YIELD/COST OPTIMIZATION OF NONLINEAR MICROWAVE CIRCUITS

Optimization Systems Associates Inc.

OSA-88-TR-1-P

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TRIO RESEARCH PROPOSAL: YIELD/COST OPTIMIZATION OF NONLINEAR MICROWAVE CIRCUITS

The Proposed Research

We propose to conduct research on the harmonic balance method, sensitivity analysis of microwave nonlinear circuits, efficient modeling of circuit responses and on algorithms for yield optimization and cost-driven design of linear/nonlinear hybrid and monolithic microwave integrated circuits. The outcome of this research will be in the form of prototype software, reports and/or papers.

Background

Design of nonlinear circuits is one of the most challenging tasks in the microwave CAD area. The pseudo-linear behaviour commonly existing in analog and microwave circuits and the intentional use of nonlinearities in circuits such as mixers are typical examples requiring nonlinear circuit CAD techniques. These techniques become more crucial for the microwave and millimeter-wave IC chips that are essential for the coming generation of radar systems, smart munitions and radio-frequency communications. The recognized number one task for such systems is cost reduction [1], thus making yield optimization unavoidable.

Judging from the available CAD techniques, yield optimization of nonlinear circuits is currently impractical. It would require prohibitive computer time and storage. Yield optimization involves iterative yield estimation; each yield estimation needs many circuit simulations and each simulation also iteratively solves nonlinear equations. Recently, the method of harmonic balance has become the most prominent one in dealing with nonlinear circuits. Commercial software using this method for analyzing nonlinear circuits has been developed. The Microwave Harmonica program [2], although considered as the world's most advanced of its kind today, suffers from extremely large memory requirements and a limited variety of circuit elements available to the user. The program can perform nominal design with only linear elements as variables. It does not perform yield analysis and optimization, a rather difficult, but nonetheless essential, task for microwave CAD.

OSA Potential for the Proposed Research

Our expertise in analysis and statistical design of linear circuits and in numerical methods establishes our confidence in tackling this difficult problem. We are currently developing a novel theory for exact sensitivity analysis of nonlinear circuits [3]. The theory extends the powerful adjoint network method that has been used as a standard in linear circuit sensitivity analysis. The use of such theory may significantly simplify and speed up the nonlinear design by using powerful gradient based optimizers. Implementing the state-of-the-art sparse matrix technique [4] into harmonic balance methods and the new efficient quadratic modeling technique [5] into yield optimization will further enhance the practicality of cost-driven design of nonlinear circuits.

We are also planning to experiment with intensive computing using supercomputers. User-friendly and efficient nonlinear CAD systems using interaction of micro- or mini-computers with a supercomputer are to be investigated. We ultimately plan that the user interface and problem formulation will be done on a micro- or mini-computer (or workstation) and the intensive number crunching work could be directed to a supercomputer, such as the Cray X-MP.

OSA's Ultimate Goal

OSA's ultimate goal in this area is to substantially develop the next generation software to be used as a necessary tool for hybrid integrated and MMIC design in a workstation environment. The results will provide the answer to the challenging cost-driven design of MMIC circuits to be used in the early 1990s.

Features to be Fully Developed Under the Present Proposal

1. Perform simulation of linear/nonlinear microwave circuits by means of the harmonic balance method.

2. Handle some commonly used components such as lumped: RLC elements, controlled sources, transformers; distributed: transmission lines, microstrip lines, junctions, bends, stubs, resonators; and nonlinear GaAs devices.

3. Specifically handle the following models: Curtice and Ettenburg [7], Madjar and Rosenbaum [8], Tajima et al. [9], Materka and Kacprzak [10].

4. Perform efficient sensitivity analysis to calculate gradients of the circuit responses w.r.t. all possible optimizable variables such as parameter values, voltage or power levels, etc.

5. Optimize circuit parameters by means of state-of-the-art powerful gradient optimizers.

6. Model circuit responses for rapid statistical evaluations.

7. Perform yield optimization of linear/nonlinear circuits.

8. Handle internally statistics to model parameter spreads, including normal and uniform distributions.

9. Handle microwave hybrid integrated and MMIC design, including design of GaAs MESFET mixers, amplifiers, power amplifiers, phase shifters, filters. (Also, oscillator designs may be considered.)

