RESEARCH PROJECTS

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RESEARCH PROJECT 1:

ROBUST MODEL PARAMETER EXTRACTION (RoMPE)

Objective of the Research

The main objective of the project is to pioneer novel theory and develop new algorithms for systematic and robust model parameter extraction for GaAs active devices. Software products implementing the new methods should be able to meet a strong immediate industrial demand for efficient and reliable tools for GaAs FET modeling in the context of microwave integrated circuit design.

Nature of the Research

This research is applied, as it is our aim to solve specific problems in electrical device modeling more efficiently. However, many aspects of basic research are involved. The fields of science involved are mathematics: optimization theory, system theory, system identifiability, and electrical circuit theory. Engineering applications are found in electronic device modeling and in the mathematical modeling of general engineering systems.

Reference Material

The key references which we have used thus far are:

A. Materka and T. Kacprzak, "Computer calculation of large-signal GaAs FET amplifier characteristics", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, 1985, pp. 129-135.

J.W. Bandler, S.H. Chen and S. Daijavad, "Microwave device modeling using efficient ℓ_1 optimization: a novel approach", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, 1986, pp. 1282-1293.

Uncertainty of the Research

The main uncertainty of the project lies in the robustness of the methods being developed. They may turn out to be sensitive to computational accuracy or the starting point of the iterative numerical solution process. Also, it is not clear to what extent the model itself is truly useful for large-signal nonlinear simulation and optimization. The success of the new approach may also depend on the ability to obtain relevant device measurement data.

Novelty of the Research

The project is based on a novel approach to device modeling pioneered by members of the team. It also involves pioneering work in large-signal nonlinear modeling, including novel techniques of electrical circuit theory.

Advance in Scientific Knowledge

The research results we have attained already constitute a breakthrough in device modeling by showing significantly improved reliability in the uniqueness of the solution over conventional methods. The project will continue to make important contributions to the advancement of computer-aided design of electrical engineering devices, circuits and systems.

Method of Research

Accepted scientific methods are employed. Since the team members have been actively working in this research area for the last three years, they are well informed of the research trends and results reported in the literature.

Long-term and short-term goals are carefully defined and milestones are scheduled. Theoretical investigations are conducted and then the new concepts are implemented in computer programs and verified through numerical examples. Promising algorithms are further tested on a number of industrial examples.

The work to date demonstrates the scientific feasibility of the methods proposed. A state-of-the-art research paper on model parameter extraction [15], emerging from our investigations, as well as a demonstrative computer program have been presented and enthusiastically received at the 1988 IEEE MTT-S International Microwave Symposium held in New York City, May 1988. A full scientific paper has been submitted to the IEEE Transactions on Microwave Theory and Techniques [16].

Progress to Date

The starting date for the project in its present form was early 1987. By December 1987 we submitted a technical paper and by May 1988 we presented it [15] in New York. The paper describes the fundamental theoretical concepts and a basic framework of the algorithm. We have also developed and demonstrated a prototype computer program called RoMPE.

Our work in the near future includes (1) consolidating the theoretical framework, (2) expanding, improving and refining the algorithms, (3) researching and implementing new GaAs device models, and (4) extensive testing and documentation.

Reports

A paper on robust model parameter extraction [15] has been published in the 1988 IEEE MTT-S International Microwave Symposium Digest. A full scientific paper has been submitted for peer review to the IEEE Transactions on Microwave Theory and Techniques [16], the most reputable journal in the field.

Description of the Project

Our research efforts are concentrated on three subjects:

(1) A theoretical framework for robust modeling optimization and unique identifiability.

(2) Implementable algorithms for electronic device model parameter extraction.

(3) State-of-the-art CAD tools for GaAs FET small-signal, DC and large-signal model parameter extraction.

To date we have made progress in each of these three aspects. The following is a brief description of our results.

The advances in GaAs material development and wafer processing achieved in the past few years have made monolithic microwave integrated circuits (MMICs) practical. The modeling of MMIC devices is recognized as a subject of fundamental importance [1-7, 10-12]. One of the major difficulties to be addressed is the uniqueness and reliability of the model parameters.

Bandler, Chen and Daijavad in 1986 [8] pioneered a novel multi-circuit approach to device modeling which also exploits the unique properties of ℓ_1 optimization techniques [9]. Since then, the theory has been significantly expanded and improved, as reported in two of our recent papers [13,15,16].

