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AN AUTOMATIC DECOMPOSITION TECHNIQUE FOR DEVICE MODELLING AND LARGE CIRCUIT DESIGN

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ABSTRACT

A novel and general approach is presented utilizing automatic decomposition to solve optimization problems arising from device modelling and from design of large microwave systems. The partitioning approach proposed by Kondoh for FET modelling problems is verified The technique was successfully tested on large scale optimization of microwave multiplexers involving 16 channels, 399 nonlinear functions and 240 variables.

INTRODUCTION

Device modelling and circuit design often give rise to optimization problems. However, the reliability of a solution and the feasibility to carry out the optimization are often deteriorated due to the increasing size and complexity of practical problems. Recently, FET modelling [1] and manifold multiplexer design [2] problems were solved using appropriate decomposition schemes. The success of these efforts motivated us to pursue the generalization and automation of decomposition approaches for microwave optimization problems.

The concept of decomposition has been a mathematically based vehicle for solving large problems, e.g., in mathematical programming [3], in circuit analysis, design and diagnosis [4-6]. In the microwave community, extensive experimentation with, or an excellent understanding of, particular devices has been a key to the success of using decomposition[1,2,7]. To our knowledge, there does not exist a general approach employing decomposition which does not require a deep understanding of physical or topological aspects of the system.

In this paper, we present a novel technique for optimization problems arising from device modelling and design of large microwave systems. Using sensitivity information obtained from a suitable Monte-Carlo analysis, we extract possible decomposition properties. The overall problem is automatically separated into a sequence of subproblems. The separation patterns are updated as the system converges to its solution. Our computerized decomposition analysis agrees with and verifies the partitioning scheme of Kondoh [1] for FET modelling problems. The technique has been successfully tested on microwave multiplexers involving up to 16 channels and 240 variables.

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DESCRIPTION OF THE DECOMPOSITION APPROACH

Let $\boldsymbol{\phi} = [\,\phi_1\ \phi_2\ ..\ \phi_n\,]^T$ represent the system parameters. In an optimization problem for modelling or design, the objective function usually involves a set of nonlinear error functions $f_j(\boldsymbol{\phi})$, $j = 1,2, ..., m$. Typically, the error functions represent the weighted differences between calculated and measured responses or, between circuit responses and given specifications.

In a decomposition approach, one attempts to reach the overall solution by solving a sequence of subproblems Suppose sets I and J are defined as

$$I \triangleq \{1, 2, ..., n\} \tag{1}$$

$$J \triangleq \{1, 2, ..., m\}. \tag{2}$$

The overall optimization problem, e.g., a minimax optimization, is

$$\underset{\phi_i,\, i\in I}{\text{minimize}}\ \ \underset{j\in J}{\max}\ \ f_j(\boldsymbol{\phi}) \tag{3}$$

A subproblem is characterized by

$$\underset{\phi_i,\, i\in I^s}{\text{minimize}}\ \ \underset{j\in J^s}{\max}\ \ f_j(\boldsymbol{\phi})\ , \tag{4}$$

where I^s and J^s are subsets of I and J, respectively.

The basic idea for decomposition is to decouple a variable ϕ_i from a function f_j if the interaction between them is weak. We perform sensitivity analysis at a set of randomly chosen points $\boldsymbol{\phi}^\ell$, $\ell = 1, 2, ...$ A measure of the interaction between ϕ_i and f_j is defined as

$$S_{ij} = \sum_{\ell} \left(\frac{\partial f_j(\boldsymbol{\phi}^\ell)}{\partial \phi_i} \ \frac{\phi_i^o}{f_j^o} \right)^2 \tag{5}$$

All the S_{ij}, $i = 1, 2, ..., n$ and $j = 1, 2, ..., m$, constitute a $n\times m$ sensitivity matrix **S**. It is reasonable to conclude that ϕ_i and f_j can be decoupled if S_{ij} is very small. The degree of decomposition is controlled by a certain decoupling factor.

The examination of interaction patterns between $\boldsymbol{\phi}$ and **f** results in the breakdown of variables into *p* groups identified by index sets $I_1, I_2, ..., I_p$. Two variables belong to the same group if they interact only with the same set of functions. Similarly, all functions are separated into *q* groups identified by sets $J_1, J_2, ..., J_q$.