10. Achieve efficiency and reasonable storage by incorporating advanced theoretical results including nonlinear adjoint sensitivity analysis, sparse matrix techniques, quadratic modeling, and a novel multicircuit approach to statistical design [6].

11. Handle up to 300 components, 15 nonlinear ports, 65 harmonics and 50 designable variables.

Features to be Developed Outside of the Present Proposal

1. User-friendly features including windowed environment, prompts, menus, interactive graphics for displaying (and modifying, if applicable) design specifications, performance spreads, response envelopes, etc.

2. Handle all components needed in MMIC design.

3. Provide for external user-defined components.

4. Provide for external user-defined or model-specific statistics.

5. Perform cost-driven design of linear/nonlinear circuits as well as yield-driven design.

6. Handle large circuit blocks having a few hundred components, up to about 30 nonlinear devices, with frequency up to 100 GHz.

Relevance to Canada and Ontario

Relevant Canadian corporations interested in the design and manufacture of microwave integrated circuits include ComDev Ltd., MA Electronics Canada Ltd., Spar Aerospace Ltd., Bell-Northern Research, Gennum Corporation (formerly Linear Technology) and the Communications Research Centre. A technical dialogue, for example, is in progress with individuals such as R. Surridge at BNR and C.A.M. Marshall at Gennum.

It is our plan to cooperate fully with such Canadian industrial and government laboratories, to explore ways of including their device models and fabrication statistics into our software and to make any CAD system we develop be compatible with their own hardware/software. We will cooperate by testing our software on specific problems, with relevant device and circuit data supplied by them. We would agree to field test our software and organize on-site demonstration.

It will, for example, be necessary to consider techniques for statistical modeling to simulate the statistical variations in device parameters due to process variations. We need efficient methods to identify process parameters by statistically analyzing large samples of measured data. Yield estimation and yield- and cost-driven design depend on simple and effective statistical models.

Our research and software will have an impact on increased automation in the electrical manufacturing industries. The work will help Canada maintain its position in relevant areas, such as in the aerospace and related electronics and communications industries. Effective use by the Canadian microwave industry of state-of-the-art microwave CAE products, including ours, will substantially improve productivity. All such products are currently purchased from the United States. Enhancing production yield will make a substantial contribution to the viability of Canadian high-technology products. Promotion of our results will be through direct interaction with potential Canadian industrial users.

References

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Time Frame

Two years.

Estimated Budget

Three man years at $40,000.00 per man year	$ 120,000.00
Overhead costs at 100%	$ 120,000.00
Purchase and maintenance of Apollo*	$ 102,505.00
Travel	$ 15,000.00
TOTAL REQUESTED FOR THIS PROPOSAL	$ 357,505.00

***Apollo Workstation**

Hardware:	DN4000 Workstation, 16Mb RAM, 348Mb HDisk, High-resolution color graphics monitor, 60Mb Cartridge Drive		$ 72,000.00
Software:	Operating system, FORTRAN and C Compilers		$ 4,160.00
Field Installation:			$ 1,615.00
Hardware:	Maintenance for 2 years at $5,052.00 per year		$ 10,104.00
Software:	Maintenance for 2 years at $3,960.00 per year		$ 7,920.00
		SUBTOTAL	$ 95,799.00
		7%PST	$ 6,706.00
		TOTAL	$ 102,505.00

OSA ADVERTISEMENT

OSA was established in 1983. The company offers software for mathematically optimized engineering designs. State-of-the-art optimizers working with advanced simulators, complemented by powerful sensitivity algorithms are customized and linked with CAE hardware and software.

Application Areas: OSA's innovations are driven by the microwave industry's growing demand for user-friendly, state-of-the-art software design tools. OSA features:

Microwave circuit analysis, design and optimization

Algorithms for automated production alignment and tuning

Statistical estimation of production yield

Robust active and passive device modeling

Automated processing of dc and rf measurement data

Powerful performance and yield driven optimizers

Manufacturing tolerance assignment and cost minimization

Customized gradient and minimax optimizers

Computer optimization of matching networks, filters and multiplexers

Harmonic balance simulation of nonlinear circuits

Expanding Staff: OSA's highly skilled technical staff continues to increase to match the challenges in the field of microwave CAE. John Bandler is recognized as a leading authority in this area. Twenty-five years of distinguished relevant CAD research insures that OSA's customers rank at the leading edge of microwave circuit design.