In the multi-circuit approach, deliberate perturbations are introduced to the device, such as changes in the FET biasing conditions. Multiple sets of measurements thus obtained are processed simultaneously to extract model parameters. The model parameters are separated as common variables and independent variables according to advanced knowledge of the device characteristics. Integrated with a recent and powerful ℓ_1 optimization technique, this approach is able to increase the identifiability of the problem and the uniqueness of the model.

For GaAs FET modeling, our method also utilizes simultaneously DC and AC measurements to extract both small-signal parameters and DC coefficients. We have also demonstrated that the model reliability can be improved by imposing DC constraints on some small-signal parameters.

Taking advantage of the team members' expertise in network sensitivity analysis, we have incorporated exact "adjoint" gradient evaluation in the new methods to make them even more efficient.

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[10] D. Estreich, "Nonlinear modeling for MMIC's", *IEEE MTT Int. Microwave Symp. Digest* (Las Vegas, NV), 1987, pp. 85-88.

[11] W.R. Curtice, "Nonlinear analysis of GaAs MESFET amplifiers, mixers, and distributed amplifiers using the harmonic balance technique", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, 1987, pp. 444-447.

[12] V.D. Hwang and T. Itoh, "An efficient approach for large-signal modeling and analysis of the GaAs MESFET", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, 1987, pp. 396-402.

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[15] J.W. Bandler, S.H. Chen, S. Ye and Q.J. Zhang, "Robust model parameter extraction using large-scale optimization concepts", *IEEE MTT Int. Microwave Symp. Digest* (New York, NY), 1988, pp. 319-322.

[16] J.W. Bandler, S.H. Chen, S. Ye and Q.J. Zhang, "Robust model parameter extraction using large-scale optimization concepts", submitted to *IEEE Trans. Microwave Theory Tech.*

RESEARCH PROJECT 2:

HARMONIC BALANCE ANALYSIS AND OPTIMIZATION

Objective of the Research

The main objective of the project is to develop new methods and algorithms aimed at analyzing and designing nonlinear microwave circuits. Software products exploiting such methods will solve many nonlinear circuit design problems which have been very difficult or even impossible to solve.

Nature of the Research

This research is both basic and applied. It is our aim to solve specific problems in nonlinear electrical circuit simulation and design. Many aspects of basic innovative scientific research are involved. The fields of science involved are mathematics: numerical methods, Fourier transforms, and electrical circuit theory. Engineering applications are found in all aspects of nonlinear analog circuit design including analysis, optimization, parameter extraction, statistical design and modeling.

Reference Material

Many references can be cited. Two important papers are:

K.S. Kundert and A. Sangiovanni-Vincentelli, "Simulation of nonlinear circuits in the frequency domain", *IEEE Trans. Computer-Aided Design*, vol. CAD-5, 1986, pp. 521-535.

V. Rizzoli, A. Lipparini and E. Marazzi, "A general-purpose program for nonlinear microwave circuit design", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, 1983, pp. 762-769.

Uncertainty of the Research

The main uncertainty of the project lies in the uncertain future of statistical design of microwave integrated circuits, and acceptance of the necessary software tools by microwave engineers. The prognosis for the affordable manufacture of monolithic microwave integrated circuits (MMICs) is particularly uncertain.

The scale of the resulting problems can be extremely large. Consequently, supercomputers and large-scale optimization techniques are likely to be required, which introduces further risk and uncertainty.

Novelty of the Research

Our recent refereed publication [8] has substantially advanced the state of the art in this area. It is considered a breakthrough contribution to large-signal nonlinear circuit analysis, introducing novel techniques of electrical circuit theory.

Further research will continue in this area, in which we have a substantial world lead.

Advance in Scientific Knowledge

Two major theoretical breakthroughs have been made as the result of this research. The method of harmonic balance has been expanded from simulation to sensitivity analysis. The syntax oriented hierarchical approach has been generalized to permit upward and downward analysis in both the original and the adjoint networks. Further breakthroughs are expected when modeling and statistical design concepts are applied to nonlinear circuits.

Method of Research

Accepted scientific methods are employed. Since the team members have been actively working in analysis, optimization, and statistical design for a number of years no extra literature search was necessary except for recent periodicals.

The team members also have sufficient experience and knowledge of harmonic balance techniques. According to our expectations, appropriate mathematical manipulations are conducted and then the new concepts are programmed. The algorithms being developed are then tested on a number of circuit examples.

The work to date shows feasibility of the methods proposed. A paper on harmonic balance simulation and sensitivity analysis, [8], emerging from our investigations, has been presented at the 1988 IEEE MTT-S International Microwave Symposium held in New York, May 1988.

