SIMULATION OPTIMIZATION SYSTEMS
Research Laboratory

PHYSICALLY UNIFIED STATISTICAL MODELLING/YIELD OPTIMIZATION OF HIGH FREQUENCY CIRCUITS

NSERC Strategic Grant No. STR0117819 FINAL REPORT

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SOS-95-1-R

January 1995

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Hamilton, Canada L8S 4L7
Department of Electrical and Computer Engineering

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Budget	Amount Requested	Amount Awarded	Amount Spent
Year 1	$97,717	$97,717	$97,717
Year 2	$98,617	$97,717	$97,717
Year 3	$99,417	$97,717	$97,717

Amount remaining in the grant account as of February 1, 1995: $0.00.

OBJECTIVES

This research was motivated by the fact that yield optimization (or statistical design centering) methodology is crucial not only for massively manufactured circuits but also for improving the probability of first-pass success in design for small volume production. The use of physical parameters should significantly improve performance-driven and yield-driven optimization of practical high frequency linear and nonlinear integrated circuits.

We were to unify statistical modelling and yield optimization through physical, geometrical and process parameters and constraints. We planned to significantly improve efficiency of yield optimization algorithms using multidimensional approximations, table look-up, etc. We envisaged the creation of a direct optimization-based approach to statistical modelling to determine the parameter statistics directly from multi-outcome measurements. We were to develop a theory for "yield-oriented" statistical estimation. We were to address an integrated methodology for simultaneous design of active devices and surrounding passive components on the same chip accounting for geometrical dimensions, process parameters and technological constraints.

To overcome the computational burden of physics based models we were to accommodate a physically based treatment of both active devices and passive components. We were to investigate a full two-dimensional, field-theory based MESFET model, particularly in the context of using physics based models as benchmarks to reflect physical parameters and constraints in equivalent circuit models. We were to link process simulators and research key variables for statistical modelling.

Long term goals were to contribute to Canadian expertise in CAD optimization system design, and establish Canada as a source, not an importer of this technology.

ACHIEVEMENT OF THE OBJECTIVES

All the objectives of the research under this grant have been achieved. We have significantly contributed to the creation of reliable, efficient, cost-effective and robust computer-aided design systems for designing practical high frequency integrated circuits in a workstation environment. We have substantially advanced the state-of-the-art in yield optimization and statistical modelling through a physically unified, meaningful methodology and corresponding algorithms.

Yield Optimization Algorithms: We created a new theoretical formulation for circuit yield optimization [3,27] and a new one-sided Huber optimization [17,23,48,66]. A yield probability function replaces the discrete and discontinuous acceptance index in the classical Monte Carlo analysis. It leads to a yield estimate suitable for gradient-based optimization. A small-signal amplifier and a FET frequency doubler demonstrate effectiveness and efficiency, comparing favourably with our well-established one-sided ℓ_1 centering algorithm. We significantly extended our original work on response surface modelling through powerful, multilevel multidimensional Q-models [8,11,36,40]. We pioneered direct yield-driven optimization of circuits containing microstrip structures accurately simulated by an electromagnetic simulator, arousing excitement throughout industry! We have continued exploiting the harmonic balance technique for simulation and statistical design of nonlinear circuits [1,20,23,28,60,61,66].

Direct Optimization-Based Approach to Statistical Modelling: We introduced a novel approach to "robustizing" circuit optimization using Huber functions [6,12,17,23,34,38,48,66]. Robust handling of both large and small measurement errors, bad starting points and statistical uncertainties can now be automated, as validated by FET modelling from data contaminated with "wild points". Our novel implementation promises to have a profound impact on analog fault diagnosis and large-scale circuit optimization, and has already been noted by referees! We developed a new statistical verification procedure [2,26,30] for device models, using yield as the statistical estimator. We have successfully overcome the deficiencies of the two-stage (parameter extraction/statistical postprocessing) approach to statistical modelling. Our new cumulative probability distribution fitting technique [15,55] directly determines statistics such as the mean values and standard deviations in a single optimization. Statistical modelling is carried out without extracting parameters of individual manufactured outcomes. Therefore, it does not have to rely on the uniqueness of the parameter extraction process.

