

A Space Mapping Method Allowing Models with Different Parameter Rank and Physical Meanings for Coarse and Fine Model

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Abstract — Automated optimization of complex microwave circuits is still a critical task in nowadays. This contribution demonstrates two new approaches in space mapping technology. One substantial benefit is the improvement of calculation efficiency of the TRASM algorithm by enhancing the multiparameter extraction step. Furthermore, the possibility of mapping coarse and fine models of different degrees of freedom, i.e. with different parameter rank, and unequal physical parameter meanings has been introduced to the method. Therefore, arbitrary microwave circuits of high complexity with well-matching coarse models can be efficiently and automatically optimized.

I. INTRODUCTION

In recent years specification for microwave components have been set harder and more restrictive. For example, frequency bands are allocated more densely and the signal to noise ratio has to be higher. This influences severely the requirements of the subcircuits of the components. To ensure a short development time of these high end circuits resulting in short time to market and cost reduction, at least partially automated optimization of subcircuits is a critical task. However, optimization of complex miniaturized subcircuits, for example microwave filters with numerous tuning parameter, with local optimization strategies like gradient method or Powell's method is not possible, as they often converge in a local optimum next to the starting point. If there possibly exists a lot of local optima in an objective function due to the great number of optimization parameters, the chance to hit the global optimum is very small. Therefore, global optimization strategies have been developed in the last decade to handle complex microwave circuits, which are based upon local optimization for the search of local optima and evaluate the results afterwards. Although these methods guarantee accurate results, the procedure is very time consuming.

In this paper new developments to the trust region aggressive space mapping optimization (TRASM) method [1] will be presented. This technique uses two models with different accuracy, a coarse and a fine model of the treated circuit. With a mathematical mapping, the parameter of the coarse model can be transformed to the fine model, and vice versa, leading to the same simulation response. Thus, the search of the optimum parameters can be performed with the coarse model, and the corresponding parameter

set can be found afterwards by transformation to the fine model. Therefore, most of the simulation effort is shifted to the coarse model, speeding up the optimization process compared to classical global methods as explained above.

In this contribution, new mathematical strategies extend the technique in a way that firstly, the method can be used with coarse models being physically not related to the fine model (e. g. coarse model: LC model; fine model: 2.5D full wave-model). Secondly, the extended algorithm can handle different degrees of freedom of the models, so that the number of optimization parameters of both models do not have to be equal. The mathematical explanation to these enhancements is given in chapter II. The validation of the algorithms is given by experiments in chapter III. Chapter IV concludes the paper and looks out to future improvements.

II. EXTENDED TRUST REGION AGGRESSIVE SPACE MAPPING ALGORITHM

A. Overview of the original TRASM-methodology

In order to explain the base algorithm, a brief repetition will be given before introducing the new approaches. A more detailed explanation is given in [2].

Generally, space mapping (SM) methods require two different models of an electrical circuit. The first one is the so called coarse model, which for example consists of LC components or mathematical descriptions of physical effects. The coarse model solver used in the examples in this contribution is *PSPice* [3]. The second one is the so called fine model, which employs field theory and is simulated using a 2.5D solver like *Sonnet em* [4], which is used here.

The n_c -dimensional parameter vector of the coarse model is denoted by $\mathbf{x}_c$, and the n_f -dimensional parameter vector of the fine model is denoted by $\mathbf{x}_f$, respectively. Up to now in all published examples the models had the same parameter rank ($n_c=n_f$). Let $\mathbf{R}_c(\mathbf{x}_c)$ denote the coarse model simulation response of $\mathbf{x}_c$. Similarly, let $\mathbf{R}_f(\mathbf{x}_f)$ denote the fine model response of $\mathbf{x}_f$.

The goal of the used TRASM algorithm is to determine a linear approximation of a mapping function $\mathbf{x}_c = \mathbf{P}(\mathbf{x}_f)$ so that

$$\|\mathbf{R}_f(\mathbf{x}_f) - \mathbf{R}_c(\mathbf{P}(\mathbf{x}_f))\| \leq \epsilon \quad (1)$$

O: Let $k := k + 1$ and go to step B.

