HETEROGENEOUS PARALLEL YIELD-DRIVEN ELECTROMAGNETIC CAD

J.W. Bandler*, R.M. Biernacki*, Q. Cai*, S.H. Chen*, P.A. Grobelny and D.G. Swanson, Jr.†

Simulation Optimization Systems Research Laboratory
and Department of Electrical and Computer Engineering
McMaster University, Hamilton, Ontario, Canada L8S 4L7

ABSTRACT

Within an integrated parallel optimization framework, we are able, for the first time, to apply electromagnetic (EM) optimization to the yield-driven design of microstrip circuits of arbitrary geometries. Parallel optimization handles the massive demand on computer resources, due to the large number of designable parameters describing an arbitrary geometry and the large number of simulations involved in yield optimization. Our parallel strategy can be implemented over local and wide area networks supporting heterogeneous workstations.

INTRODUCTION

The accuracy of EM models is a crucial aspect of first-pass success design. It is, however, obtained at the expense of drastically increased analysis time. The use of EM simulators in CAD has been advocated in [1, 2], in which work the obstacle of excessive CPU time is circumvented by running the EM analyses off line. More recently, we pioneered the integration of EM models into automated design utilizing a modern EM solver, efficient optimizers and novel data base techniques [3-6].

In our current efforts to advance the state of the art, one of the focal points is the ability to capture arbitrary geometries for EM optimization [7]. It is to allow the designer to analyze and optimize a microstrip subcircuit as a whole instead of having to decompose it into pieces of library elements which are simulated by an EM solver separately and then reconnected via circuit theory. Considering a subcircuit as a whole gives a more complete account of the electromagnetic couplings and leads to more accurate simulation results. It also means, however, that a larger number of designable parameters are included in a single EM model. As a consequence, EM optimization of arbitrary geometries may exert a massive demand on computer resources which, while inducing euphoria in hardware vendors, can severely frustrate engineers constrained by time and budget.

In this work, we overcome this problem by distributing the computational load over a network of computers on which EM simulations are carried out in parallel. Parallel computation is an effective means of speeding up CPU intensive optimization tasks (e.g., in VLSI interconnect design [8]). We integrate the parallelization scheme with our novel interpolation/modeling mechanism in Empipe [5] to further improve the efficiency. Based on standard UNIX protocols, our strategy of parallel computations is implementable over local and wide area networks supporting heterogeneous workstations, making it an affordable solution for practical applications.

The benefits of our approach are demonstrated by both nominal and statistical designs of two microstrip circuits: a 3-section impedance transformer and a 10 dB distributed attenuator. We utilize the OSA90/hope optimization system with the Empipe interface [5] to the Sonnet field simulator *em* [6]. These software tools reside on a file server accessible from 16 Sun SPARCstation 1+ computers via a local area network.

ELECTROMAGNETIC CAD WITH GEOMETRY CAPTURE

Automated EM optimization raises a number of challenges. We have refined interpolation and modeling techniques [4, 5, 9, 10] in order to reconcile the discrete nature of numerical EM solvers and the requirement of continuous variables and gradients by the optimizers. We have also introduced an integrated data base system to store simulation results from distributed computation.

There is also the problem of geometrical parameterization. Conventional circuit theory based simulators assume a library of built-in elements with predefined parameters. Circuits to be simulated must be modeled as a set of such interconnected elements. The characteristics of each element can be modified parametrically by, for instance, changing a numerical entry in the netlist. EM simulators, on the other hand, deal directly with the layout representation of a circuit. The numerical values contained in their "netlist" are typically geometrical coordinates which cannot be related in an obvious way to designable parameters.

An Empipe element library [5] was created in our earlier work. The library contains geometrical primitives (lines, bends, junctions, gaps, stubs, etc.) from which a subcircuit structure can be built. This approach gained immediate acceptance by CAD users by virtue of its familiarity and ease of use. Also, it

This work was supported in part by Optimization Systems Associates Inc. and in part by the Natural Sciences and Engineering Research Council of Canada under Grants OGP0007239, OGP0042444 and STR0117819. Additional support was provided through a Natural Sciences and Engineering Research Council of Canada Industrial Research Fellowship granted to Q. Cai.

* J.W. Bandler, R.M. Biernacki and S.H. Chen are also with and Q. Cai is with Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7.