Measurement Data Manipulation: We developed an interpolator to align measurement data [2,26,30], necessary when measured device responses are taken under slightly different biasing conditions for different manufacturing outcomes. We exploited the Materka and Kacprzak FET model for its superior matching flexibility. We have experimented with database creation, editing, etc. Massive measurement data can now be effectively manipulated. Statistical modelling using both the parameter extraction/statistical postprocessing approach and the direct cumulative probability distribution fitting technique directly processes and sorts measurement data for many device outcomes.

Integrated Design Methodology: We are forging ahead with physics-based models (PBMs) [2,5,13,23,25,26,29,30,46,66], to treat device statistics at the geometrical/process parameter level. PBMs offer the opportunity of optimizing the active devices. Although expensive to implement in manufacturing, it may be justified if it significantly increases yield, and reduces production cost. Including FET gate length and channel thickness as designable variables, we demonstrated [2,5,23,29,30,66] significantly higher yield through simultaneous circuit and device optimization. Device optimization will become more attractive with further advances in technology. A particularly useful yield sensitivity analysis technique [2,11,26,40] has been developed to select key variables for yield optimization. It can extract more information from a single Monte Carlo analysis than in the past, for example, yield as a function of a varying specification. The integrated design methodology has been recently extended to cost-driven design where the manufacturing cost is modelled and minimized [23,66].

Process-Independent Physically Based Simulation: As planned, we have improved computational efficiency and robustness of the Khatibzadeh and Trew model through simplifications for uniform doping and introducing a new transition function for free electron density calculation [5,29]. Our new physics-based statistical GaAs MESFET model (KTL) [2,13,25,26,30,46] merges the advantages of the DC Khatibzadeh and Trew model with the Ladbrooke formulas. The KTL model shows excellent statistical properties, as confirmed by predictable yield optimization of a broadband small-signal amplifier. The KTL model is a bias-dependent small-signal model and as such is not suitable for large-signal simulations. To address fast and reliable physics-based large-signal statistical FET modelling we adapted [23,66] a modified Statz model following the D'Agostino *et al.* formulas.

Electromagnetic Field-Theory Based Optimization: We have overcome [7,19,33,35,39] significant challenges arising when electromagnetic (EM) field simulations are to be directly optimization driven. We developed a smart interface to drive Sonnet's ***em***: for the first time a comprehensive approach to microwave filter design, which exploits accurate field simulations driven directly by a gradient based minimax optimizer, is possible. Challenges we faced included efficiency, discretization of geometrical dimensions, continuity of optimization variables, and gradient estimation. We have been able to design an optimal microstrip structure of unconventional geometry (a folded double stub filter) which would otherwise be very difficult to represent using standard microstrip components. In cooperation with Watkins-Johnson Co. of Stanford we have performed a filter design with interdigital capacitors simulated by ***em*** and the overall circuit design carried out by our software. In cooperation with Westinghouse Science and Technology Center of Pittsburgh we successfully approached design of a narrow-band filter to be realized in HTS (high-temperature superconductor) technology [16,56,62]. Each represents a major step forward. We worked on full two-dimensional field theory based MESFET model following Reiser and Snowden and used it as a benchmark to reflect physical parameters in the Plessey equivalent circuit model [5]. This technology is critical in experimental validation [73]. Key to our solutions is the software architecture, exemplified by Spicepipe - our optimization-ready interface to SPICE [9,24,31,37,41,68], allowing hybrid and multi-level simulation and optimization. We have experimented with parallel processing and distributed data bases [18,22,47,67].

Incorporating Process-Dependent Simulators: We have developed a general purpose modeling interface (GPMI) [24,52,68,71] capable of automated interaction with process-dependent external simulators. The syntax of the external simulator input file is provided to GPMI in a template which is filled with the parameter values. The external simulator is then automatically invoked. GPMI captures the simulator output by extracting the relevant information from the simulator's output file and sends the results to the optimizer. Results of experiments with a link to SUPREM 3.5 from Stanford University are yet to be published. The GPMI interface, in fact, goes far beyond our originally planned work on incorporating process simulators. It allows easy replacement of the process simulator! Also, it allows for significant saving of the computational effort through built-in response modelling and data base mechanisms.