B. New initialization approach for handling parameters with different physical meanings in the coarse and the fine model's space

Due to different rank and physical meaning of the coarse and fine model parameters, several new aspects have to be considered during the initialization phase of the algorithm.

First, it is necessary to initialize the Broyden matrix with values representing an approximation of the correlation of the two parameter spaces. This means that the elements of the Broyden matrix must be chosen in a way which enables mapping a parameter vector of the fine model to the parameter vector of the coarse model so that (1) is satisfied. For defining the correct values it is necessary to use known relations between the two model spaces as mentioned in [6] or to consider the changes of the simulation responses caused by variations of particular parameters. Secondly, the start value of the vector $\mathbf{x}_f$ has to be chosen in a way that $\|\mathbf{R}_f(\mathbf{x}_f^{(0)}) - \mathbf{R}_c(\mathbf{x}_c^*)\|$ is as small as possible. Furthermore, the initial trust region size depends on the number and dimensions of the fine model parameters and has to be chosen in a suitable form.

C. An improved parameter extraction technique

The crucial step in every space mapping algorithm is the so called parameter extraction (PE). In this step, the parameter set of the coarse model whose response matches a known fine model response is obtained. Therefore,

$$\mathbf{x}_c^{(k)} = \arg \min_{\mathbf{x}_c \in \mathbb{D}} \|\mathbf{R}_f(\mathbf{x}_f^{(k)}) - \mathbf{R}_c(\mathbf{x}_c)\| \quad (11)$$

has to be solved, using a local optimization method. In many cases this method leads to wrong results because of local convergence. To improve the results of the parameter extraction step a multiparameter extraction (MPE) concept was proposed [7]. In this extension of the simple PE the two models (coarse and fine) are simultaneously matched at a number of points. Thus, more fine model simulations are needed and thereby, the optimization time is increased.

A reduction in required optimization time can be obtained with a new improvement of the MPE, which enables parameter extraction without calculating the gradient of the MPE-objective function. Therefore, beside the error vectors mentioned in [7], a further error vector

$$\|\hat{\mathbf{e}}\| = \min \|\mathbf{R}_c(\mathbf{x}_{c,\tilde{k}} + \Delta \mathbf{x}_c^{(k)}) - \mathbf{R}_f(\mathbf{x}_f^{(k)})\|, \quad (12)$$

has to be evaluated, where $\tilde{k}$ is the iteration index of the MPE optimization method. This new vector denotes the minimal distance between the fine model response at $\mathbf{x}_f^{(k)}$ and the known coarse model responses at the points $\mathbf{x}_{c,\tilde{k}} + \Delta \mathbf{x}_c^{(i)}$. If

$$\|\hat{\mathbf{e}}\| < \|\mathbf{R}_c(\mathbf{x}_c) - \mathbf{R}_f(\mathbf{x}_f^{(k)})\| \quad (13)$$

is satisfied, $\mathbf{x}_{c,\tilde{k}+1} = \mathbf{x}_{c,\tilde{k}} + \Delta \mathbf{x}_c$ is the new point. It minimizes the MPE-objective function with $\Delta \mathbf{x}_c$ being

taken as the result of (12). Thus, the new point $\mathbf{x}_{c,\tilde{k}+1}$ is obtained without analyses of the coarse model and without additionally calculating the gradient of the MPE-objective function, respectively.

Because of this improvement it is possible to reduce the number of required simulations of the coarse model from $|\mathcal{V}| \cdot (n_c + 1)$ to $|\mathcal{V}|$ per iteration.

