MULTI-LEVEL MODELING FRAMEWORKS FOR PLANAR ANTENNAS

Guy A. E. Vandenbosch, Bart Van Thielen, Mark Vrancken

K.U.Leuven, ESAT-TELEMIC, Kasteelpark Arenberg 10, 3001 Leuven, Belgium
guy.vandenbosch@esat.kuleuven.ac.be
bart.vanthielen@esat.kuleuven.ac.be
mark.vrancken@esat.kuleuven.ac.be

ABSTRACT

In recent years, the analysis of devices is performed more and more in a "rigorous" manner. Maxwell's equations are transformed into matrix equations, either using a differential or an integral equation approach. The solution of these matrix equations yields a discrete approximation of the solution. If the transformation is done correctly, demanding a higher accuracy results in a larger size of the matrix problem. In most practical devices, the number of unknowns rapidly becomes prohibitive. Two examples of two-level modeling are discussed. They involve modularity and hierarchy. Modularity is defined as "treating a problem at its own complexity level". It is shown that a reduction of computer resources with one to two orders of magnitude is typical.

INTRODUCTION

There are a lot of commercial software packages for the analysis and design of electromagnetic structures, both for 2.5D multilayered structures (HP-momentum, Ensemble, IE3D, SAPHIR, …) and for 3D structures (HP-HFSS, Ansoft HFSS, EMPIRE, MAFIA, Sonnet em, …). Most of these CAD packages are based on a single numerical technique (Method of Moments (MoM), Finite Elements (FE), Finite Difference Time Domain (FDTD), …). The consequence is that they can handle only so-called “small” structures. The size of “small” strongly depends on the computer power being used. In practice, with the workstations or PCs of today, these software packages are able to handle typically a single component or an assembly of a few components. They are by no means ready to handle complete complex systems. However, due to the accuracy of designing using a full-wave approach, even nowadays there is a clear trend towards the use of EM CAD software for sub-assemblies. Industry already is looking at the future and a lot of requests for EM software able to handle complete systems are being investigated. The steady increase of computer power is certainly a factor. However, in my view the current trend in the EM modeling community, using modularity and hierarchy in the EM modeling code, will prove to be a crucial factor in order to reach the ultimate goal: the full-wave analysis of complete systems.

In this paper, it is discussed how the framework developed at K.U.Leuven tries to cope with the problem mentioned. The direct goal of this paper is not to explain in detail the working mechanism of each numerical technique. The direct goal is to illustrate the use of modularity and hierarchy. In our view, this is one of the ways to reach the goal of analyzing and designing complete systems with EM software. A modular and hierarchical scheme to analyze a 2.5D system in a multi-layer environment is illustrated in Fig. 1. Practical devices like planar antenna arrays, planar circuits, PCBs, etc. can be described in this way. Although designers indeed tend to follow this modular scheme while thinking about the structure, a look at the analysis engines of most of the commercial CAD packages today reveals that they treat the complete system as just a single physical entity, using the same numerical technique throughout. In a large planar antenna array for example, the mutual coupling between two elements far apart is described with the same number of unknowns as the mutual coupling within the elements themselves. This is a waste of computer power. The inter-element coupling can be described with much less unknowns than the intra-element coupling. How to implement this in practical procedures?

A TWO-LEVEL FRAMEWORK BASED ON THE EXPANSION WAVE CONCEPT

This model was developed to analyze medium-sized and large antenna arrays. The idea is to use the characteristic waves of the layer structure (surface wave and space wave) to describe mutual coupling [1]. First, the coupling between the components is solved at the element level with a moment method applied to the component integral equations. This means that each so-called “element type” is solved in the same way as done in software as HP-momentum, Ensemble, and IE3D. The calculation time is depending on the size and complexity of the element type. Note that only the element types have to be solved, and not each element separately. This yields a first considerable reduction in calculation time. The coupling between the elements is described with expansion waves [2]. Each element has a number of “outgoing waves" generated by the element, and a number of "incoming waves", incident on the element and generated by the rest of the planar structure. The number of waves per element depends on the layer structure and the lateral size (in the plane parallel to the layer structure) of the element type under consideration, not on its internal complexity. It is typically at least an order of magnitude smaller than the number of unknowns in the MoM used to solve the internal coupling of the element type.

