Minimal-Order Multi-Dimensional Linear Interpolation for a Parameterized Electromagnetic Model Database

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***Abstract* — We present a minimal-order multi-dimensional linear interpolation schema used to interpolate in an N-dimensional EM model database. The EM model database is used to link a computation time expensive EM simulator with a general purpose circuit simulator. The EM model database enables fast EM/Circuit co-simulation, co-optimization and the simultaneous tuning of lumped component elements and distributed layout parameters. The interpolation scheme is minimal-order in the sense that it minimizes the number of samples needed to perform the multi-dimensional linear interpolation. The accuracy and computational efficiency of the proposed modeling technique are validated through different circuit simulation examples.**

I. Introduction

Over the past decade, planar electromagnetic simulators [1-2] have been extensively used for the simulation and physical verification of layout interconnects in RF board and microwave circuit applications. In [3], direct electromagnetic optimizations were presented for the first time, allowing to reach the design specifications with full EM accuracy, by automatically adjusting physical layout variations in the design. In this approach the optimizer directly drives the EM engine. An integrated EM optimization with nonlinear Harmonic Balance simulation is presented in [4], enabling to fully optimize the physical layout in conjunction with non-linear circuit performance.

Building upon these concepts, we have integrated an electromagnetic model database between a commercially available circuit simulator and planar electromagnetic engine. This approach provides a transparent and seamless integration of EM simulations in a circuit design environment preserving the full flexibility to combine time domain (Transient) or frequency domain circuit analysis (DC, AC, Harmonic Balance, Envelope...) with EM generated models.

An optimizer is build around the circuit simulator. During the circuit optimization process, both lumped component and physical layout parameters can vary simultaneously in order to realize the specified goals.

II. Electromagnetic Model Database

The diagram in Figure 1 depicts the building blocks and their dynamic links during an EM/Circuit co-optimization process. The layout components are parsed from the input netlist. The model control and layout parameters are set by the user or automatically selected by the optimizer and passed through the circuit simulator to the dynamically linked electromagnetic engine. A S-parameter model for the layout component is generated during the circuit optimization if the component is being simulated for the first time.

An electromagnetic model database between the circuit simulator and the EM engine keeps track of the generated S-parameter model samples. Database model interpolation is checked upon for varying layout parameters. As gradient based circuit optimizers cannot cope with numerical noise in the generated S-parameters, a linear interpolation scheme is implemented in the EM model database. This avoids the generation of S-parameter models for very small layout variations.

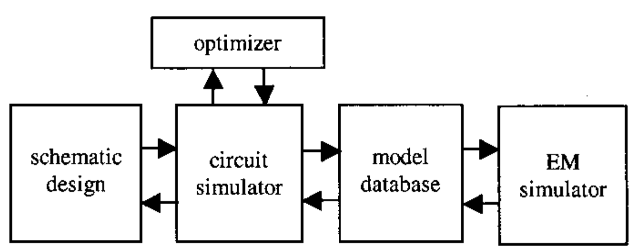

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Figure 1. Block diagram of EM/Circuit co-simulation and co-optimization flow.

The interpolation scheme is dynamic, in the sense that it automatically determines the minimum number of additional samples needed to obtain an interpolated result for the requested parameter values. This minimizes the number of time-consuming EM simulations during the circuit optimization. The model database is build dynamically during the EM/circuit co-simulation process. Once enough samples are calculated and stored in the database, all additional new samples can be retrieved using the interpolation scheme. This will significantly increase the efficiency of the co-simulation process, without sacrificing the accuracy of the models.

III. MULTI-DIMENSIONAL LINEAR INTERPOLATION

Consider a layout component parameterized with N parameters (p_1, p_2,..., p_N). Each set of parameter values represents a sample or point **P** in the N-dimensional parameter space. The S-parameter model S(**P**) generated by the electromagnetic simulator for each sample is stored in the electromagnetic model database.