† D.G. Swanson, Jr., is with Watkins-Johnson Company, Palo Alto, CA 94304-1204, USA.

minimizes the complexity of EM analysis since each time only one elementary geometry is analyzed. However, this approach inherently omits possible proximity couplings between the elements since they are connected by the circuit-level simulator. Furthermore, it does not accommodate structures which cannot be decomposed into library elements.

To provide a tool for parameterizing arbitrary structures, we created the user-friendly "Geometry Capture" [5, 7]. Using a graphical layout editing tool (such as ***xgeom*** for ***em*** from Sonnet Software [6]), the user generates a set of geometries marking the evolution of the structure under consideration as the designable parameters change. The resulting geometries are then processed by Empipe to extract the information from which a mapping between the geometrical coordinates and the designable parameter values is established. Fig. 1 illustrates an arbitrary geometry which cannot be decomposed into Empipe library elements but can be parameterized using Geometry Capture for EM optimization.

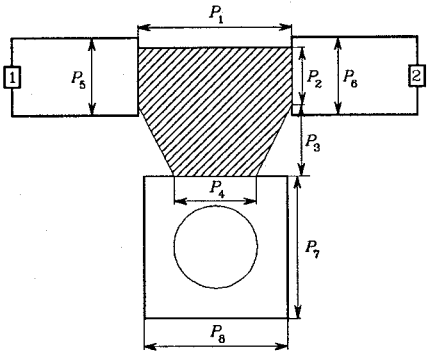

Fig. 1. An arbitrary geometry which cannot be decomposed into Empipe library elements but can be parameterized using Geometry Capture for EM optimization.

PARALLEL COMPUTING

The general concept of parallel computing can be realized in many different ways, including multiprocessor computers and specialized compilers. In the context of this paper, it means distributing the load of EM analyses over a computer network and such distribution is organized by the application software Empipe. We rely on standard UNIX protocols (remote shell and equivalent hosts) instead of any platform specific mechanisms. This allows us to apply the concept to both local and wide area networks of heterogeneous workstations.

We chose to split the load of EM analyses on the component/subcircuit level for two reasons: to reduce the complexity of implementation and to best suit the operational flow of interpolation, optimization and statistical analysis. For instance, if the parameter values are off the mesh grid imposed by the EM simulator, a number of EM analyses are needed at adjacent on-grid points for interpolation. In order to estimate the gradients for optimization, a number of perturbed analyses are required in addition to the analysis at the nominal point. For statistical analysis, EM analyses are to be performed at many Monte Carlo outcomes. By carrying out these analyses in parallel, the overall simulation time can be reduced by a factor of n, where n denotes the ratio between the combined effective computing power of the networked computers and that of a single computer (assuming that the overhead of parallelization is negligible compared with the CPU-intensive EM analyses).

The distribution of computational load is organized by Empipe from one of the networked computers (master host). Using the UNIX remote shell command, an EM analysis is started on each of the available hosts. When the analysis is finished on a host, the next job, if any, is dispatched to that host. The EM simulation results are gathered from all the hosts and stored in a data base created on the master host. Fig. 2 illustrates this mechanism.