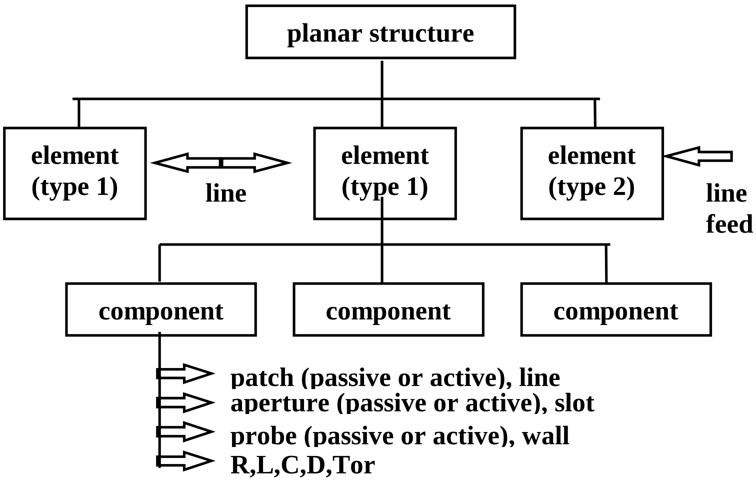

Fig. 1. Planar structure in a multilayer environment. The 2.5D structure consists of elements of several types. Each element type consists of components. The elements can be connected through transmission lines (microstrip or strip line, coplanar waveguide, …). The structure is solved at different levels. First the internal coupling within the element types is described using a moment method. Second the mutual coupling between the elements is described using the Expansion Waves. Third the elements are linked through the transmission lines (= links), assuming the fundamental modes only on these links (no mutual coupling with these links is taken into account).

Example

An 11x11 array of an aperture type element, embedded within a layer structure involving 7 layers is considered (Fig. 2). The number of unknowns used to solve the internal element coupling is 720. This means that the commercial software packages would have to solve a system of 87120 unknowns (= 121 elements x 720 unknowns), involving a full matrix. The expansion wave concept uses 48 unknowns per element (15 times smaller). The calculation time was about 3 hours per frequency point on an HP 9000/780 160 MHz 512 MB RAM workstation. The inversion at the array level took about 1.5 hours. Extrapolation yields an inversion time at the array level 15^3 times larger for traditional techniques.

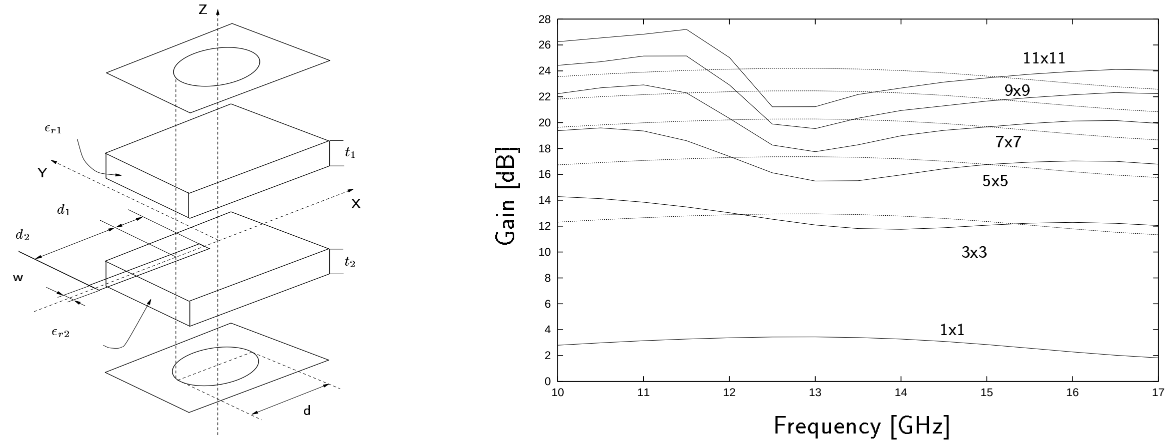

Fig. 2. Left: element type consisting of two stacked circular apertures in two conducting plates fed by a strip line in the middle region. Right: gain calculated with the EWC of a 1x1, 3x3, 5x5, 7x7, 9x9, and 11x11 array of the element type. As a reference the gain calculated without taking into account mutual coupling is also depicted (curves without oscillation). The oscillation is at the frequency where the distance between the elements is one wavelength. It becomes more pronounced for larger arrays.