III. EXPERIMENTS

A. Optimization of a planar MSL rectangular resonator

In order to check the function of the algorithm with a well known example, the optimization of a planar microstrip line (MSL) rectangular resonator is considered. The corresponding coarse model simply consists of a capacitor C and a serial inductor L, as shown in the inset of Fig. 2. The values of these lumped elements are

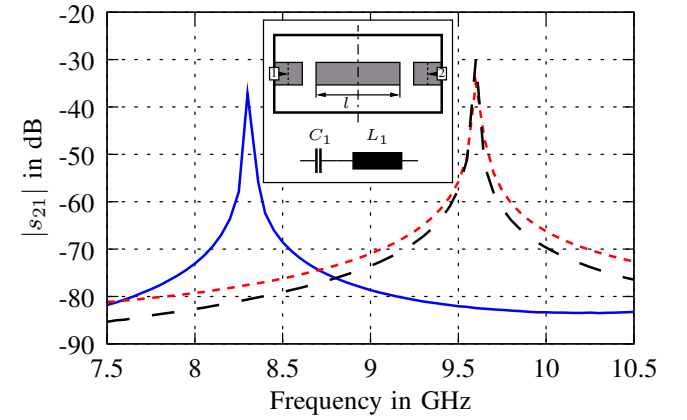


Fig. 2. The transmission coefficient of the optimal coarse model (—), and of the fine model at the starting point (—) and at the ending point (- - -) of the optimization. The simulation models are shown in the inset.

the coarse model's parameters, and the parameter of the fine model is the length of the resonator l . Thus, in this simple example models with different parameter rank and different physical parameter meanings are used. The goal of the optimization is to move the resonant frequency of the fine model to 9.6 GHz.

The initial value in fine model's space is $\mathbf{x}_{f,\text{start}} = [19.7 \text{ mm}]$ for the line length and the optimal parameter vector, which is obtained by optimization of the coarse model is $\mathbf{x}_c^* = [0.07 \text{ fF} \ 3.85 \text{ nH}]^T$ for the LC circuit, respectively. The simulation responses for these values are shown in Fig. 2. The initial value of the Broyden-matrix is $\mathbf{B}_{\text{start}} = \begin{pmatrix} 1 & 1 \end{pmatrix}^T$.

The optimization is finished after four iterations, which include seven simulations of the fine model. $\mathbf{x}_f^* = [17.08 \text{ mm}]$ is the optimal parameter vector in fine model's space. This basic example with low complexity but with different parameter rank demonstrates the great advantage of the SM-optimization technique over a direct optimization of the fine model with respect to the number

of time consuming analyses of the 2.5D fullwave model. In comparison, direct optimization would require about twenty or more simulations of the physical structure.

B. Optimization of a miniature three resonator suspended stripline filter.

The second example is the design and optimization of a three resonator suspended stripline (SSL) bandpass filter. This circuit has been chosen to demonstrate the function of the extended SM technique using models with many parameters and high complexity. The fine model is shown in Fig. 3(a), and the corresponding coarse model in Fig. 3(b). This type of microwave filter and the used design method has been proposed in [6]. The given design specifications for this filter are center frequency $f_0 = 8$ GHz and bandwidth $f_b = 1$ GHz.

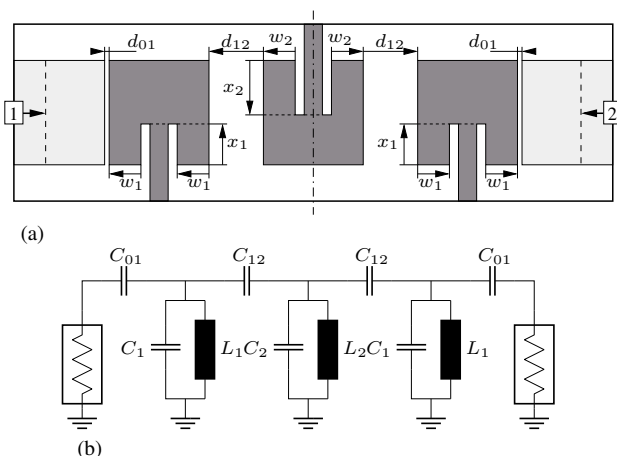


Fig. 3. The physical structure (a) and the LC-circuit-model (b) of the three resonator SSL-filter. ((a): dark gray: front side metalization, light gray: back side).

The optimal coarse parameter vector is calculated using classical filter theory [8]. With approximated start values for the correlations between the fine model's space and the coarse model's space, it is possible to define the initial values of the Broyden matrix and the vector $\mathbf{x}_f$. The scattering parameter amplitudes $|s_{11}|$ and $|s_{21}|$ responses of both models at the points $\mathbf{x}_f^{(0)}$ and $\mathbf{x}_c^*$ are shown in Fig. 4(a) and (b), respectively.

