LINEAR/NONLINEAR/STATISTICAL MODELING FOR COMPUTER-AIDED ENGINEERING OF MICROWAVE INTEGRATED CIRCUITS

OSA-89-OS-9-P

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1. Title of the Proposal

LINEAR/NONLINEAR/STATISTICAL MODELING FOR COMPUTER-AIDED ENGINEERING OF MICROWAVE INTEGRATED CIRCUITS

2. Company Background

General Information

Optimization Systems Associates (OSA) was established in 1983 and was incorporated in 1986. OSA is privately owned.

OSA is driven by the microwave industry's growing demand for user-friendly, state-of-the-art software design tools. OSA provides consulting services to several major microwave companies and software houses.

In 1988, OSA released its own product RoMPE™ - a program for FET parameter extraction. It is marketed by OSA in Canada, and by Compact Software outside Canada.

In 1989, OSA announced HarPE™ - a program for FET parameter extraction under large-signal conditions using harmonics. It is marketed exclusively by OSA worldwide.

OSA's Facilities

Computers

1 DEC microVAX II
1 Apollo DN3500 workstation
6 IBM AT personal computers or compatibles

Operating Systems

VMS 4.5, BSD 4.2 UNIX, System V UNIX, DOS

Language Compilers, Linkers and Other Tools

Fortran, C, Pascal
Phoenix Plink 86
AI Architect Development Tools
GMR2D Graphics Library

3. Company Commitment

The overall cost of the proposed project is estimated as follows.

1.	Technical personnel	$118,496.30
2.	Overhead	70,849.63
	TOTAL ESTIMATED COST	$189,345.93

OSA is committed to contribute $101,345.93 to the project. This will be derived from operating profits.

Commercialization of the results will be by direct offering to prospective customers. Promotion of the final product will be by advertisement in trade journals, by demonstration at symposia and on site.

4. Company Technical Capability

OSA's competence has been established by our substantial contributions to the literature and our innovations in several major commercial software in the microwave CAE market.

OSA's Microwave CAE Innovations

OSA has originated features never previously offered by commercial microwave software houses.

In 1983, OSA developed a system for efficient simulation, sensitivity analysis and optimization of waveguide multiplexers. The leading manufacturer of multiplexers, namely, ComDev Ltd. (Cambridge, Ontario, Canada), commissioned this system.

OSA has reshaped Touchstone by developing state-of-the-art optimizers, originally featured in Version 1.5, including minimax, quasi-Newton and generalized least pth optimizers.

From 1986 to 1989, OSA played a key role in the restructuring and enhancement of the popular microwave CAE products Super-Compact, Microwave Harmonica, Super-Compact PC and Microwave Harmonica PC.

Since 1985 OSA has supported Raytheon Company's initiatives towards the U.S. DoD's MIMIC (Microwave/Millimeter-Wave Monolithic Integrated Circuits) Program. Currently, OSA is a subcontractor on the Raytheon/Texas Instruments/Compact Software MIMIC team under a Phase 1 Subcontract.

OSA's FET parameter extractor (small-signal measurements) - RoMPE™ - has been reviewed favourably by experts in the area. This product was released in 1988. OSA's FET parameter extractor (large-signal measurements) - HarPE™ - is being released in 1989.

OSA's Distinctive Competence

long and extensive experience in CAE

high level of technical and mathematical expertise

implementation of advanced theory and techniques in commercial software

high standard of professional programming

experience on many platforms: Apollo, CRAY, FPS, IBM mainframe, PC, VAX

several programming languages

OSA's Recent R&D Activities

OSA's recent R&D activities concentrated on the following projects.

Project 1: ROBUST MODEL PARAMETER EXTRACTION

- a theoretical framework for robust modeling, optimization and unique identifiability,
- implementable algorithms for device model parameter extraction.

These techniques have been implemented in OSA's RoMPE™.

Project 2: HARMONIC BALANCE ANALYSIS AND OPTIMIZATION

- an extremely efficient adjoint network approach to sensitivity analysis of nonlinear circuits,
- general hierarchical analysis in both the original and the adjoint networks,
- yield optimization of nonlinear circuits,
- parameter extraction of nonlinear devices for large-signal operation (implemented in OSA's HarPE™).

Project 3: EFFICIENT STATISTICAL CIRCUIT DESIGN OF INTEGRATED CIRCUITS

- extremely efficient algorithms for statistical circuit design,
- highly efficient algorithm for one-side nonlinear ℓ_1 optimization,
- efficient quadratic approximation technique to reduce the number of circuit simulations in statistical design.