Software Development Milestones: Close collaboration with OSA (Optimization Systems Associates Inc.) was vital to the success of this research, offering timely validation and testing of new algorithms and ideas. Available to us are the commercial products HarPE (device modelling) and OSA90/hope, whose open architecture facilitates rapid insertion of new modules. The C language has been used for new developments, both mathematical modules and user-interface, graphics, etc. ANSI standard was conformed to for portability. Live demonstrations of our software have been made in Europe, Canada and in the US, both at international microwave symposia and in industry.

Spinoff Research: Several new research topics have emerged from our work on this projects. We have initiated relevant research as we feel that the importance of those subjects is pressing. The most important area is automated direct optimization-driven electromagnetic design of high frequency and high speed circuits. We have discovered the breakthrough concept of *Space Mapping* [14,16,21, 56,57,59,62,63]. As a result, we are convinced that CAD and modelling of engineering devices, circuits and systems will reach a level of precision and computational efficiency previously undreamed of.

The Contribution of Each Co-Investigator: Close interaction between Dr. Bandler (the applicant) and Dr. Biernacki (co-investigator) results in a true "team effort" extremely beneficial to all parties and essential to the overall success of our research. Tasks are rarely separated to be exclusively carried out by any of the co-investigators. Instead, joint effort characterizes our research activities. This scheme of cooperation includes Dr. Chen, the other research engineers, postdoctoral fellows and graduate students supervised by the co-investigators.

Scientific and Engineering Significance of the Results: The significance of the area and our contribution to the area is evidenced by the Special Issue of the *IEEE Transactions on Microwave Theory and Techniques* (Bandler and Jansen, Co-Editors) on *Process-Oriented Microwave CAD and Modeling*, July 1992, Panel Session on Circuit Design with Direct Optimization-Driven Electromagnetic Simulators at the IEEE MTT-S International Microwave Symposium in San Diego, CA, May 1994 (Bandler, Organizer and Moderator), and the coming Workshop on Automated Circuit Design Using Electromagnetic Simulators at the IEEE MTT-S International Microwave Symposium in Orlando, FL, May 1995 (Bandler and Sorrentino, Co-Organizers and Co-Chairmen) [72,76,84]. Our journal papers were published in the single, most reputable journal in the field: the IEEE Transactions on Microwave Theory and Techniques. Most of our conference contributions were presented at the highest forum in the field: IEEE MTT-S International Microwave Symposium. Our work is highly regarded by other researchers and makes a significant impact on the state of the art in automated CAD of high frequency circuits. Our breakthrough results on direct optimization-driven EM simulations opened up an important avenue for immediate research that may provide industry with extremely powerful new CAD tools. This NSERC research was a decisive factor in nominating Dr. John W. Bandler for the prestigious Automated Measurements Career Award presented by the Automatic RF Techniques Group of the Microwave Theory and Techniques Society of the IEEE "For a Career of Meritorious Achievement and Outstanding Technical Contribution in the Field of Automated Microwave Techniques". We will deliver an invited presentation at the 25th European Microwave Conference in Bologna, September 1995. We are invited to the Workshop on Large Scale Optimization, Institute for Mathematics and its Applications, Minneapolis, MN, July 17-21, 1995 (Bandler, Invited Participant). The only non-American to participate, Dr. Bandler was invited to the US Army Electronics Research Strategy Planning Workshop, Myrtle Beach, SC, January 9-12, 1995, contributing to the Thrust "Novel Methodologies for Modeling, Simulation and CAD."

TRAINING OF RESEARCH PERSONNEL

The grant assisted in the salaries and support for our team, which includes extremely talented individuals (as seen by the various scholarships). Participation in the project provided an excellent vehicle for the research of our graduate students and helped them to significantly develop professionally. Some supporting projects [49,50,51,64,65] were also carried out.