The correlation patterns between groups of variables and functions can be represented using a $p\times q$ decomposition dictionary matrix **D** whose (k, ℓ)th component is

$$D_{k\ell} = \sum_{i \in I_k} \sum_{j \in J_\ell} S_{ij} \quad (6)$$

If $D_{k\ell}$ is zero (nonzero), variables in the kth group and functions in the ℓth group are decoupled (correlated)

Using the **D** matrix we have developed a scheme for automatic determination of I^s and J^s for the suboptimzation of (4). Suppose that the ℓth group of functions is to be optimized. The candidate groups of variables are those which affect $f_j, j \in J_\ell$ For a selected candidate, e.g., the one corresponding to set I_k, the index set J^s indicates all functions which correlate with variables in group k. I^s identifies variables in the kth group, as well as all other variables correlating with only the functions in $f_j, j \in J^s$.

SENSITIVITY ANALYSIS AND DECOMPOSITION FOR FET DEVICE MODELS

Through extensive experiment on practical FET devices, Kondoh[1] summarized 8 suboptimization problems which can be repeatedly solved to yield a FET model with improved accuracy The equivalent circuit is shown in Fig. 1. Table I shows results of our Monte-Carlo sensitivity analysis, indicating interconnection patterns between each individual parameter and different groups of functions. Table II provides an example of the decomposition dictionary calculated and normalized from Table I. Table II yields 8 subproblems which agree with and further verify the decomposition scheme proposed in [1]. The feasibility of computerized automatic decomposition is demonstrated by this example.

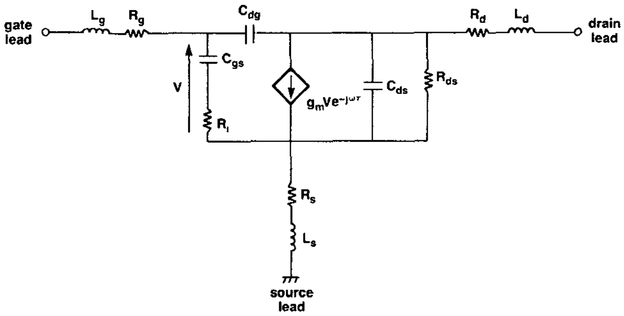

Fig. 1 A FET equivalent circuit

AN ALGORITHM FOR AUTOMATIC DECOMPOSITION

An automatic decomposition algorithm for optimization of microwave systems has been developed and implemented. The algorithm iterates between the following basic steps.

1) Calculation of sensitivity matrix **S**, grouping of functions and variables, construction of dictionary matrix **D**, updating of the decoupling factor.
2) Examination of the current status of the system whether at the solution or not, determination of the worst of the response functions.
3) Automatic selection of function groups to be penalized, automatic determination of all candidate groups of variables arranged in decreasing priority.
4) Dynamic selection of a candidate variable group.
5) Automatic formulation of a subproblem, monitoring the entire system responses during the suboptimization procedure.

As a special case, if all variables interact with all functions, our approach solves only one subproblem, this being identical to the original overall optimization.

TABLE I
RESULTS OF SENSITIVITY ANALYSIS FOR THE FET MODEL

(a) FUNCTION GROUPS INVOLVING THE ENTIRE FREQUENCY BAND

Variables	Function Groups			
	S_{11} Entire Freq. Band	S_{21} Entire Freq. Band	S_{12} Entire Freq. Band	S_{22} Entire Freq. Band
g_m	18.55	100.00	87.55	68.33
C_{gs}	100.00	89.74	67.98	62.25
C_{ds}	4 88	67.74	45.73	100 00
C_{dg}	4.24	48.88	100 00	81.27
R_s	35.53	37.14	100.00	5 88
R_{ds}	17.44	97.68	70.51	100 00

(b) FUNCTION GROUPS INVOLVING THE UPPER HALF FREQUENCY BAND

Variables	Function Groups			
	S_{11} Upper Freq. Band	S_{21} Upper Freq. Band	S_{12} Upper Freq. Band	S_{22} Upper Freq. Band
τ	31.91	100.00	36.61	59 31
R_g	100.00	50.67	24.87	29.89
R_d	34.65	74.31	85.85	100.00
R_i	100.00	65.63	88 43	39.53
L_g	100 00	87.85	57.16	37 44
L_d	9.99	97.88	61.78	100.00
L_s	62.94	31.31	100.00	21.99

Entries of the table, e.g., the one corresponding to the ith variable and the ℓth function group, are calculated by

$$\sum_{j \in J_\ell} S_{ij}, \qquad i \in I, \ell = 1,2,...,8,$$

where S_{ij} is defined in (5) and the function f_j represents the weighted difference between the calculated and the measured values of the modulus or the phase of a particular S parameter. I contains indices of all variables. For Table I(a), J_ℓ, ℓ = 1, 2, 3, 4, contain indices of all functions related to S_{11}, S_{21}, S_{12}, S_{22} (at frequencies [1.5, 26.5] GHz), respectively. For Table I(b), J_ℓ, ℓ = 5, 6, 7, 8, contain indices of all functions related to S_{11}, S_{21}, S_{12}, S_{22} (at frequencies [14, 26.5] GHz), respectively. Each row of the table has been scaled.