Progress to Date

The starting date for the project was August 1, 1987. By July 31, 1988 a unified framework for harmonic balance simulation and sensitivity analysis has been developed and published. The other topics of our research are in an early stage of development.

In the near future we plan to work on nonlinear parameter extraction using the harmonic balance technique. This includes problem formulation, implementation and extensive testing.

In future years we will perform yield optimization on nonlinear circuits. This will include proper formulation of the problem, study of the statistical properties of nonlinear circuits. Final implementation and testing will be required.

Reports

A paper on harmonic balance simulation and sensitivity analysis [8] has been presented at the 1988 IEEE MTT-S International Microwave Symposium held in New York, May 1988. A full version of the paper has been submitted for peer review to the IEEE Transactions on Microwave Theory and Techniques [9], the most reputable journal in the field.

Description of the Project

Our research efforts are concentrated on four subjects:

(1) An extremely efficient adjoint network approach to sensitivity analysis of nonlinear circuits,

(2) General hierarchical analysis in both the original and the adjoint networks,

(3) Parameter extraction of nonlinear devices,

(4) Statistical analysis and design of nonlinear circuits.

To date the first two subjects have been successfully completed. The following is a brief description of our results.

A unified approach to the simulation and sensitivity analysis of linear/nonlinear circuits in the frequency domain has been developed. The linear part of the circuit can be large and can be hierarchically decomposed, highly suited to modern microwave CAD. Analysis of the nonlinear part is performed in the time domain and the large signal steady-state periodic analysis of the overall circuit is carried out by means of the harmonic balance method.

The harmonic balance method has become an important tool for the analysis of nonlinear circuits. The work of Rizzoli et al. [1], Curtice and Ettenberg [2], Curtice [3], Gilmore and Rosenbaum [4], Gilmore [5], Camacho-Penalosa and Aitchison [6] stimulated work on harmonic balance in the microwave CAD community. The excellent paper of Kundert and Sangiovanni-Vincentelli [7] provided systematic insight into the harmonic balance method. The first step towards design optimization was made by Rizzoli et al. [1] who used the perturbation method to approximate the gradients.

We have extended to nonlinear circuits, considered in the frequency domain, the powerful adjoint network concept, a standard sensitivity analysis approach in linear circuits. The concept involves solving a set of linear equations whose coefficient matrix is available in many existing harmonic balance programs. The solution of a single adjoint system is sufficient for the computation of sensitivities w.r.t. all parameters in both the linear and nonlinear subnetworks, as well as in bias, driving sources and terminations. No parameter perturbation or iterative simulations are required.

The sensitivities we propose are exact in terms of the harmonic balance method itself. Our exact adjoint sensitivity analysis can be used with various existing harmonic balance simulation techniques, e.g., the basic harmonic balance [7], the modified harmonic balance [5]. Computational effort includes solving the adjoint linear equations and calculating the Fourier transforms of all time domain derivatives at the nonlinear element level. Significant CPU time savings are achieved over the perturbation method. A MESFET mixer example has been used to verify our theory.

The other two subjects are in an early stage of development.

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[8] J.W. Bandler, Q.J. Zhang and R.M. Biernacki, "A unified framework for harmonic balance simulation and sensitivity analysis", *IEEE Int. Microwave Symp. Digest* (New York, NY), 1988, pp. 1041-1044.

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RESEARCH PROJECT 3:

EFFICIENT STATISTICAL CIRCUIT DESIGN OF INTEGRATED CIRCUITS

Objective of the Research

The main objective of the project is to develop new methods and algorithms aimed at improving efficiency of statistical design of analog electrical circuits. In particular our aim is to produce novel results and software relevant to the emerging area of monolithic microwave integrated circuits (MMICs). Software products exploiting such methods should run faster, reliably and on much larger circuits. These software products will then be competitive commercially.

Nature of the Research

This research is applied. It is our aim to solve specific problems in microwave circuit design more efficiently. However, many aspects of basic research are involved. The fields of science involved are mathematics: approximation theory, statistical analysis; and electrical circuit theory. Engineering applications are specifically found in all aspects of nonlinear analog circuit design including analysis, optimization, parameter extraction, statistical design and modeling.

Reference Material

Many references can be cited. An important new contribution is:

J.W. Bandler and S.H. Chen, "Circuit optimization: the state of the art", (invited), *IEEE Trans. Microwave Theory Tech.*, vol. MTT-36, 1988, pp. 424-443.