A TWO-LEVEL FRAMEWORK BASED ON TRANSMISSION LINES AND EQUIVALENT DIPOLES

This new method was especially developed to analyze mutual coupling effects, for example in antenna feeding circuits. This analysis is not possible with traditional circuit simulators, where no mutual coupling is modeled. Using traditional full wave solvers, mutual coupling is included, but calculation times rapidly become prohibitive. The key idea here is to divide the planar structure into three classes of substructures: lines, small discontinuities, and larger meshed structures. Intra- and inter-class couplings are analyzed based on efficient techniques developed especially for the class interaction under consideration.

The module for the calculation of mutual coupling between transmission lines ([3] and [4]) is developed starting from the general method of moments that can handle random shapes. Only first order coupling is taken into account: the radiation effect of the induced currents is neglected. This approximation explains the differences with a rigorous MoM technique. The calculations are speeded up for the specific case of coupling between lines by assuming that all lines are terminated in their characteristic impedances and using the travelling current waves on these matched lines. The current on the observation line can then be calculated by convolving the incident field on this line with its "impulse response". The impulse response is the current on an infinitely long line when a spatial Dirac impulse is applied in the middle. This results in a much faster method because no matrix inversion has to be performed. Full details can be found in [3] and [4].

For the calculation of mutual coupling between discontinuities [5], the discontinuities must be small compared to the wavelength and compared to the distance between them. For most circuits these assumptions are valid. Under these circumstances the component's (discontinuity) radiation behavior can be accurately modeled by using adequately placed dipoles. This method uses far less unknowns than the method of moments. If the distances between the components become smaller or the components become bigger, then the accuracy can be improved by using more dipoles. The position of the dipoles and their excitation (depending on which port of the component is being fed) are determined by an optimization procedure that matches the combined radiation pattern of the dipoles to that of the component. The data about the component's S-parameters, dipole excitations and positions as a function of frequency are then stored in a library file. These library files are used when the circuit itself is calculated. Similarly to the line-coupling module, this module also only takes first order coupling into account (scattering of EM fields at the dipoles is ignored). Full details can be found in [6].

Meshed structures are treated using the method of moments. The normal method of moments only works with currents and fields. For circuits (e.g. feeding the antenna elements), where one is interested in the relations between incoming and outgoing waves on the feeding lines, an additional deembedding step (such as [7]) is therefore required. In [6], the MoM is altered in such a way that incoming and outgoing waves at the structure's ports are just extra unknowns in the coupling matrix, along with the segment couplings. This makes it possible to insert the MoM coupling matrix directly into the circuit simulation (along with lines and discontinuities), thereby providing a close integration between the classical MoM, the new modules and the S-parameter circuit simulator. The excitations of the structure's feeding lines are chosen in such a way that they generate incident waves on these lines. The feeding line's self-coupling matrix is modified so that it appears to be matched at the feeding point. These modifications make it possible to get S-parameters immediately after inverting the structure's Z-matrix, without needing an extra deembedding step. Full details can be found in [6].

Example

Consider the 2 x 2 edge-fed, dual polarisation, patch array that is shown in Fig. 3. The patches resonate at 7.2 GHz and have an impedance of about 100 Ohm at that frequency. The characteristic impedance of all lines is 100 Ohm. This results in an input impedance of 50 Ohm at the inputs (the line sections between port and T-junctions are a multiple of a half wavelength at 7.2 GHz). The substrate has a thickness of 1.575 mm and a relative permitivity of 2.2. The port 2 T-junction should be offset by ¼ wavelength up or down (see Fig. 3) for normal operation (horizontal polarisation when fed at port 1 and vertical when fed at port 2) to avoid the vertically polarized patches being fed 180 degrees out of phase. This offset is not present here in order to increase coupling between both ports, because we want to demonstrate the validity of the new analysis method for large rather tightly coupled structures. The patches of the structure are meshed with 24 x 31 segments. The dense mesh is needed to accurately model the incisions. The lines have 3 segments across their width. The structure was calculated using the method of moments (needing 663 MByte and 41 minutes and 26 seconds per frequency point on a Hp J-5000, 445 MHz workstation). This result was compared to the result of the new method, using 32 dipoles on the patch (many dipoles needed here because the patches are not small compared to the wavelength and very close to lines and bent) and 6 dipoles for the bent. The new method only needs about 100 KByte and 8 seconds. The calculation times given do not include the time needed to calculate the Green's functions. The structure was calculated for L=6.43 mm (case shown in Fig. 3) and for L=4.43 mm (results in Fig. 4).

CONCLUSIONS

In this paper two modular approaches are explained. They illustrate the use of modularity and hierarchy in electromagnetic analysis engines. In our view the use of modularity and hierarchy is essential in the search for engines able to cope with larger and larger problems. The key feature in such an approach is to address each problem at its own level of complexity. The expansion wave concept and the dipole model are examples of this.