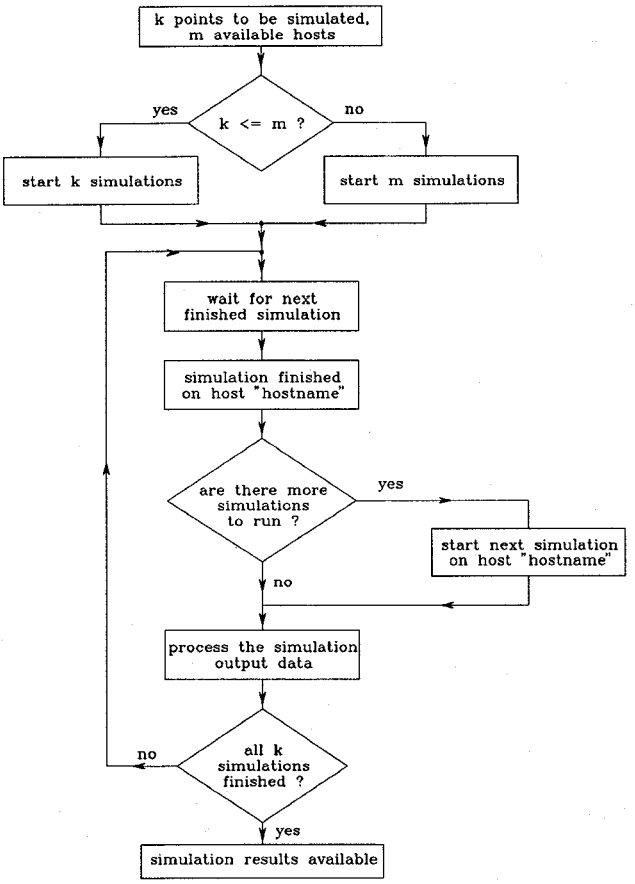

Fig. 2. Parallel computing by distributing EM analyses over a network of computers.

YIELD OPTIMIZATION OF A THREE-SECTION MICROSTRIP IMPEDANCE TRANSFORMER

We perform nominal and statistical design of a 3-section 3:1 impedance transformer [4]. The transformer is simulated by ***em*** [6] as a two-port and the results are embedded into the OSA90/hope [5] circuit definition, together with the source and load impedances of 50 and 150 Ω, respectively. The design specification is given as

$$|S_{11}| \leq 0.11, \text{ from 5 GHz to 15 GHz}$$

The EM simulation frequencies are from 5 to 15 GHz with a 0.5 GHz step. The transformer is built on a 0.635 mm thick substrate with relative dielectric constant 9.7.

Using Geometry Capture, the transformer is analyzed by ***em*** as one piece (we could also decompose the transformer into

three Empipe library elements in which case any couplings between the three pieces would be omitted). It takes approximately 3 CPU minutes to analyze the transformer at a single frequency on a Sun SPARCstation 1+.

For minimax optimization, we consider the widths W_1, W_2 and W_3 as designable parameters. The linear interpolation model in Empipe [5] is used. Consequently, a maximum of 4 EM analyses (the number of designable parameters + 1) may be parallelized. In the actual experiment, 31 EM analyses were performed during optimization, with an average of 3.1 analyses run in parallel. Assuming comparable computing power available from each of the 4 workstations, the CPU time needed to obtain the solution is cut by 2/3 through parallel computing.

For statistical design we assume normal distributions on the widths W_1, W_2 and W_3, with a standard deviation of 5 μm, as well as on the lengths L_1, L_2 and L_3, with a standard deviation of 2% of the nominal values. Yield estimated from 250 outcomes at the minimax nominal design is 61%, and is increased to 77% after yield optimization. The Monte Carlo sweep of $|S_{11}|$ at the centered design is shown in Fig. 3. The parameter values at the starting point, the minimax nominal solution and the centered design are listed in Table I.

TABLE I
MINIMAX AND YIELD OPTIMIZATION OF
A 3-SECTION MICROSTRIP TRANSFORMER

Parameter	Standard Deviation	Starting point (mm)	Minimax solution (mm)	Centered solution (mm)
W_1	5 μm	0.65	0.3479	0.3749
W_2	5 μm	0.35	0.1402	0.1660
W_3	5 μm	0.15	0.0390	0.0495
L_1	2%	3.0	3.0	3.0
L_2	2%	3.0	3.0	3.0
L_3	2%	3.0	3.0	3.0
Yield			61%	77%

W_1, W_2 and W_3 are designable parameters.
L_1, L_2 and L_3 are fixed.

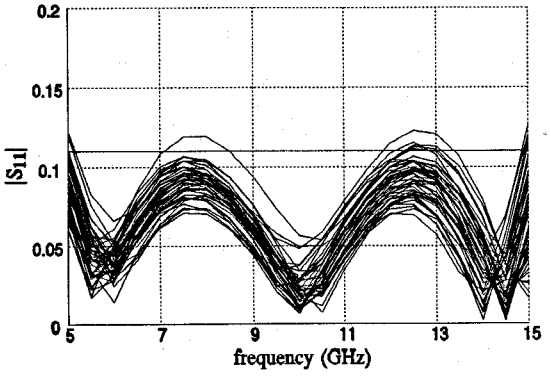

Fig. 3. $|S_{11}|$ Monte Carlo sweep after yield optimization.

