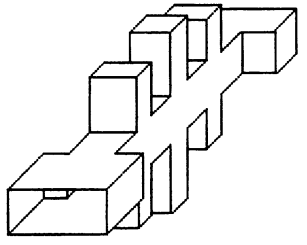
Fig. 2: Double Plane irises, structure and scattering parameters.

Although the above results could be obtained by simple inspection of the symmetry properties of the structure and of the excitation, this could not be done in the general case of complex geometries and arbitrary excitations. As a further example consider the fixed phase shifter, shown in Fig. 3, already proposed in an earlier paper [3]. For this medium-comlexity structure, a starting mode set consisting of 1302 modes was considered. In this case, the SS solution time was of 55.4 s per frequency point on an IBM RS 6000 25T. The mode selection module has discarded 1158 modes, indicating an optimal mode set of 144 modes. With such a reduction, the computational time on SS drops down to 0.01s.

4 Conclusions

In this paper we have proposed a method to select the modal set composed of the minimum number of modes to guarantee a given spatial resolution in a complex network in rectangular waveguide technology. This is fundamental both to reduce computational efforts and to avoid possible numerical instability. Three examples have been presented to assert the validity of the method, which can be applied to any complex structure. The method is general, and can be

easily customized to each MM-based package. The symmetries of any complex structure are automatically detected and redundant modes are cut off.without requiring any consideration on the geometric properties of the circuit.



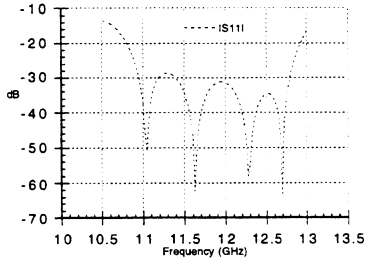


Fig. 3: Fixed Phase Shifter, structure and scattering parameters.

The use of the method allows a substantial speed-up of the performances of the MM simulator, and in particular with a medium-complexity structure as the phase shifter in the third example the computation time is reduced by two orders of magnitudes.

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