Research Engineers: Dr. S.H. Chen - significantly contributed to all aspects of the project as evidenced by the publications. His role was key to the success of the project. S. Werczak - contributed to reshaping our programming tools [45].
Postdoctoral Fellow: Dr. Q. Cai - substantially contributed to the parts of the project on active device modelling, including an interface to the network analyzer system [43,44].
Ph.D. Students: Q. Cai (McMaster Scholar, now NSERC Industrial Fellow, OSA) [69] and P.A. Grobelny (OGS Scholar) [71] - both have contributed to the project on active device modelling and software architecture, respectively. K. Gu and N. Hoole also participated.
M.Eng. Students: R. Hemmers (NSERC Scholar), H. Yu (OGS Scholar, now with Bell-Northern Research) [70] - both participated in selected aspects of the project: EM optimization and Huber optimization, respectively. P. Wu (OGS Scholar), X. Zhou, Lin Nanzhi, Ching Ying, Wei Yujing, Lai Wei also participated.
Summer Students. NSERC: A. Esmaili, R. Hemmers, C. Kolking and C. Sakr; other: S. Chandanakeerthi, B. Leduc (contributed to reshaping our programming tools [45]) and S. Pirbhai - all participated in selected documentation, small programming tasks, and various testing.

Many other Canadian students utilize our software for their courses and as a vehicle in graduate level research, not only at McMaster University but also at Victoria, Toronto, Carleton, Queen's and Ecole Polytechnique. Topics resulting from this research are incorporated into our graduate courses and will soon find their way into our undergraduate curriculum. Our software tools are already extensively used in undergraduate laboratories (more than 100 new 3rd and 4th year students each year).

ACCESSIBILITY OF RESULTS TO THE INTENDED USER COMMUNITY

Dissemination of Results Our group has a well-established system of dissemination of results through publication, consulting, education and software demonstration. Through personal discussions, seminars, consulting and contracts, we transfer our knowledge and expertise to industry.. We welcome Canadian exploitation and collaboration. New techniques and algorithms developed under this grant are available to supporting Canadian organizations. Further promotion of our results will be through direct interaction with potential Canadian industrial users.

Industrial Interactions Close interaction with Optimization Systems Associates Inc. (OSA) was particularly beneficial. OSA's software was made available to our group. It let us more quickly develop and test new ideas. It also permitted significant national and international industrial exposure and interaction regarding software needs, requirements and user-oriented features. In return, it facilitated transfer of technology from university to industry. Developments from earlier stages of this project have already been included in new releases of OSA's products (HarPE, OSA90/hope and Empipe). They provide an excellent vehicle for transfer to the user sector. Full commercialization of all results is expected within one year after completion of the project. We welcome additional commercialization by other Canadian companies.

Canadian interactions include Bell-Northern Research, ComDev, the Communications Research Centre, Gennum, Harris Farinon, Lucas Aerospace, Mitec, Northern Telecom, Optotek, Quantic Laboratories, and Spar Aerospace. Collaboration is under way with Dr. Poltz (OptEM, Calgary). International interactions have included Alcatel, AT&T, Daimler Benz, British Telecom, Cascade Microtech, General Electric, Hughes, IBM, IMST, JPL, Loral, M/A—COM, Philips, Plessey, Raytheon, Rockwell, Siemens, Sonnet, Texas Instruments, Thorn-EMI, TriQuint, TRW, Watkins-Johnson, Westinghouse. We have delivered talks - in 1992 at: Rockwell International, TRW, Interstate Electronics, Hughes, Gennum, Bell-Northern Research; in 1993 at: Philips Semiconductors, Daimler Benz, Texas Instruments, Nissho Iwai; in 1994 at: JPL, TRW, Hughes, Space Systems Loral, M/A—COM, Raytheon Research Division, Alcatel Telettra, Westinghouse Electronic Systems.