Software for the 1990's: OSA's software is dramatically impacting the efficient CAE of microwave integrated circuits, and will continue to do so into the next decade. OSA has originated features never previously offered by commercial microwave software houses. OSA continues to play a key role in current releases of the most popular microwave CAD products such as Super-Compact® Version 2.0.

Productivity Increase: Our staff is ready to discuss your needs. Enhance the capabilities of your existing CAE tools and increase your productivity! We offer advice on how optimum use can be made of existing CAE tools, including courses and customer training programs.

Enquiries: Please call (416) 627 5326

OSA's EQUIPMENT

Hardware

1 DEC microVAX II:
6Mb RAM, 71Mb HDisk, 4 ports, TK50 96Mb cartridge drive, VMS operating system.

1 IBM AT personal computer:
640Kb RAM, 20Mb HDisk, 1.2Mb Floppy, 360Kb Floppy, EGA Color Monitor, 80287 math co-processor, DOS operating system.

2 Zenith AT personal computers:
640Kb RAM, 40Mb HDisk, 1.2Mb Floppy, 360Kb Floppy, EGA Color Monitor, 80287 math co-processor, (1 has 2Mb RAM memory above board expansion), DOS operating system.

1 HP LaserJet series II printer.

Software

VAX: Fortran Language Compiler, Super-Compact Version 2.0.

PC's: Microsoft Assembler, FORTRAN, Pascal and C Compilers, WordPerfect, Lotus 1-2-3, Touchstone V1.5, Super-Compact PC.

OSA's hardware is also supported by software including Touchstone, SPICE and SPICE-PAC. Our state-of-the-art programs: optimizers, sparse matrix solvers, specialized circuit simulators, data processing routines, etc., are readily available on all computers.

OSA's RESEARCH AND DEVELOPMENT PROGRAMS

Microwave Research Background

Twenty-five years of work in computer-aided design of microwave circuits by Bandler, OSA's president and research director, has focussed on the modeling of components, the effects of sensitivity and tolerances on performance, the origin and nature of manufacturing uncertainties and parasitic effects, as well as the simulation, design, testing and tuning of microwave circuits. Pioneering work in the application of optimization techniques to microwave circuits has established test examples now used by applied mathematicians as benchmarks for new algorithms. Original least pth and minimax algorithms have been applied to active and passive circuits. Adjoint network concepts based on Tellegen's theorem have been applied to microwave circuit structures. Special attention has been devoted to all aspects of cascaded microwave circuit analysis, including branched structures.

OSA's Research and Development

OSA's R&D programs are applying and extending pioneering work carried out by Bandler and his colleagues in circuit design optimization, design centering, optimal assignment of component tolerances, postproduction tuning and the optimization of production yield [1]. A new theoretical treatment by Bandler and Chen [1] of a hierarchical device/circuit/system modeling scheme, exposing statistical tolerance phenomena at different parameter/response levels are being studied and implemented. A novel generalized ℓ_p centering algorithm will be implemented in a multilevel, multicircuit environment [2,3]. OSA is implementing parameter extraction techniques for analog microwave devices and circuits [4-6], including linear, nonlinear, active and passive microwave integrated circuit elements.

Algorithms for large signal frequency domain device modeling and circuit simulation, following recent work by Kundert and Sangiovanni-Vincentelli [7] of Berkeley and Rizzoli et al. [8] of the University of Bologna are being studied. In particular, OSA will exploit efficient adjoint sensitivity approaches within the framework of the harmonic balance method of nonlinear circuit simulation [9].

OSA's future plans include the exploitation of interactive graphics for displaying specifications, response envelopes and distributions, monitoring parameter behaviour, etc., for yield driven optimization for a workstation environment. Furthermore, OSA will develop efficient techniques for optimization of large microwave systems [10].