TABLE II
NORMALIZED DECOMPOSITION DICTIONARY **D**

(a) CORRESPONDING TO THE SENSITIVITY ANALYSIS OF TABLE I(a)

Variable Groups	Function Groups			
	S_{11} Entire Freq. Band	S_{21} Entire Freq. Band	S_{12} Entire Freq. Band	S_{22} Entire Freq Band
R_{ds}, C_{ds}	0 00	0.00	0.00	1 00
C_{gs}	1 00	0.00	0.00	0 00
C_{dg}, R_s	0.00	0.00	1.00	0.00
g_m	0.00	1.00	0.00	0 00

(b) CORRESPONDING TO THE SENSITIVITY ANALYSIS OF TABLE I(b)

Variable Groups	Function Groups			
	S_{11} Upper Freq. Band	S_{21} Upper Freq. Band	S_{12} Upper Freq Band	S_{22} Upper Freq. Band
R_d, L_d	0 00	0.00	0.00	1 00
R_g, R_l, L_g	1.00	0 00	0 00	0.00
L_s	0.00	0 00	1 00	0.00
τ	0 00	1.00	0.00	0.00

LARGE SCALE OPTIMIZATION OF MULTIPLEXERS

A contiguous band 5-channel microwave multiplexer was specifically optimized to illustrate the novel process of automatic decomposition. Design specifications were imposed on the common port return loss and individual channel insertion loss functions. Design variables for each channel include 12 couplings (M_{ij}, $i, j \in \{1, 2, ..., 6\}$), input and output transformer ratios (n_1 and n_2) and the distance measure from the channel filter to the short circuit main cascade termination (d). Figs. 2(a)-(d) show the multiplexer responses for the first 3 suboptimizations 11 suboptimizations were used reaching the optimal solution shown in Fig. 2(e). The final subproblem was the overall optimization.

Until our recent paper on multiplexers[2], the reported design and manufacturing of these devices were limited to 12 channels[8-10]. We tested our approach on a 16-channel multiplexer involving 240 variables and 399 nonlinear functions. A comparison between the optimal design with and without decomposition is provided in Table III When used to obtain a good starting point for subsequent optimization, the decomposition approach offers considerable reductions in both CPU time and storage. The feasibility of obtaining a near optimum for large problems using computers with memory limitations is observed from the table. However, when close to the desired solution, the sizes of the subproblems may approach that of the overall problem. In this case, the performence of optimization does not differ significantly with or without decomposition, unless the original problem is almost completely decomposable.