Scientific Interactions We chaired sessions: on Nonlinear Modeling and Analysis at the IEEE MTT-S Int. Microwave Symposium in San Diego, CA, May 1994, on Analog CAD at the IEEE Int. Symposium on Circuits and Systems in London, England, May/June 1994, and on Nonlinear Circuit Design at the Third Int. Workshop on Integrated Nonlinear Microwave and Millimeterwave Circuits INMMC'94, in Duisburg, Germany, October 1994 [77,78,82]; lectured at workshops, meetings and short courses: on Critical Issues in Experimental Validation at the IEEE MTT-S in Atlanta, GA, June 1993 [73], Scandinavian Workshop on Linear Programming in Lyngby, Denmark, August 1993 [53,74], IEEE Foothill Section in Claremont, CA, January 1994 [58], DAIE/CRC Topical Meeting on Numerical Methods and Optimization Techniques as Applied to EMI and EMC, at CRC, Ottawa, September 1994 [79], on Optimization Technology and Applications in High Frequency and Microwave Circuit Design at Gerhard Mercator University Duisburg, Department of Electromagnetic Theory and Engineering, Germany, October 1994 [81], and organized and moderated Panel Session on Circuit Design with Direct Optimization-Driven Electromagnetic Simulators, at the IEEE MTT-S Int. Microwave Symposium in San Diego, CA, May 1994 [76]. We have also served on the Technical Program Committees of the IEEE MTT-S Int. Microwave Symposia (San Diego, CA, 1994, and Orlando, FL, 1995), and of the Third Int. Workshop on Integrated Nonlinear Microwave and Millimeterwave Circuits INMMC'94, (Duisburg, Germany, 1994) [75,80,83]. We have delivered seminars - in 1991 at: George Washington University; in 1992 at: University of Leeds, University of Kent, Carleton University, University of Ghent, Université Catholique de Louvain, Technical University Delft, Duisburg University, Technical University of Denmark, University of Toronto, École Polytechnique; in 1993 at: Technische Hochschule Darmstadt, IMEC, Technische Universität Wien, ETH (Switzerland), CNM (Spain); in 1994 at: University of Bologna, CRC, Carleton University, Duisburg University, CNAM (France).

We collaborate actively with Dr. Hoefer (Victoria, BC) on physics-based TLM circuit optimization [10,54]. Drs. Zhang and Nakhla (Carleton) have made breakthroughs in VLSI interconnect yield optimization through our innovations. Cooperation with the McMaster's CRL (Dr. Litva) and Dr. Ghannouchi (École Polytechnique) is well under way. Dr. Salama (Micronet, Toronto) entered the parameter extraction field using our results. International interactions include Drs. Ingo Wolff and Adalbert Beyer (Duisburg), Dr. Robert Trew (Case Western University). We continue our fruitful collaboration with Dr. Kaj Madsen (Denmark) [6,12,17,34,38,48], who visited us and gave a seminar in 1994.

POTENTIAL SOCIO-ECONOMIC BENEFITS

Our work has contributed to the enhancement of Canada's position in high technology through advancement of knowledge and national expertise in simulation, design and testing of high frequency analog and high speed digital circuits. Our work has led to the development of new capabilities that go far beyond the features considered as most advanced just a few years ago.

Viability and competitiveness of the high tech Canadian industry, including software, in the global market is the most important benefit. Some success stories: our results are finding their way into both software and hardware production in Canada, all substantially export-directed (e.g., BNR, CRC, ComDev, OptEM), as well as to advance research (Micronet, TRIO). Our goal is to provide tools assisting in reducing the design cycle (e.g., Swanson's microstrip filter fabrication [19,39]). Our close link with Optimization Systems Associates Inc. enhances our posture in an arena still dominated by US companies (HP, HP-EEsof, Compact Software). It is absolutely essential for Canadian software industry to have leading technical edge, supported by state-of-the-art research at Canadian universities, over American software vendors. It is clear that we have made, and continue to make, significant contributions toward that goal.

The techniques and software will have an impact on increased design automation in the electronics manufacturing industries. Availability of unified design methodology comprising physics-based statistical modelling, accurate electromagnetic simulation and enhancing production yield is of utmost importance. The work will help Canada maintain its position in relevant areas such as in the aerospace, electronics and communications industries.

PUBLICATIONS

Our work on the strategic project has resulted in 23 refereed papers already published or accepted for publication in the most reputable journals and conference proceedings, and one additional paper submitted for publication. The work has been documented in 44 internal reports and constituted substantial parts of three graduate theses.

<u>Refereed Journal Papers, Conference and Workshop Contributions</u>

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