Major Research Collaborators

Dr. K. Madsen, of the Technical University of Denmark, recently spent time at OSA's expense with OSA's research staff. He is the world's leading authority on minimax and ℓ_p optimization. During his stay we planned future cooperation on novel implementations of state-of-the-art optimizers for design and modeling, with a view to commercial exploitation in software products. In particular, we will cooperate on efficient algorithms for

one-sided and generalized ℓ_p functions and algorithms specialized to statistical yield-driven and cost-driven design for MMICs.

Bandler's pioneering research on optimization with tolerances and yield optimization since the early 1970s drew the attention of Dr. R.A. Pucel, probably the world's foremost expert in microwave solid state devices. Pucel, in a frequently referenced paper [11], pointed out that GaAs MMICs will prove successful only if their cost of production can be reduced. He proposed that high yield and low cost should be the driving forces of their CAD, not the conventional performance-driven approach. Design should always include tolerances.

Consequently, OSA has participated since 1985 with Raytheon Company's initiatives towards the MIMIC (Microwave/Millimeter-Wave Monolithic Integrated Circuits) program. At this time OSA has been designated a subcontractor on the Raytheon/Texas Instruments/Compact Software MIMIC team. OSA's mandate is to develop computational approaches to cost and yield driven design on a large scale for GaAs monolithic circuits. In particular, OSA will be developing yield optimization techniques for nonlinear circuits with many active devices.

Dr. R.M. Biernacki, Senior Research Engineer at OSA, who has made major research contributions to analog circuit diagnosis and statistical design will play a leading part in the research.

OSA's Research Objectives

OSA's objectives are to produce software products which are commercially successful in the microwave circuits CAD arena. These products will either compete with or be linkable with major CAD systems now offered to the public, such as Touchstone and Libra produced by EESof, Super-Compact and Microwave Harmonica produced by Compact Software, TECAP produced by Hewlett-Packard, etc. The products will incorporate the latest numerical analysis and optimization tools. To that end OSA must focus its research on the most effective number crunching algorithms, within an attractive user-friendly computing environment. Computing systems to be employed include IBM PC/AT compatibles, Apollo workstations, VAX mainframes, etc.

References

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BIOGRAPHICAL SKETCH OF JOHN BANDLER

Academic Qualifications

John Bandler graduated from Imperial College of Science and Technology, University of London, in 1963 with first class honours in Electrical Engineering. His graduate studies from 1963 to 1966 at Imperial College in the Communications and Electronics section of the Department of Electrical Engineering were concentrated in Microwaves. He received the Ph.D. degree of the University of London in 1967. His D.Sc.(Eng.) was conferred in 1976 by the University of London for his contributions to microwaves, computer-aided design, and optimization of circuits and systems.

Experience

Dr. Bandler joined Mullard Research Laboratories, Redhill, Surrey, England in 1966, where he continued work on microwave tunnel-diode amplifier design and diode measurements, research for which he became widely known. From 1967 to 1969 he worked at the University of Manitoba, where he established himself as an expert in optimization methods and their applications to computer-aided network design.

He joined McMaster University in 1969, where he was promoted to Professor at the age of 32. He has served as Chairman of the Department of Electrical Engineering, Dean of the Faculty of Engineering and currently directs research in the Simulation Optimization Systems Research Laboratory, which he formed in 1983. He was a member of McMaster's famous Communications Research Laboratory in its founding years (1970-73), later forming the interdisciplinary group on Simulation, Optimization and Control, which he coordinated from 1973 to 1983.

Dr. Bandler has published some 220 technical reports, including numerous documented computer programs ranging from mathematical optimization to electrical power systems optimization to microwave circuit design. A very large number of industrial organizations and educational institutions have acquired and are currently using the software. He has presented some 100 seminars and special lectures internationally.

He has established himself as an expert on sensitivity analysis of electrical circuits, least pth and minimax optimization, fault location of analog circuits, optimal load flow in power systems, microwave filter and multiplexer design. He has been employed as a consultant by several major companies.

Dr. Bandler's significant contributions to technology transfer through education, consulting and software development have resulted in his founding of Optimization Systems Associates Inc. Optimization Systems Associates has originated features never previously offered by commercial microwave software houses. It shaped the evolution of Touchstone™, a major commercial product, through its development of the Version 1.5 optimizers. It developed the world's first yield driven option offered by a microwave CAD product into Super-Compact® Version 2.0.