Consider a set of M+1 sample points $\{\mathbf{P}^{(0)}, \mathbf{P}^{(1)}, ..., \mathbf{P}^{(M)}\}$ with $1 \leq M \leq N$ for which a model has been generated. Provided that the set of M difference vectors $\{\mathbf{P}^{(1)}-\mathbf{P}^{(0)}, ..., \mathbf{P}^{(M)}-\mathbf{P}^{(0)}\}$ is linear independent, they span an M-dimensional subspace in the N-dimensional parameter space. Hence, each point in the subspace can be uniquely represented as a linear combination by its subspace coordinates (r_1, ..., r_M):

$$\mathbf{P} = \mathbf{P}^{(0)} + r_1(\mathbf{P}^{(1)} - \mathbf{P}^{(0)}) + ... + r_M(\mathbf{P}^{(M)} - \mathbf{P}^{(0)})$$

By introducing the extra coordinate r_0, this can be rewritten as:

$$\mathbf{P} = \sum_{j=0}^{M} r_j \mathbf{P}^{(j)} \qquad (1)$$

with

$$r_0 = 1 - \sum_{j=1}^{M} r_j \qquad (2)$$

The S-parameter model in the sample point **P** is obtained by the M-dimensional linear interpolation (3) from the known S-parameter models in the sample points $\mathbf{P}^{(j)}$.

$$S(\mathbf{P}) = \sum_{j=0}^{M} r_j S(\mathbf{P}^{(j)}) \qquad (3)$$

Equation (3) provides a good approximation provided that

- the sample **P** is inside the cell build by the set of M difference vectors $\{\mathbf{P}^{(1)}-\mathbf{P}^{(0)}, ..., \mathbf{P}^{(M)}-\mathbf{P}^{(0)}\}$
- the sample **P** lays "close enough" to the M+1 sample points $\{\mathbf{P}^{(0)}, \mathbf{P}^{(1)}, ..., \mathbf{P}^{(M)}\}$

The first condition translates to the requirement that all subspace coordinates must fulfill the relation:

$$0 \leq r_j \leq 1 \qquad (4)$$

The second condition requires the introduction of a distance measure. We are using the normalized L_1-distance (5), which can easily be calculated from the parameter values. The normalization for each parameter p_k is with respect to a by the user selected interpolation delta Δp_k.

$$L_1(\mathbf{P}, \mathbf{P}^{(j)}) = \sum_{k=1}^{N} \left| \frac{p_k - p_k^{(j)}}{\Delta p_k} \right| \qquad (5)$$

The sample **P** is considered to be "close enough" to the sample point $\mathbf{P}^{(j)}$ if the normalized L_1-distance is smaller than the number of parameters N.

For a 2-dimensional parameter problem (N=2), the multi-dimensional linear interpolation (3) reduces to the well known linear interpolation over a line segment for M=1 (figure 2(a)) and to the linear interpolation over a triangle for M=2 (figure 2(b)).

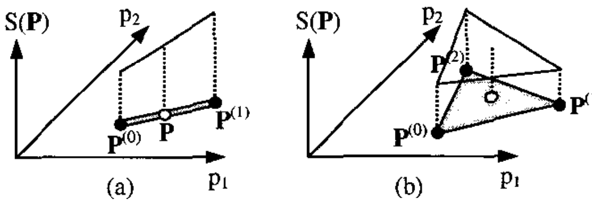

Figure 2. Multi-dimensional linear interpolation for a 2-parameter problem (a) M=1 (b) M=2

IV. MINIMAL-ORDER INTERPOLATION SCHEME

When the model for a new sample is requested by the circuit simulator, the EM model database is first queried. If the requested sample is already stored in the model database it is retrieved and reused. If the sample is new, the model database is checked if the model for the new parameter values be can created by interpolation from the existing samples in the model database. In this process, it is taken care that:

(1) the samples used for interpolation are close enough to each other such that the interpolation error is kept low enough
(2) the order of the M-dimensional interpolation is selected such that the number of new samples that require an EM model generation process is kept minimal
(3) samples for which a new EM model is generated are not too close to existing samples.