Uncertainty of the Research

The main uncertainty of the project lies in the robustness and reliability of the methods being developed since they are partially heuristic in nature. While we have already shown applicability of the methods to statistical design of large-scale microwave circuits, we will not be able to fully implement them if they turn out to be unreliable, highly sensitive to computational accuracy or fail to provide satisfactory results for large variety of circuits. Supercomputers and large-scale optimization techniques are likely to be required, which introduces further risk and uncertainty.

The uncertain future of statistical design of microwave integrated circuits, and acceptance of the necessary software tools by microwave engineers also makes this a high risk project. The prognosis for the affordable manufacture of monolithic microwave integrated circuits (MMICs) is particularly uncertain.

Novelty of the Research

This research is a followup of state-of-the-art published works by members of the team, namely, Bandler and Abdel-Malek's "Optimal centering, tolerancing, and yield determination via updated approximations and cuts" (1978), their "Yield optimization for arbitrary statistical distributions: Part I-theory" (1980), Biernacki and Styblinski's "Statistical circuit design with a dynamic constraint approximation scheme" (1986), Bandler and Chen's "Circuit optimization: the state of the art" (1988), Bandler, Daijavad and Zhang's "Exact simulation and sensitivity analysis of multiplexing networks" (1986), Biernacki, Bandler, Song and Zhang's "Statistical design via efficient quadratic modeling"

(1987), Bandler, Biernacki, Chen, Renault, Song and Zhang's "Yield optimization of large-scale microwave circuits" (1988), Biernacki, Bandler, Song and Zhang's "Efficient quadratic approximation for statistical design". As such it is novel.

Advance in Scientific Knowledge

If this research is successfully completed, the algorithms may constitute a true breakthrough in the numerical approach to the simulation and statistical analysis and yield optimization of large engineering systems.

Method of Research

Accepted scientific methods are employed. Since the team members have been actively working in this research area for a number of years no extra literature search was necessary except for recent periodicals. According to our expectations, appropriate mathematical manipulations are conducted and then the new concepts are programmed. The algorithms being developed are then tested on a number of circuit examples.

The work to date confirms applicability of the methods proposed to the statistical design of large microwave circuits. A paper on yield optimization of large-scale microwave circuits [10], emerging from our investigations, will be presented at the 1988 European Microwave Conference to be held in Sweden. Also, a paper describing the theory [11] has been submitted to IEEE Transactions on Circuits and Systems, the most reputable journal in the field. A paper describing a novel one-sided ℓ_1 optimization technique was presented by Dr. Madsen at the IEEE International Symposium on Circuits and Systems in Finland [12].

Progress to Date

The starting date for the project was August 1, 1986. By July 31, 1987 feasibility of an extremely efficient method for quadratic approximation of circuit response functions has been successfully demonstrated. Between August 1, 1987 and July 31, 1988 we continued our work on this project. The work included testing, reliability studies and, especially, applying the methods to the yield optimization of a large-scale practical microwave circuit, namely a 5-channel multiplexer.

In collaboration with Dr. K. Madsen of the Technical University of Denmark, we have created a new and highly efficient algorithm for one-sided nonlinear ℓ_1 optimization. The new method has been tested as an integral part of an approach to design centering and yield enhancement.

In the future we will generally concentrate on new methods and algorithms aimed at improving efficiency of analog and microwave electrical circuit simulation.

Reports

The report [9] and papers [10] and [11] summarize our achievements within the framework of this project. Reference [10] will be presented at the 1988 European-Microwave Conference to be held in Sweden. Reference [11] has been submitted to IEEE Transactions on Circuits and Systems, the most reputable journal in the field. Reference [12] has appeared in the Proceedings of the IEEE International Symposium on Circuits and Systems, the most important conference in its field. It was presented by Dr. K. Madsen in Finland.

Description of the Project

Statistical circuit design, or yield optimization has been a subject of extensive research in the last decade, e.g., [1-7]. However, only small circuits can be effectively treated by existing methods. On the other hand, because of high production cost of present MMICs due to various fluctuations in the manufacturing process, yield-driven design should become an indispensible tool in the microwave CAD area [1].

In this research we concentrate our efforts on extremely efficient algorithms for statistical circuit design. To date, the applicability of our method to statistical design of large-scale microwave circuits has been successfully shown. The following is a brief description of our results.

We have had a long and fruitful association with Dr. K. Madsen of the Technical University of Denmark. With his collaboration, we have created a new and highly efficient algorithm for one-side nonlinear ℓ_1 optimization. An important application of this algorithm is in design centering and yield optimization. Basically, the technique implements the Monte Carlo method to sample circuit outcomes. Measures of performance of these circuits are combined into an objective function which attempts to center the cluster of outcomes into the region of acceptability, such that the largest number of outcomes satisfy the performance requirements. In an example of an 11-element low pass filter with 1.5% tolerances, the yield was driven from 49% to 84% by the new approach.