Publications

Dr. Bandler has more than 220 publications covering many *IEEE Transactions*, including *Circuits and Systems; Microwave Theory and Techniques; Acoustics, Speech and Signal Processing; Automatic Control; Education; Power Apparatus and Systems* and the *Proceedings of the IEEE*. He has published papers in the *Journal of Optimization Theory and Applications* and in *Mathematical Programming* as well as in many other refereed journals.

Four of his papers were selected for the book *Computer-Aided Filter Design*, one in *Microwave Integrated Circuits*, another in *Microwave Integrated Circuits, 2nd Edition*, one in *Low-Noise Microwave Transistors and Amplifiers*, one in *Statistical Design of Integrated Circuits*, and one for the forthcoming *Analog Fault Diagnosis*. In 1985 he published an invited paper for the Proceedings of the IEEE reviewing "Fault diagnosis of analog circuits". In 1988 his invited paper "Circuit optimization: the state of the art" will appear in the *IEEE Transactions on Microwave Theory and Techniques*.

Professional Contributions

Dr. Bandler was an Associate Editor of the IEEE Transactions on Microwave Theory and Techniques from 1969 to 1974. He was Guest Editor of the Special Issues of the IEEE Transactions on Microwave Theory and Techniques on Computer-Oriented Microwave Practices (March 1974). He has served on numerous international technical committees, editorial boards, conference program committees and has organized and chaired many special symposium sessions. He has made invited contributions to many symposium workshops.

Honors and Citations

Dr. Bandler was elected a Fellow of the IEEE in 1978 at age 36 with the citation "for contributions to computer-oriented microwave and circuit practices". In 1978 he also became a Fellow of the IEE (London). He is listed in Who's who in Engineering, American Men and Women of Science and in Who's Who in America.

He is recognized for his pioneering work in optimal design centering, tolerancing, tuning and yield optimization, in particular for his 1976 papers "A nonlinear programming approach to optimal design centering, tolerancing and tuning" and "Integrated approach to microwave design".

In 1986, he was elected Fellow of the Royal Society of Canada.

BIOGRAPHICAL SKETCH OF RADEK BIERNACKI

Academic Qualifications

Radek Biernacki graduated from the Technical University of Warsaw, Warsaw, Poland in 1969 with the highest grade, receiving the M.Sc degree in Electronics. His M.Sc. thesis was concerned with the spectral properties of audio signals and nonlinear distortions in electronic circuits. He received the Ph.D. degree (with honors) in Technical Sciences from the Technical University of Warsaw, Warsaw, Poland, in 1976. His Ph.D. research was in the field of circuit theory and concentrated on the matrix synthesis of active and passive RC filters. Not for the credit of the aforementioned degrees, from 1967 to 1970 he also studied theoretical mathematics and numerical methods at the University of Warsaw.

Experience

Dr. Biernacki joined the Institute of Electronics Fundamentals, Technical University of Warsaw, Warsaw, Poland, as a Research and Teaching Assistant. He taught courses on circuit theory and communications and conducted research towards his Ph.D. In 1976 he became an Assistant Professor and continued his work on active RC filters, research for which he became internationally known. He also worked on computer-aided design of electronic circuits. His library of CAD oriented routines and his circuit simulator for semisymbolic analysis have been widely used in Poland.

From 1978 to 1980 he was on leave with the Research Group on Simulation, Optimization and Control and with the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Ont., Canada, as a Post-Doctorate Fellow. He worked on optimization algorithms, simulation methods of cascaded microwave circuits and, primarily, on fault diagnosis methods for analog circuits. His major research contributions to analog fault diagnosis has been widely recognized.

From 1984 to 1986 he was a Visiting Associate Professor at the Texas A&M University, College Station, Texas, USA. He taught courses on circuit theory and electronics, and conducted research on statistical analysis, modeling and on robust control.

He joined Optimization Systems Associates Inc. (OSA), Dundas, Ont., in 1986, where he was appointed Senior Research Engineer for his research achievements. While with OSA, he has substantially contributed to its R&D programs as well as to the state-of-the-art software development for industrial applications. Within the period of one year he contributed to 11 internal reports.