The first requirement is taken care of by the user selected interpolation delta's Δp_k, k=1,..,N. The second requirement is important as the EM model generation process in general is a slow process when compared to the interpolation process. The latter requirement guarantees that numerical discretisation noise present in the EM derived models does not affect the accuracy of numerically derived gradients required for the optimization algorithms.

The interpolation scheme starts with the identification of all samples $\mathbf{P}^{(j)}$ in the database with a normalized L_1-distance smaller than the number of parameters.

$$L_1(\mathbf{P},\mathbf{P}^{(j)}) \le N \qquad (6)$$

If no sample is found at an L_1-distance smaller than one, the model for the new sample is generated by invoking the EM simulator and added to the model database. If one or more samples are found satisfying (6) and at least one sample has a distance smaller than one, than the model for the new sample will be retrieved by interpolation.

The first step in the interpolation scheme is to look for the minimal order M and M+1 linear independent sample points that satisfy the condition (6) in conjunction with the requirement that the subspace coordinates for the new sample point are all positive and smaller than one. If such a set of sample points can be identified, the model for the new sample point is retrieved using the M-dimensional linear interpolation (3) from the known models in the sample points $\mathbf{P}^{(j)}$. For a 2-dimensional parameter problem (N=2), interpolation over a line segment (M=1) will be considered first prior to interpolation over a triangle (M=2) (figure 1).

If the minimal order M with M+1 sample points cannot be found in the model database, a minimal set of additional sample points will be auto-selected and added to the model database prior to the interpolation. The order M is set equal to the minimal number of parameters for which the new sample $\mathbf{P}$ and an existing sample $\mathbf{P}^{(k)}$ in the model database have different values. The set of indices for these parameters is denoted as $I = \{i_1, i_2, ..., i_M\}$. The sample $\mathbf{P}^{(k)}$ is the first sample needed for the interpolation. The M other samples are constructed as follows:

$$\mathbf{P}^{(j)} = \mathbf{P}^{(k)} \pm \mathbf{E}^{(i_j)}\Delta p_{i_j} \qquad j=1,..,M \qquad (7)$$

Here $\mathbf{E}^{(i_j)}$ is the unit sample with has all parameter values equal to zero except for parameter p_{i_j} whose value is one. The sign in (6) is chosen + or - such that the value of the parameter p_{i_j} for the new sample $\mathbf{P}$ lays between that of sample $\mathbf{P}^{(k)}$ and $\mathbf{P}^{(j)}$. All models for the new interpolation samples $\mathbf{P}^{(j)}$ are first generated and added to the model database. After this, the model for the new sample $\mathbf{P}$ is retrieved using the M-dimensional linear interpolation scheme (3).

V NUMERICAL EXAMPLES

To illustrate the accuracy and computational efficiency of EM-database models we considered two simple test cases; a rectangular spiral inductor (figure 3) and a LC harmonic trap circuit. In both cases we used the full-wave solution models as benchmark to test against. Figure 4 shows the error, with respect to the full-wave model, in the extracted inductance of the spiral inductor as a function of frequency. From this figure we see that the maximum error in the model obtained through interpolation is less than 0.3%. In figure 5, we show the error in the extracted inductance as a function of the inductor size. The maximum error in this case is less than 0.5%. It is important to note from both figures 4 and 5, that the error variation with frequency as well as with layout dimensions is almost uniformly bounded. This is an important advantage of the interpolation-based model over other conventional modeling methods, which are generally valid only over limited frequency and geometry ranges.