Project 4: ADVANCES IN MICROWAVE COMPUTER-AIDED-ENGINEERING (CAE)

- highly-interactive user-interface,
- decomposition technique for design of large-scale engineering systems,
- general DC and n-port analysis of microwave circuits.

Implementation of these techniques has been made within various CAE systems.

Project 5: STATISTICAL MODELING OF MICROWAVE DEVICES

- reviewing of state-of-the-art in statistical modeling,
- categorizing various existing approaches, their advantages and disadvantages,
- identifying data structure and individual subtasks required in statistical modeling.

OSA's Technical Personnel

JOHN W. BANDLER, Ph.D., D.Sc.(Eng.), P.Eng., C.Eng., FIEEE, FIEE (London), Fellow of the Royal Society of Canada

OSA Founder, President and Research Director; Professor of Electrical and Computer Engineering and Director of the Simulation Optimization Systems Research Laboratory, McMaster University, Hamilton, Ontario; 25 years of professional experience; expert in optimization methods and their applications to computer-aided network design, 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; recognized for his pioneering work in optimal design centering, tolerancing, tuning and yield optimization; author of more than 220 publications, listed in Who's Who in Engineering, American Men and Women of Science, Who's Who in America and in Canadian Who's Who.

RADEK M. BIERNACKI, Ph.D., SMIEEE

Senior Research Engineer in OSA; Professor (part-time) of Electrical and Computer Engineering, McMaster University, Hamilton, Ontario; 20 years of professional experience; expert in electronic circuits, computer-aided design, circuit theory, fault diagnosis of analog circuits, statistical analysis and in robust control; author of more than 50 publications.

SHAOHUA CHEN, Ph.D., MIEEE

Research Engineer in OSA; 5 years of professional experience in optimization theory and algorithms, computer-aided circuit design, device modeling, statistical analysis and optimization, computer graphics, and control systems; expert in programming languages; author of 16 publications.

JOHN LOMAN, B.Sc.

Software Engineer in OSA; 1.5 years of professional experience in computer-aided design of digital circuits, microwave device modeling, small-signal parameter extraction techniques; currently pursuing a Masters degree in electrical engineering at McMaster University on a part-time basis.

MONIQUE RENAULT, M.Eng., MIEEE

Research Engineer in OSA; 6 years of professional experience in optimization theory and algorithms, computer-aided circuit design, device modeling, statistical analysis and optimization, software quality control, and documentation; author of 3 publications.

QI-JUN ZHANG, Ph.D., MIEEE

Research Engineer in OSA; 5 years of professional experience in analysis and optimal design of linear/nonlinear microwave circuits, large-scale simulation and optimization, small- and large-signal parameter extraction of FET devices, sensitivity analysis, statistical modeling, diagnosis and tuning of analog circuits; author of 13 publications.

5. Project Objectives

We propose to research the area of microwave device modeling including extraction of small-signal and large-signal model parameters in the presence of device statistics. Based on the results of the research we plan to develop a new software system for parameter extraction of linear/nonlinear statistical models of microwave devices.

6. Project Technical Background

General Background

Microwave analog circuits are essential elements in satellite communications, radar systems space technology, etc. Such circuits operate in the analog mode, similar to that of radio receivers and transmitters, but at much higher frequencies. High frequency circuits are much more difficult to design and manufacture than the low frequency ones. For example, the mutual coupling effects between two adjacent elements, negligible in low frequency operations, can substantially distort the circuit's performance in high frequency operations.

While silicon semiconductors are typically used in digital circuits and lower frequency circuits, microwave engineers have found Gallium Arsenide (GaAs) to be the material most suitable for microwave circuits. The GaAs development and wafer processing achieved in the past few years have made monolithic microwave integrated circuits (MMICs) practical. MMICs have been successfully applied to microwave circuits such as power amplifiers, mixers, oscillators, etc.

The production of MMIC chips is becoming massive. In such production, devices are designed and manufactured in batches rather than individually. Small random variations in the manufacturing process typically result in a portion of "bad" devices. The yield, defined as the ratio between the number of "good" devices and the total number of devices, directly affects the cost of manufacturing. Consequently, the need for yield optimization has become more and more pressing.