Quadratic approximation has been used as a powerful tool to reduce the number of circuit simulations in statistical design [3-6]. The determination of a quadratic model itself for a large number of variables, however, is generally expensive. For example, a circuit with 20 variables needs 231 circuit simulations and the solution of a 231x231 linear system of equations in order to uniquely identify a quadratic model.

Following [5] we derived a set of formulas drastically simplifying the computation of the quadratic model. While retaining the advantage of [5], i.e., using a small number of base points, our method, taking advantage of a particular fixed pattern of the base points, offers additional and much more significant savings of computer time and storage. All coefficients of the quadratic model can be obtained explicitly using simple analytical formulas.

We have extensively tested our approach. An example of a 5-channel multiplexer with 75 design and toleranced variables, 124 constraints, and up to 200 statistically perturbed outcomes, was used to demonstrate the feasibility of yield optimization of large-scale microwave circuits, both tunable and nontunable. We attacked this difficult problem by: (1) the use of supercomputers, (2) a novel multi-circuit optimization technique for yield optimization [7], [12], (3) the use of a fast, dedicated simulation technique [8], and (4) the efficient approximation to circuit responses [11]. No microwave circuit design of this type and on this scale has ever been reported.

Currently, we concentrate our efforts on incorporating possible gradient information to even further reduce the number of actual circuit simulations needed for constructing a reliable quadratic model. These results have not been published or reported yet.

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[12] J.W. Bandler, S.H. Chen and K. Madsen, "An algorithm for one-sided ℓ_1 optimization with application to circuit design centering", *Proc. IEEE Int. Symp. Circuits and Systems* (Espoo, Finland), 1988, pp. 1795-1798.

RESEARCH PROJECT 4:

STATISTICAL MODELING OF MICROWAVE INTEGRATED CIRCUITS AND DEVICES

Objective of the Research

The main objective of the project is to establish the mathematical theory and algorithms aimed at modeling the statistical behaviour of manufactured microwave integrated circuits and devices. Software products implementing such algorithms should provide reliable statistical device models for manufacturing yield analysis and optimization. These software products will build the bridge between process engineers and circuit designers in a volume production environment.

Nature of the Research

This research is both basic and applied. It is our aim to solve specific practical problems in microwave circuit modeling and design. In that sense it is applied. However, many aspects of basic research are involved. The fields of science involved: numerical methods, electrical circuit theory, microwave theory and techniques, statistical analysis, physics. Engineering applications will be found in all engineering areas involving mathematical modeling and volume production.

Reference Material

Many references can be cited. Two important papers are:

S. Liu and K. Singhal, "A statistical model for MOSFETs", *IEEE Int. Conf. on Computer-Aided Design* (Santa Clara, CA), 1985, pp. 78-80.

J. Purviance, D. Criss and D. Monteith, "FET model statistics and their effects on design centering and yield prediction for microwave amplifiers", *IEEE Int. Microwave Symp. Digest* (New York, NY), 1988, pp. 315-318.

Uncertainty of the Research

One important uncertainty of the project lies in the identification of critical process/geometrical parameters and establish physical/empirical formulas for such parameters. The second uncertainty is the reliability of statistical descriptions for electrical model parameters.

A scientific risk lies in the robustness and reliability of the methods being developed. We will not be able to properly implement them if they turn out to be unreliable, or unable to provide usable results.

The uncertain future of statistical modeling and design of microwave integrated circuits, and acceptance of the necessary software tools by microwave engineers also makes this a high risk project. The prognosis for the affordable manufacture of monolithic microwave integrated circuits (MMICs) is particularly uncertain.

Novelty of the Research

To our knowledge, there exist very few papers in the literature for statistical modeling of microwave integrated circuit devices. This research will extend, where possible, statistical modeling techniques used in VLSI digital circuits to microwave circuits. We will develop new techniques otherwise.

Microwave circuits are often operated under high power conditions. They may be analyzed under periodic signals rather than transient signals. It is our intent to model devices under such operating conditions, a state-of-the-art concept. As such it is novel.

Advance in Scientific Knowledge

If this research is successfully completed, the result will significantly enhance microwave engineers' understanding of device statistics. It will establish a framework for complete statistical characterization and design of microwave integrated circuits.