As a second practical example that illustrates the accuracy of the proposed technique, we look at a simple LC circuit that is commonly used as a harmonic trap in a verity of RFIC circuits. The circuit is designed to obtain maximum attenuation at a frequency of 2.6 GHz. Based on an ideal lumped model, we can meet our goal using an inductance L=2 nH and a capacitance C=2.3 pF. In a GaAs process, such values can be obtained with a 150x150 um2, 4.25 turns inductor in series with a 6110 um2 capacitor. A full-wave simulation shows that the resonant frequency of such circuit is fr=2.35Ghz, almost 15% off the desired value. An EM-database model was generated and used to retune the circuit layout to meet the desired specifications. Figure

6 shows the S21 values as the circuit layout is tuned. The figure also shows the full-wave S21 solution of the final tuned circuit layout. The discrepancy in the resonant frequency of the final circuit predicted by the EM-database model and that computed through full-wave simulation is less than 0.2%.

Finally, to highlight the computational efficiency of the proposed modeling technique we note that in all previous simulations, the CPU time using EM-database models was less than a second as compared to few minutes for the full-wave simulation; that is a gain in speed by a factor of few 100's. Hence, the combination of relatively small error in the interpolation-based EM-models together with the significant gain in simulation speed, makes this modeling approach an invaluable tool for modern day complex circuit designs, where fast and reliable tuning and optimization of circuit layout parameters are of prime importance.

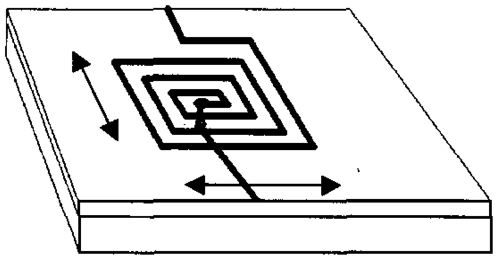

Figure 3. Spiral inductor layout

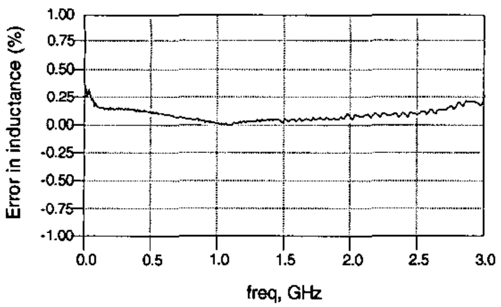

Figure 4. Error in extracted L versus frequency

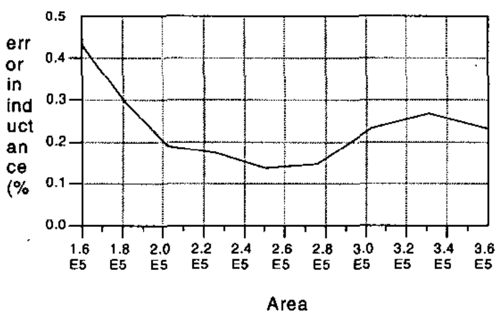

Figure 5. Error in extracted L versus inductor area (um2).

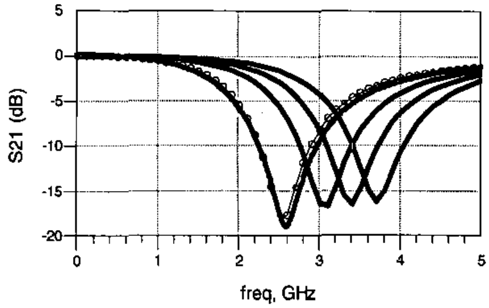

Figure 6. Tuning S21 of the LC-shunt circuit using EM-database models. Full-wave solution of tuned circuit layout marked with circles.

VI Conclusion

This paper presented a novel and elegant physical modeling technique that combines both accuracy and fast simulation time. The modeling method is based on the use of pre-generated EM model databases to compute new models of the circuit layout using a minimal-order linear interpolation scheme. An important advantage of the proposed technique is its seamless integration in commercial circuit simulation softwares. This allows the co-simulation of the EM-database models with other conventional passive and active models, thereby allowing the designer to optimize his circuit layout for design specifications such as gain, efficiency, intermodulation, etc...

Acknowledgement

The authors wish to acknowledge the contributions of Filip Demuynk, Chun-Wen Paul Haung, Hee-Soo Lee and Shihab Al-Kuran to this work.

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