The optimal parameter values of the fine model are obtained after 11 simulations of the 2.5D full wave model, including the MPE. The absolute scattering parameter values at the optimal point $\mathbf{x}_f^*$ are shown in Fig. 4, too. In contrast, optimizing the fine model directly using a gradient method was not possible because of local minima of the objective function.

IV. CONCLUSION

The proposed improvements of the TRASM method offer the possibility to map models with different degrees

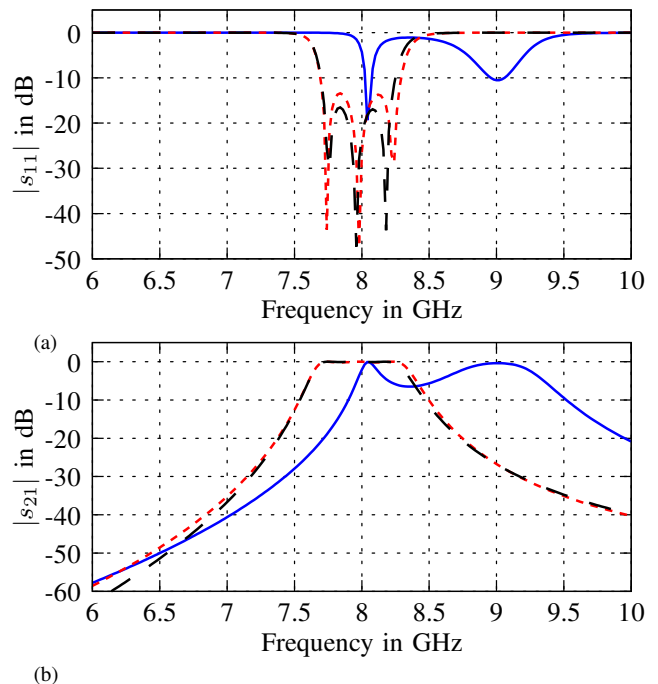


Fig. 4. The optimal coarse model response (—) and the fine model responses at the starting point (—) and the ending point (---) of the optimization.

of freedom and physical parameter meanings. Thus, nearly arbitrary microwave circuits with equivalent lumped element models can be optimized. The new approaches make simulation more efficient by decreasing the number of necessary simulation steps for the MPE algorithm.

In order to validate the operability of these methods, two different circuits were considered. A microstrip line resonator with a LC circuit coarse model and a complex SSL-filter, again with a LC circuit coarse model, has been optimized. Results of excellent accuracy have been achieved in short simulation time compared to the handling of these problems with classical optimization methods.

REFERENCES

- [1] M. H. Bakr, J. W. Bandler, R. M. Biernacki, S. H. Chen, and K. Madsen, "A trust region aggressive space mapping algorithm for em optimization," *IEEE Transactions on Microwave Theory and Techniques*, vol. 46, no. 12, pp. 2412–2425, Dec. 1998.
- [2] J. W. Bandler, R. Biernacki, S. Chen, R. Hemmers, and K. Madsen, "Electromagnetic optimization exploiting aggressive space mapping," *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-43, no. 12, pp. 2874–2882, Dec. 1995.
- [3] OrCAD, Inc., *PSpice A/D*, version 10.0.
- [4] Sonnet Software, Inc., *SonnetLite*, version 9.51.
- [5] J. J. Moré and D. C. Sorensen, "Computing a trust region step," *SIAM J. Sci. Stat. Comput.*, vol. 4, no. 3, pp. 553–572, Sept. 1983.
- [6] W. Menzel, "A novel miniature suspended stripline filter," *European Microwave Conf., Munich*, pp. 1047–1050, Oct. 2003.
- [7] M. H. Bakr, J. W. Bandler, and N. Georgieva, "An aggressive approach to parameter extraction," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 12, pp. 2428–2439, Dec. 1999.
- [8] G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave filters, impedance-matching networks, and coupling structures*. 685 Canton Street, Norwood, Massachusetts 02026: Artech House, INC., 1980.