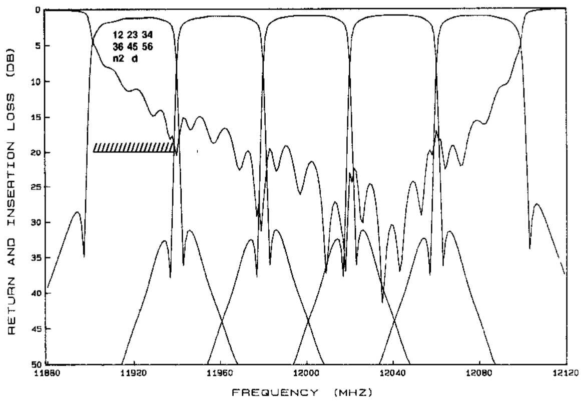

Fig. 2(a) Responses at the starting point

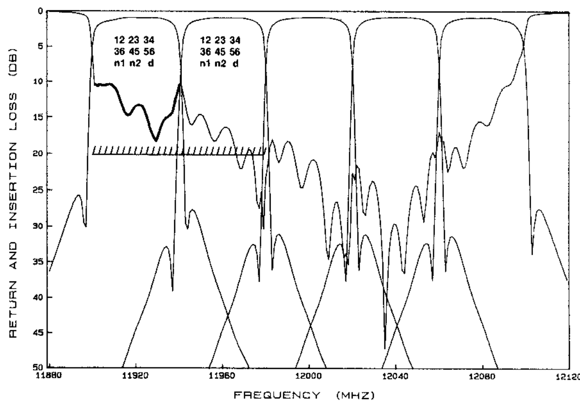

Fig. 2(b) Responses after the first suboptimization

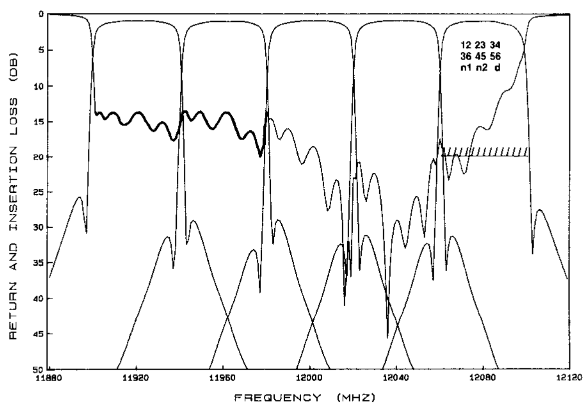

Fig. 2(c) Responses after the second suboptimization

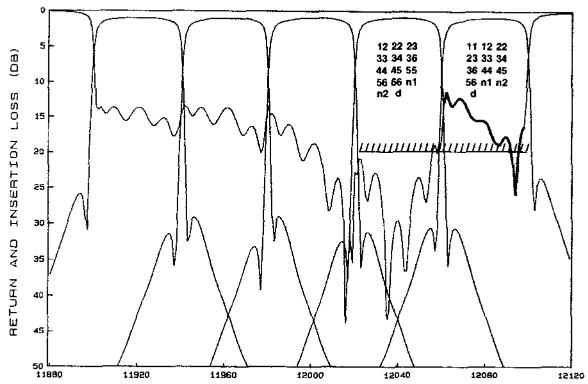

Fig. 2(d) Responses after the third suboptimization

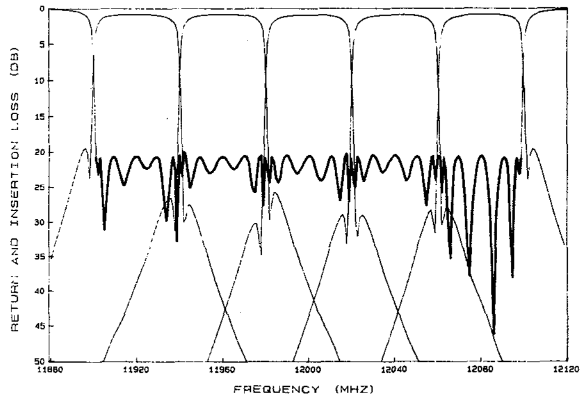

Fig. 2(e) Responses at the optimum solution

Fig. 2 Return and insertion loss responses of the 5-channel multiplexer for each suboptimization. The 20 dB specification line indicates which channel(s) is to be optimized in the next subproblem. The variables to be selected are indicated, e.g., 35 representing coupling M_{35}. The previously optimized channels are highlighted by thick response curves.

CONCLUSIONS

We have presented an automated decomposition approach for device modelling and optimization of large microwave systems. Compared with the existing decomposition methods, the novelty of our approach lies in its generality in terms of device independency and its automation. Advantages of the approach are (1) a very significant saving of CPU time and/or computer storage and (2) efficient decomposition by automation. By partitioning the overall problem into smaller ones, the approach promises to provide a basis for computer-assisted tuning. It contributes positively towards future general computer software for large-scale optimization of microwave systems.

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TABLE III
COMPARISON OF 16-CHANNEL MULTIPLEXER OPTIMIZATION WITH AND WITHOUT DECOMPOSITION

Purpose of Optimization	Reduction in Objective Function	Criteria for Comparison	With Decomp.	Without Decomp.
to provide a good starting point for subsequent optimization	from 13.46 to 2.4	CPU time *	99	250
		working space needed +	2,197	483,036
to obtain a near optimum solution	from 13.46 to 0.32	CPU time *	651	553
		working space needed +	73,972	483,036
to obtain optimum solution	from 13.46 to −0.09	CPU time *	1045	1289
		working space needed +	483,036	483,036

* seconds on the FPS-264 mainframe.
\+ of machine memory units (one unit per real number) required by the minimax optimization package[10].

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