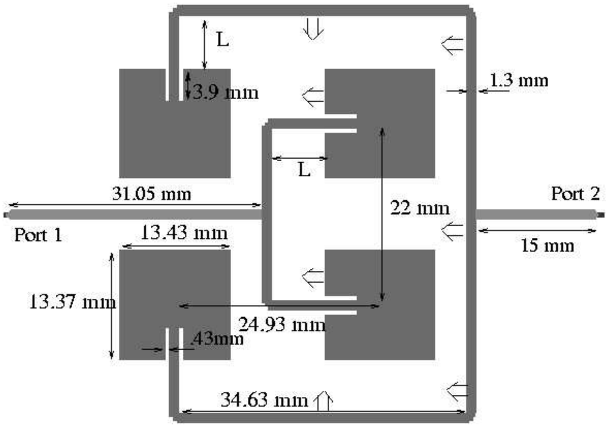

Fig. 3. 2 x 2, dual polarization, edge-fed array of patch antennas. In the position shown L = 6.43 mm. Double arrows indicate parts movement when L is made smaller.

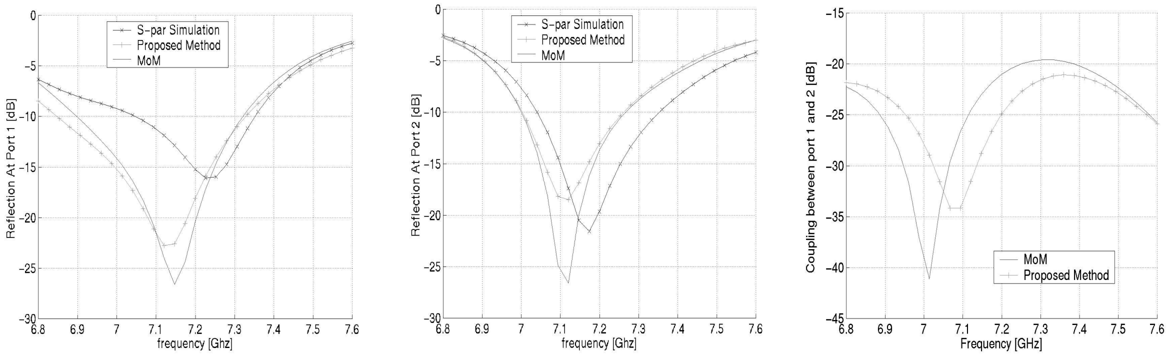

Fig. 4 Results for the structure of figure 3. L=4.43 mm. Continuous line is result of MoM, '+' line is result using new method. All S-parameters are referenced to 50 Ohm.

References

[1] F. J. Demuynck, G. A. E. Vandenbosch, and A. R. Van de Capelle, "The expansion wave concept – part I: Efficient calculation of spatial Green's functions in a stratified dielectric medium", IEEE-AP, vol. 46, no.3, pp. 397-406, March 1998

[2] G. A. E. Vandenbosch and F. J. Demuynck, "The expansion wave concept – part II: A new way to model mutual coupling in microstrip arrays", IEEE-AP, vol. 46, no.3, pp. 407-413, March 1998

[3] B. L. A. Van Thielen and G. A. E. Vandenbosch, "Method for the acceleration of transmission-line coupling calculations," IEEE Trans. Microwave Theory Tech., vol. 48, No. 9, pp. 1531-1536, Sept 2000.

[4] B. L. A. Van Thielen and G. A. E. Vandenbosch, "Fast transmission line coupling calculation using a convolution technique," IEEE Trans. Electromagn. Compat., vol. 43, no. 1, pp. 11-17, Feb 2001.

[5] B. L. A. Van Thielen and G. A. E. Vandenbosch, "Method for the calculation of mutual coupling between discontinuities in planar circuits," published in January 2002 issue of IEEE Trans. Microwave Theory Tech.

[6] B. L. A. Van Thielen and G. A. E. Vandenbosch, "Fast S-parameter extraction method for the analysis of planar structures using the method of moments," International Journal of Microwave and Millimeter-Wave Computer-Aided Engineering, vol. 11, no. 6, pp. 404-415, Nov 2001

[7] J. Sercu, N. Fache and D. De Zutter, 'Characterisation of TEM and non-TEM Planar Transmission Lines with a Full-Wave 3D Field Analysis Technique", Proceedings of the 23rd European Microwave Conference, pp. 328-329, 1993.