He has established himself as an expert in circuit theory, active and passive filters, fault location of analog circuits, statistical analysis and in robust control.

Publications

Dr. Biernacki has about 50 publications covering *IEEE Transactions on Circuits and Systems*, *IEEE Transactions on Automatic Control*, the *International Journal on Circuit Theory and Applications*, and other refereed journals and conference proceedings.

Honors and Awards

Dr. Biernacki joined the Institute of Electrical and Electronics Engineers (IEEE) in 1985. In 1986 he was elevated to the grade of Senior Member. He has also been awarded prizes several times for his research and teaching achievements.

BIOGRAPHICAL SKETCH OF SHAO HUA CHEN

Shao Hua Chen graduated from the South China Institute of Technology, Guangzhou, China, with top class honours in 1982. He was awarded a graduate scholarship by the Chinese Ministry of Education in 1983. 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. He has been awarded an Ontario Graduate Scholarship in 1985 and 1986.

He has been a teaching assistant in the Department of Automation, South China Institute of Technology, from 1982 to 1983, and in the Department of Electrical and Computer Engineering, McMaster University, from 1984 to 1987. He joined Optimization Systems Associates Inc. in 1987 as a Research Engineer responsible for developing state-of-the-art CAD software.

His 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. His experience in CAD software development includes contributions to minimax, ℓ_2, ℓ_1 and one-sided ℓ_1 optimization routines, the optimizers of Touchstone, the yield optimization features of Super-Compact, FET device modeling packages, as well as user-friendly graphics utilities for the IBM PC/AT and Texas Instruments PC.

He has contributed to 12 technical papers in the *IEEE Transactions on Microwave Theory and Techniques*, the *Proceedings of the IEEE, Electronics Letters*, the *International Journal of Circuit Theory and Applications*, and many technical conferences. He published an invited paper for the 1988 Special Issue on Computer-Aided Design of the *IEEE Transactions on Microwave Theory and Techniques* reviewing the field of "Circuit optimization: the state of the art". During his stay in McMaster University between 1983 and 1987, he has contributed to 20 technical reports.

BIOGRAPHICAL SKETCH OF MONIQUE RENAULT

Ms. M.L. Renault has been employed by Optimization Systems Associates Inc. (OSA) on a project basis since 1983, and on a regular part-time basis since July 1986. She graduated from McMaster University in 1982 with a B.Eng. from the Department of Electrical and Computer Engineering, and is presently pursuing a master's degree on a part-time basis. She has been employed by the University as a research engineer since 1984.

Ms. Renault's position as a research engineer for both OSA and the University has given her experience in many aspects of computer-aided design of circuits. She has actively participated in many projects with contributions to: software creation and management, algorithm implementation, testing of examples, interpretation and presentation of results. The scope of design features she routinely deals with covers optimization objective functions, sensitivity analysis, modeling of objective functions, circuit parameter identification, statistical analysis, design centering and yield maximization.

Ms. Renault has worked with many in-house software systems some of which are: a microwave multiplexer design program which handles up to 20 channel structures, a user friendly graphics program running on a personal computer for the design and modeling of cascaded circuit structures, and many smaller systems which deal with aspects of sparse matrix techniques, numerical random number generators, contour plots, etc. She has also worked on commercial software systems, one of which is Super-Compact V2.0, in which the optimizers are improved upon and the design centering, quadratic modeling and yield optimization features are introduced.

Ms. Renault's software management experience is with programs written in FORTRAN and various computers and operating systems: PC's running DOS, VAX/VMS, Cyber/NOS, IBM/VM and the FPS array processor. Her work considers the transfer of software between systems, machine dependencies and numerical accuracy issues.

Ms. Renault is also familiar with software and hardware equipment acquisition, installation and maintenance procedures. She routinely procures quotations from various suppliers and often assists in the preparation of equipment grants. She is also responsible for the installation of software and hardware and its general upkeep.

Ms. Renault's research interests in computer-aided design of circuits include circuit design, identification of circuit model parameters, statistical design and yield optimization.