Method of Research

Accepted scientific methods are employed. Since the team members have been actively working in device modeling, parameter extraction and statistical design areas for a number of years, we have a solid background in this research. A relevant literature search has been carried out.

According to our expectations, parameter extraction programs will be extensively used. Accepted statistical analyses will be performed.

The project particularly requires interaction with integrated circuit process and fabrication engineers to determine and obtain relevant measured data. The mathematical algorithms being developed will then be tested on a number of practical devices using real measurement data.

Progress to Date

The starting date for the project was June 1, 1987. By July 31, 1988, a comparative review [4] of the state of the art in statistical modeling has been completed. Various existing approaches, their advantages and disadvantages have been categorized.

In the near future, we will establish a theoretical framework for actual GaAs MESFET device statistical modeling. This will involve extensive use of parameter extraction programs and interaction with process/fabrication engineers.

Reports

Technical documentation of our findings to date is in progress.

Description of the Project

Our research efforts are concentrated on four subjects:

(1) Review of state of the art in statistical modeling. Categorize various existing approaches, their advantages and disadvantages. Identify data structure and individual subtasks required in a statistical modeling procedure.

(2) Study special aspects of GaAs FET integrated circuit devices related to statistical modeling. Apply statistical modeling techniques to such devices reflecting fabrication parameters and response measurements.

(3) Interact with process and fabrication engineers for measurement data and

process information.

(4) Perform statistical modeling using real measurement data.

Possible future research in this area includes:

(5) The establishment of necessary theory for an optimization approach to statistical modeling.

(6) The implementation and testing of the optimization approach.

(7) The derivation of a framework for a comprehensive statistical modeling system for monolithic integrated microwave devices.

To date the first subject, i.e., (1) above, has been successfully completed. The following is a brief description of our results.

Statistical modeling is a prerequisite to using statistical design techniques. Such a procedure has been successfully used in the design of MOSFET devices, CMOS and other types of VLSI digital circuits [1-3].

GaAs integrated circuits now play an important role in microwave engineering. Yield optimization and cost minimization of such circuits is becoming a high priority for circuit designers. How to obtain the statistical models is a vital step towards effective use of yield analysis and optimization. However, such modeling techniques are relatively new to most microwave engineers. The literature on this subject in the microwave community is very sparse, e.g., [2].

Generally speaking, statistical modeling is to find a model and the statistical distribution of the model parameters. The available information are measurements of external behaviour of circuits or devices, and possibly process/geometrical measurements. Different levels of information may be hierarchically classified, from top to bottom, as response level, electrical model parameter level, intermediate parameter level and basic process/geometrical parameter level.

Approaches that can be suggested are a process/geometrical based approach, an electrical model parameter based approach, a reduced electrical model based approach, a direct process/geometrical based approach and a direct response based approach.

Subtasks required in statistical modeling include: response measurements, circuit simulation, parameter extraction, identification of critical process/geometrical parameters, modeling of process disturbances, statistical analysis of data, factor analysis, statistical tests of hypothesis, linear and nonlinear regression analysis.

Technical Personnel

Dr. J.W. Bandler, Director of Research

Ms. M.L. Renault

Dr. Q.J. Zhang

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RESEARCH PROJECT 5:

ADVANCES IN MICROWAVE COMPUTER-AIDED-DESIGN (CAD)

Objective of the Research

The main objective of the project is to survey the field of microwave CAD and to propose and implement advanced features and techniques as extensions to state-of-the-art software systems. We are developing new algorithms that may further improve robustness and efficiency of the software systems. Software products exploiting such features and techniques will then become more competitive.

Nature of the Research

This research is essentially applied. It is our aim to develop advanced features and techniques to solve general microwave circuit CAD problems more efficiently. For example, an advanced feature implemented to date includes a highly-interactive graphical user-interface. We have originated a decomposition technique for design of large-scale systems and we have developed the world's first statistical design option for general microwave CAD systems. Highly robust end efficient algorithms for DC and general n-port electrical circuit analyses are being developed.

Reference Material

Many references can be cited. Important CAD software systems are:

SUPER-COMPACT, Compact Software Inc., Paterson, NJ 07504.

TOUCHSTONE, EEsof Inc., Westlake Village, CA 91362.

Uncertainty of the Research

The main uncertainty of the project lies in the mathematical robustness and reliability of the methods being developed. While they seem to be attractive and quite promising at the present stage of development, we will not be able to implement them if they turn out to be unreliable, highly sensitive to computational accuracy or fail to provide satisfactory results.