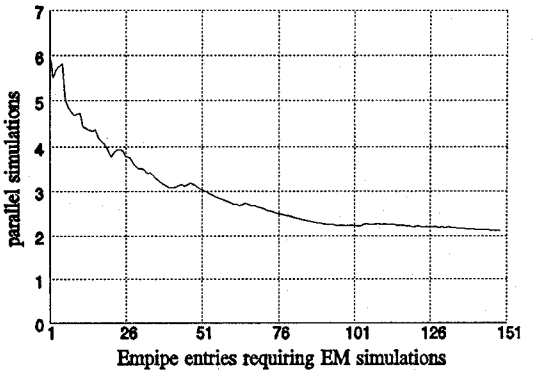

Fig. 4. The cumulative average number of EM analyses run in parallel.

Fig. 4 shows the utilization of parallel computation during statistical design. Here, up to 7 EM analyses can be parallelized (the number of designable/statistical parameters + 1). In the early stages of yield optimization the utilization is high: the average number of EM analyses run in parallel is approximately 6. As the optimization converges, the parameter values mostly stay in the vicinity of the solution, and the interpolation and modeling techniques in Empipe enable the reuse of EM results stored in the data base. This minimizes the number of new EM analyses required, and consequently fewer jobs are available for parallelization. A total of 311 EM analyses were performed for both statistical analysis and yield optimization. In comparison, without the interpolation/modeling/data base techniques, 500 EM analyses would be required for the two Monte Carlo simulations (before and after yield optimization) and an additional 400 EM analyses would be required *per iteration* during optimization. It clearly demonstrates that parallel computing and the interpolation/modeling/data base techniques complement each other in improving computational efficiency.

STATISTICAL DESIGN OF A 10 DB DISTRIBUTED ATTENUATOR

Consider the distributed attenuator depicted in Fig. 5. The 15 mil substrate has a relative dielectric constant of 9.8. It exemplifies structures which are difficult, if not impossible, to be decomposed into library primitives. We treat the attenuator as one piece and define 8 geometrical parameters for Geometry Capture, namely P_1, P_2, ..., P_8. P_1, P_2, P_3 and P_4 are assumed to be designable parameters. EM simulation of the attenuator at a single frequency requires about 7 CPU minutes on a Sun SPARCstation 1+.

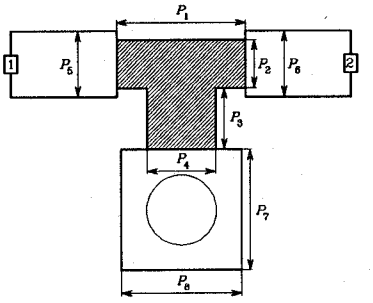

Fig. 5. 10 dB distributed attenuator. The shaded T area corresponds to metallization of a high resistivity (50 Ω/sq) and the feed lines and the grounding pad are assumed to be lossless.

The design specifications are given as

-10.5 dB $\leq$ insertion loss ≤ -9.5 dB from 2 GHz to 18 GHz
return loss ≤ -10 dB from 2 GHz to 18 GHz

The error functions are calculated at three frequencies: 2, 10 and 18 GHz.

First, we obtain a nominal design by minimax optimization. It requires 30 EM analyses, with an average of 3.8 analyses run in parallel. The nominal design took about 168 minutes on the network of Sun SPARCstations 1+. On a single computer, the same optimization requires 630 minutes.

For statistical design we assume normal distributions with a standard deviation of 0.25 mil for all 8 geometrical parameters. Estimated from 250 Monte Carlo outcomes, the yield is 82% at the minimax nominal solution. The yield is increased to 97% after design centering. The statistical simulation and optimization called for 113 additional EM analyses, with an average of 2.5 analyses run in parallel. Fig. 6 shows the Monte Carlo sweep of the attenuator responses. The parameter values are listed in Table II.