Analog circuits can be classified as linear or nonlinear. In linear (nonlinear) circuits, the level of the output signal changes proportionally (non-proportionally) with that of the input signal. Simulation of nonlinear circuits is much more complicated than that of linear ones.

For microwave circuits, whether a circuit is linear or nonlinear is typically decided according to the power level of the input-signal. Small-signal circuits are linear while large-signal circuits are nonlinear. Design of nonlinear circuits is one of the most challenging tasks in the microwave computer-aided engineering (CAE) 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 CAE techniques. The harmonic balance technique has recently become a popular tool for solving nonlinear circuits.

Computer simulation of circuits needs mathematical models to describe the behaviour of devices in the circuit. Device modeling and parameter extraction techniques are designed to determine the structure and parameters of device models. Statistical modeling techniques have evolved to determine the device model taking random process variations and other uncertainties into account.

The proposed research is directed at a software/hardware system for modeling of analog microwave devices that takes into account manufacturing tolerances, model uncertainties, variations of the process parameters, environmental uncertainties, etc. It is particularly important for large volume production of MMICs.

Device Modeling

In the area of device modeling or parameter extraction, e.g., for GaAs field effect transistor (FET) devices, the traditional small-signal model alone does not provide satisfactory solutions in the design and analysis of nonlinear circuits. A nonlinear or large-signal model is needed to model the device operating under large-signal conditions.

There are difficulties in modeling of such devices with techniques presently used by industry. The large signal model extracted from direct current (DC) measurements does not agree well with radio frequency (RF) measurements. There are parasitic circuit elements. There are too many variables and inaccessible nodes to create a unique solution based only upon one set of broadband scattering parameter measurements.

OSA has evolved a robust model parameter extraction approach that simultaneously processes DC and RF measurements (Bandler, Chen, Ye and Zhang 1988). The DC characteristics are used to constrain bias-dependent parameters, thus improving the uniqueness and reliability of small-signal modeling. This feature has been implemented into OSA's RoMPE™.

OSA has pioneered a novel approach to large-signal nonlinear parameter extraction of GaAs FET devices measured under harmonic conditions (Bandler, Zhang, Ye and Chen 1989). A powerful nonlinear adjoint based optimizer simultaneously processes multi-bias, multi-power-input, multi-frequency excitations and multi-harmonic measurements to uniquely reveal the parameters of the intrinsic FET. Our results demonstrate an excellent match between computed and measured power over the entire frequency spectrum. This feature is implemented into OSA's new product HarPE™.

Researchers at Raytheon Company and Texas Instruments in the U.S. have shown great excitement with this novel approach. They have provided us with actual device measurement data and have urged the release of the software.

Statistical Device Modeling

Yield optimization requires effective statistical representation of devices. The model statistics originate from simple random variations of basic process/physical/geometrical parameters. They are reflected in complicated distributions and correlations of device responses or equivalent model parameters. Statistical modeling has been seriously studied for metal-oxide semiconductor (MOS) and complementary metal-oxide semiconductor (CMOS) circuits for more than 10 years. The subject has recently gained attention of MMIC microwave engineers.

The equivalent circuit based approach (Purviance et al. 1988) and the process/geometry based approach (Liu and Singhal 1985) are two important methods for statistical modeling. The first approach typically results in a large number of statistical variables with complicated correlations. Consequently, the yield optimization problem will deal with a large number of variables and functions. The second approach requires physical/empirical formulas to express the device model in terms of basic process/geometrical parameters. Such formulas may be highly nonlinear and extremely complicated. These nonlinear formulas have to be computed or solved for each outcome of the device during each iteration of optimization.

OSA has already initiated research in this field (see: page 4, Project 5). We have investigated a systematic treatment of statistical modeling using hierarchical model description. The statistical behaviour of devices is effectively characterized using statistical concepts including confidence levels, multi-dimensional normal and discrete distributions.

7. Proposed Investigation

The ultimate goal of the proposed research is to develop a software system for device parameter extraction and modeling including statistics. Necessary research, development and milestones are outlined in the following subsections.

Research towards Parameter Extraction and Statistical Modeling System

study special aspects of GaAs FET integrated circuit devices related to statistical modeling,

develop theory for an optimization approach to statistical modeling,

implement and test the optimization approach to statistical modeling,

develop a framework for a comprehensive statistical modeling system for monolithic integrated microwave devices,

apply statistical modeling techniques to such devices reflecting fabrication parameters and response measurements,

interact with process and fabrication engineers for measurement data and process information,

test statistical modeling using real measurement data.