It is not clear how large the improvement in efficiency will eventually be and whether the methods will be sufficiently cost-effective in their implementation.

Novelty of the Research

This research represents new work on state-of-the-art software systems. Our group has achieved world recognition in this area. As such our contributions are novel.

Advance in Scientific Knowledge

If this research is successfully completed, the advanced features and techniques developed may constitute a true breakthrough in CAD tools available to electrical circuit design engineers in general and microwave circuit design engineers, in particular.

Method of Research

Accepted scientific methods are employed. Since the team members have been actively working in this research area for a number of years no extra literature search was necessary except for recent periodicals. Existing CAD software systems are continually studied.

According to our expectations, appropriate mathematical manipulations are conducted and then the new concepts are programmed. The algorithms being developed are then tested on a number of circuit examples. Such features as computational efficiency, robustness and reliability are scientifically investigated.

Progress to Date

Advanced features and techniques implemented to date include: a highly-interactive graphical user-interface, a mathematical decomposition technique for design of large-scale systems and a statistical design option for general CAD systems.

The highly-interactive user-interface has been implemented in the context of a CAD system for design and modeling of inhomogeneous rectangular waveguide structures [1].

The decomposition technique has been implemented in the context of a CAD system for design of microwave multiplexers [2]. We have solved the world's largest microwave circuit optimization problems and published the results.

The statistical design option has been implemented in the context of a general purpose CAD system for design of microwave circuits [3]. This also represents the yield driven design features to be created for general purpose microwave CAD system. We are unquestionably in the forefront of research in this area.

Reports

A Master's degree thesis has recently reported on several aspects of this research [4]. A report documenting our work related to general DC and n-port analysis of microwave circuits is in progress.

Description of the Project

Our research efforts are presently concentrated on four subjects:

(1) A highly-interactive CAD user-interface.

(2) A decomposition technique for design of large-scale engineering systems.

(3) A statistical design option for general purpose CAD systems.

(4) General DC and n-port analysis of microwave circuits.

Implementation of these features and techniques has been made within the context of various CAD systems.

One CAD system is for the design and modeling of inhomogeneous rectangular waveguide structures [1]. Exact sensitivity expressions [4] have been developed and coded, and existing sophisticated ℓ_1 and minimax gradient optimizers [5] have been incorporated in the CAD system. The CAD system is highly interactive with menu-driven commands and graphical displays of information. In particular, the system features the graphical entry of user-defined optimization specifications.

A second CAD system is for the design of large-scale microwave circuits, namely microwave multiplexers. The design procedure utilizes a novel decomposition approach to large-scale minimax optimization. This work has been published in the European Microwave Conference by Bandler, Chen, Daijavad, Kellermann, Renault and Zhang [2].

A third CAD system features a statistical design option used for yield maximization. Bandler and Chen [3] have proposed an implementable algorithm. Successful implementation has been verified through design examples in which yield improvements are evident.

Currently, we are working on a novel algorithm capable of handling variable circuit topology due to short-circuits appearing anywhere inside the circuit being analyzed. The algorithm will suit the requirements of DC analysis very well, an indispensible part of the harmonic balance method for analysis of nonlinear circuits.

We are also working on general n-port circuit analysis of microwave circuits. The algorithm will be capable of handling any port configuration and will incorporate an efficient elimination technique, so the expected robustness and efficiency will outperform all known methods. No results relating to this subject have been published so far.

Technical Personnel

Dr. J.W. Bandler, Director of Research

Dr. R.M. Biernacki

Dr. S.H. Chen

Mr. R. Csermak

Ms. M.L. Renault

Mr. G.R. Simpson

Mr. K. Vojdani

Dr. Q.J. Zhang

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TECHNICAL PERSONNEL

Director of Research

Dr. J.W. Bandler is President of Optimization Systems Associates Inc., established in 1983, and Director of Research.

Dr. Bandler studied at Imperial College of Science and Technology, London, England, from 1960 to 1966. He received the B.Sc. (Eng.), Ph.D and D.Sc. (Eng.) degrees from the University of London, London, England, in 1963, 1967 and 1976, respectively.

Dr. Bandler joined Mullard Research Laboratories, Redhill, Surrey, England in 1966. From 1967 to 1969 he was a Postdoctorate Fellow and Sessional Lecturer at the University of Manitoba, Winnipeg, Canada. He joined McMaster University, Hamilton, Canada, in 1969, where he is currently a Professor of Electrical and Computer Engineering. He has served as Chairman of the Department of Electrical Engineering and Dean of the Faculty of Engineering. He currently directs research in the Simulation Optimization Systems Research Laboratory. He has more than 220 research publications.