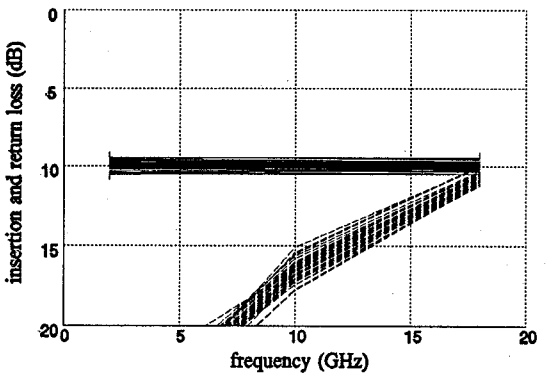

Fig. 6. Monte Carlo sweeps of the attenuator insertion loss (——) and return loss (---) after yield optimization.

TABLE II
MINIMAX AND YIELD OPTIMIZATION OF A 10 dB DISTRIBUTED ATTENUATOR

Parameter	Starting point (mil)	Minimax solution (mil)	Centered solution (mil)
P_1	22.0	15.00	15.70
P_2	11.0	14.16	14.06
P_3	7.0	6.06	6.22
P_4	10.0	12.53	11.97
P_5	15.0	15.0	15.0
P_6	15.0	15.0	15.0
P_7	24.0	24.0	24.0
P_8	24.0	24.0	24.0
Yield		82%	97%

P_1, P_2, P_3 and P_4 are designable statistical parameters. P_5, P_6, P_7 and P_8 are fixed statistical parameters. A normal distribution with standard deviation of 0.25 mil is assumed for all parameters.

CONCLUSIONS

We have proposed a parallel optimization framework for yield-driven EM optimization of microwave circuits. We have demonstrated that integrating parallel computing with interpolation, response function modeling and data base techniques can immensely reduce the overall design time. We have offered a practical approach to consolidating a network of moderately powered workstations into an optimization environment of tremendous potential. Since this is one of the most cost effective use of computer resources, our approach has broad applicability and can profoundly change the way EM simulators are perceived and used as a CAD tool.

ACKNOWLEDGEMENT

The authors thank Dr. J.C. Rautio, President of Sonnet Software, Inc., Liverpool, NY, for making *em* available for this work.

REFERENCES

[1] R.H. Jansen and P. Pogatzki, "A hierarchically structured, comprehensive CAD system for field theory-based linear and nonlinear MIC/MMIC design," *1992 2nd Int. Workshop of the German IEEE MTT/AP Joint Chapter on Integrated Nonlinear Microwave and Millimeterwave Circuits Dig.* (Duisburg, Germany), 1992, pp. 333-341.

[2] *LINMIC+/N Version 3.0*, Jansen Microwave, Bürohaus am See, Am Brüll 17, W-4030 Ratingen 1, Germany, 1992.

[3] J.W. Bandler, R.M. Biernacki, S.H. Chen, D.G. Swanson, Jr. and S. Ye, "Microstrip filter design using direct EM field simulation," *IEEE Trans. Microwave Theory Tech.*, vol. 42, 1994, pp. 1353-1359.

[4] J.W. Bandler, R.M. Biernacki, S.H. Chen, P.A. Grobelny and S. Ye, "Yield-driven electromagnetic optimization via multilevel multidimensional models," *IEEE Trans. Microwave Theory Tech.*, vol. 41, 1993, pp. 2269-2278.

[5] *OSA90/hope*™ and *Empipe*™, Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7, 1994.

[6] *em*™ and *xgeom*™, Sonnet Software, Inc., 135 Old Cove Road, Suite 203, Liverpool, NY 13090-3774, 1994.

[7] J.W. Bandler, R.M. Biernacki, S.H. Chen, Q. Cai and P.A. Grobelny, "Integrated harmonic balance and electromagnetic optimization with Geometry Capture," *IEEE MTT-S Int. Microwave Symp.* (Orlando, FL), 1995.

[8] R. Griffith, E. Chiprout, Q.J. Zhang and M. Nakhla, "A CAD framework for simulation and optimization of high-speed VLSI interconnections", *IEEE Trans. Circuits and Systems*, vol. 39, 1992, pp. 893-906.

[9] R.M. Biernacki and M.A. Styblinski, "Efficient performance function interpolation scheme and its application to statistical circuit design," *IEEE Int. J. Circuit Theory and Appl.*, vol. 19, 1991, pp. 403-422.

[10] R.M. Biernacki, J.W. Bandler, J. Song and Q.J. Zhang, "Efficient quadratic approximation for statistical design," *IEEE Trans. Circuits and Systems*, vol. 36, 1989, pp. 1449-1454.