Modules for Parameter Extraction and Statistical Modeling System

User Interface and Command Processor

File Parser

Editor

Memory Manager

Circuit Element Library

Linear Simulator

Harmonic Balance Simulator

Optimizers

Library of Packaging Models

Library of Parasitic Models

Library of FET Intrinsic Models

Driver for Multi-Circuit Simulation

Driver for Error Function for Linear Modeling

Driver for Error Function for Nonlinear Modeling

Statistical Processor of Extracted Parameters

Interface to Measurement Equipment

Output Data Processor

Graphics Interface

Bar Chart

Development schedule is illustrated by the bar chart in Table I.

Planned Features of Parameter Extraction and Statistical Modeling System

1. Utilization of spectrum or waveform measurements of nonlinear devices. S parameter measurements, power measurements, voltage and current waveforms will be accommodated.

2. Extraction of small- and large-signal device parameters to simultaneously fit measurements at DC, fundamental frequency and higher harmonics.

3. Uniqueness of the solution supported by using a multi-circuit concept including multi-bias, multi-power-input and multi-fundamental-frequency excitation.

4. Numerical efficiency achieved by implementing advanced adjoint sensitivity analysis, and state-of-the-art optimizers.

5. Handling the following FET models: Curtice and Ettenberg (1985), Materka and Kacprzak (1985), and Raytheon model (Statz et al. 1987). Diode and bipolar models will also be accommodated. Automatic generation of parasitic subcircuits for these models will be featured.

6. Compatibility with models of popular CAE software systems such as EEsof's Libra and Compact Software's Microwave Harmonica.

7. User-friendly features including a menu-driven command system, flexible input file syntax, interactive graphics for displaying (and modifying, if applicable) response matching, device characteristics, user-formatted output and report writer.

8. Convenient access to measurement data through interface to test equipment.

TABLE I. BAR CHART FOR THE PROPOSED INVESTIGATION

Item Description	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
Research	═	═	═	═	═	═	═	═				
Structural Planning	═	═	═									
Mathematical and Statistical Routines		═	═			═	═	═				
Simulators			═	═	═							
Library				═	═	═	═	═	═	═		
Drivers & Parser				═	═	═	═	═				
Graphics					═	═	═	═				
Integration									═	═	═	
Testing/Debugging										═	═	═
Documentation						═	═	═	═	═	═	═

8. Project Team

J.W. Bandler	15% time	Research Director
R.M. Biernacki	30% time	Project Consultant
S.H. Chen	70% time	Project Co-Leader
J. Loman	50% time	Project Engineer
M. Renault	50% time	Project Engineer
Q.J. Zhang	85% time	Project Co-Leader

For individual expertise relevant to the project please see section "OSA's Technical Personnel" on page 5. No new hirings for this project are planned.

9. Subcontractors and Consultants

No subcontractors or external consultants are planned for this project.

10. Projected Market

The commercial market in the field of device modeling is addressed by: TECAP distributed by Hewlett-Packard; Xtract produced by EEsof; Utmost produced by Silvaco; and RoMPE™ and HarPE™ produced by OSA. In Canada, these products, except RoMPE™ and HarPE™, must be purchased from the United States.

These modeling programs (except OSA's HarPE™) primarily solve a field effect transistor (FET) with direct current (DC) and/or small-signal measurements. HarPE™ is the world's first commercial program for FET modeling within a true nonlinear environment.

There is no commercially available software for statistical FET modeling for analog microwave applications. Therefore, our achievements in the proposed research will contribute towards OSA's advantage over other software companies.

We propose an initial fee for the final product of $30,000 per copy, and an annual maintenance fee of 20% of the then current price. Within the first two years after release we expect a sale of 3 to 5 copies in Canada and of 30 to 50 copies outside Canada. In order to contribute to Canadian competitiveness we will consider price discounts to Canadian companies, in particular, to those willing to cooperate, share measurement data, etc.

11. Impact of Support

OSA has the technical expertise for the proposed project. However, without financial assistance the project could not be carried out. Successful completion of the project will substantially contribute to profitability and development of OSA. Thus, the expected growth of the company will generate jobs in Canada, for example, to create a technical support department for customers of OSA products. Also, the algorithms and software modules will be extremely valuable in future OSA's products, thus reducing their development cost.

The project will contribute to Canadian competitiveness in the microwave CAE arena and in the high-tech industry in general, currently dominated by the Americans.

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