Dr. Bandler is a Fellow of the Royal Society of Canada, a Fellow of the Institute of Electrical and Electronics Engineers and a Fellow of the Institution of Electrical Engineers (Great Britain). He is a member of the Association of Professional Engineers of the Province of Ontario (Canada).

Senior Research Personnel

Dr. R.M. Biernacki received the Ph.D. degree from the Technical University of Warsaw in 1976. He has 19 years of professional experience which includes several academic and research positions.

Dr. Biernacki joined Optimization Systems Associates Inc., in 1986, as Senior Research Engineer. In 1988 he was appointed Professor of Electrical and Computer Engineering (part-time) at McMaster University, Hamilton, Canada.

Dr. Biernacki's research interests include system theory, optimization and numerical methods, computer-aided design of integrated circuits and control systems. He has more than 50 publications in IEEE journals and proceedings of IEEE and other conferences.

Dr. Biernacki is a Senior Member of the Institute of Electrical and Electronics Engineers.

Research Personnel

Dr. S.H. Chen received the B.S.(Eng.) degree from the South China Institute of Technology, Guangzhou, China, with top class honours, in 1982. He pursued his graduate studies in the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, where he received the Ph.D. degree in 1987.

Dr. Chen joined Optimization Systems Associates Inc. in 1987 as Research Engineer. He is responsible for developing state-of-the-art CAD mathematics, algorithms and software.

Dr. Chen's professional interests include optimization theory and algorithms, computer-aided microwave circuit design, statistical analysis and yield optimization, robust device modeling, and user-friendly computer graphics. He has contributed to 12 technical papers, including an invited paper for the 1988 Special Issue on Computer-Aided Design of the IEEE Transactions on Microwave Theory and Techniques entitled "Circuit optimization: the state of the art". During his stay in McMaster University between 1983 and 1987, he has contributed to 20 technical reports.

Ms. M.L. Renault received the B.Eng. and M.Eng. degrees, both in electrical engineering from McMaster University in 1982 and 1988, respectively.

Ms. Renault has been employed by Optimization Systems Associates Inc. on a project basis since 1983 and on a regular part-time basis since July 1986. She joined Optimization Systems Associates Inc. as a full time Research Engineer in 1988.

Ms. Renault's research interests include statistical circuit design and identification of circuit model parameters.

Dr. Qi-jun Zhang received the B.Eng. degree from the East China Engineering Institute, Nanjing, China in 1982. He pursued his graduate studies in the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, where he received the Ph.D. degree in 1987.

Dr. Zhang was a research assistant in Tianjin University, Tianjin, China in 1982 and 1983. He was a Postdoctoral Fellow in the Department of Electrical and Computer Engineering, McMaster University from September 1987 to March 1988. He joined Optimization Systems Associates Inc. in 1988 as Research Engineer.

Dr. Zhang's professional interests include large-scale optimization techniques for design and modeling of microwave circuits, analysis and optimization of nonlinear microwave circuits, sensitivity analysis, diagnosis and tuning of analog circuits. He has published 11 technical papers.

Assistant Research Personnel

Mr. J.F. Loman received the B.Sc.E.E. degree in electrical engineering from the University of Calgary in 1986. He worked for National Semiconductor Canada Ltd. in workstation ASIC design automation from 1987 to 1988, prior to joining Optimization Systems Associates as Software Engineer in 1988.

Mr. Loman is pursuing an M.Eng. degree on a part-time basis in the Department of Electrical and Computer Engineering at McMaster University. His interests include device modeling, model parameter extraction and CAD tools.

Mr. K. Vojdani received the M.A.Sc. degree in electrical engineering from the University of Windsor, Canada, in 1987. He was with Optimization Systems Associates Inc. as Computer Engineer from August 1987 to September 1987. While there Mr. Vojdani designed and developed computer codes to facilitate advanced forms of user-interaction and computer graphics, including multiuser, multitasking environments.

Engineering Students

Mr. R. Csermak was employed by Optimization Systems Associates Inc. as an Engineering Assistant from May to August 1988. He is presently a student at McMaster University, where he expects to graduate in 1989 with a B.Eng.Mgt. from the Department of Electrical and Computer Engineering.

Mr. G.R. Simpson was employed by Optimization Systems Associates Inc. as an Engineering Assistant from May to August 1988. He is presently a student at McMaster University, where he expects to graduate with a B.Eng in Computer Engineering from the Department of Electrical and Computer Engineering in 1989.

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