# AUTOMATED DIRECT OPTIMIZATION-DRIVEN ELECTROMAGNETIC DESIGN OF HIGH-FREQUENCY AND HIGH-SPEED CIRCUITS

NSERC Strategic Grant No. STR0167080 FINAL REPORT

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| Budget | Amount Requested | Amount Awarded | Amount Spent |
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| Year 1 | $96,730 | $96,730 | $96,730 |
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## OBJECTIVES

This work was driven by our perception that direct exploitation of electromagnetic (EM) simulators in the optimization of high-frequency analog and high-speed digital integrated circuits will be crucial for first-pass success CAD. EM field simulators offer high accuracy, handle arbitrary geometrical shapes and are valid up to millimetre-wave frequencies. We believed that the prevailing use of EM simulators for validation of designs obtained through traditional techniques did not fully exploit their predictive power. Our breakthroughs on direct optimization-driven EM simulations opened important avenues for immediate research that should lead to highly effective CAD tools for industry.

We were to significantly advance the state-of-the-art in automated EM-based design. We planned to develop theory and algorithms to facilitate user-defined parameterization of arbitrary structures. We were to investigate techniques for automated geometrical decomposition as dictated by proximity, electromagnetic coupling or higher-order modes. We planned work on a universal interface to various simulators for integrating them into optimization systems. We were to develop theory and algorithms for parameter space mapping, the expected cornerstone for successful EM optimization. We planned to generalize the adjoint sensitivity analysis technique to general multi-level hierarchical systems. In particular, we were to extend our FAST adjoint analysis to handle "space-mapped" EM sensitivity evaluations. The efficiency of all algorithms were to be subjected to the demanding requirements of statistical yield-driven design.

Our goal was to provide Canadian industry with algorithms for first-pass success in circuit design, with dramatic reduction in prototype and product fabrication costs.

## ACHIEVEMENT OF THE OBJECTIVES OF THE ORIGINAL APPLICATION

The objectives of the research under this grant have been achieved. We successfully addressed the central problem of user-defined parameterization of arbitrary structures. We have significantly advanced the theory and algorithms for parameter space mapping optimization. We have achieved international recognition for these important concepts. Our results on direct optimization-driven EM simulations have already provided industry with the extremely powerful new CAD tools Empipe and Empipe3D. Independent reviewers of Microwave Engineering Europe (May 1996) described us as "pioneers of integrating third party modules into the simulators", referring to commercial EM simulators from Ansoft Corporation, Sonnet Software and HP-EEsof.

Optimization of Microstrip Structures with Arbitrary Geometries: We successfully solved the challenging problem

of user-defined parameterization of arbitrary geometrical structures [1,2,14,29,48,60]. We employ concepts from analytic geometry. The technique is specifically developed to facilitate graphical interfacing. Relevant rules have been established for imposing bounds on the variables, preserving meaningful structure evolution, and for proper discretization. The technique, first developed for planar structures, has been subsequently generalized to arbitrary 3D structures [13,18,35,43]. (Our original proposal was written in terms of planar structures).

Electromagnetic (EM) Design Benchmark Problems: In consultation with industry we developed several microwave structure benchmarks. Planar and 3D structures were treated in the course of this project to test new theories and corresponding algorithms: (1) a double folded stub filter (Sonnet Software), (2) a 10 dB distributed attenuator (Watkins-Johnson), (3) a high-temperature superconducting (HTS) four pole quarter-wave parallel coupled-line microstrip filter (Westinghouse), (4) an interdigital C-band filter (Watkins-Johnson), (5) a nonlinear FET class B frequency doubler (Microwave Engineering Europe), (6) a microstrip 3:1 transformer, (7) waveguide transformers, (8) mitered waveguide bends (Hughes) and (9) an H-plane resonator filter with rounded corners.

Space Mapping (SM): Our work on parameter space mapping has been advanced far beyond our original expectations [4-9,11,13,15,19,21,22,25,30,33,35,40-42,44,46-48,49,50,53,56,57,59]. Already noted by reviewers as: "An important further step in the practical use of EM simulation for MIC design". We have developed an aggressive strategy based on the Broyden update, reducing by half (w.r.t. our original SM) the number of CPU intensive EM simulations needed to converge. An automated implementation of the corresponding quasi-Newton algorithm has been successfully developed using a novel two-level Datapipe architecture [13]. We performed aggressive space mapping optimization of an H-plane resonator filter with rounded corners through automatic alignment of the results of waveguide models based on mode-matching (MM) and finite elements (FEM). A hierarchical family of the computational models including equivalent circuit, empirical, and coarse grid numerical EM models have been considered. A statistical approach to unique parameter extraction for space mapping was developed [21,46,53]. Our novel SM concept has attracted other noted microwave researchers (Guglielmi, Guillon, Jansen, Mansour, Levy, Pavio, Rizzoli, Snowden, Swanson, etc.) as it embodies critical design steps familiar to engineers, yet hitherto never implemented in an abstract, multidimensional manner.

Universal Interface to Various CAD Simulators: We have expanded our interprocess pipe communication (IPPC) technique for integrating simulators into optimization systems [1-3,6,17,23,28,58]. This includes distributed computations on a network of heterogeneous workstations, enhanced by interpolation, modelling and database management systems. The capability of handling any specific syntax of a given simulator has been demonstrated using Sonnet's MoM solver for predominately planar structures ***em***, FEM solvers HP-EEsof's HFSS and Ansoft's Maxwell Eminence [18,43,46,53] and SPICE. We have collaborated in engineering optimization connections to TLM (2D-TLM and 3D-TLM developed by Dr. W.J.R. Hoefer, University of Victoria) and MM solvers (RWGMM - an efficient and accurate code developed by Dr. F. Arndt, University of Bremen, and the MM code of the University of Perugia). Our results facilitate multi-level distributed calculations with design variables defined at different levels. For example, active device models, captured from SPICE, have been integrated into the overall circuit level harmonic balance simulation and optimization with passive microstrip subcircuits simulated by ***em*** [17,23].

Geometrical Decomposition of Large Systems has received serious investigation [15,19,37,41,44]. Specifically, successful decomposition-based design of a C-band interdigital filter is carried out by EM simulations of selected subcircuits (coupled lines, vias) while empirical models are used for the remainder of the circuit. Coarse-grid models are used to speed up the EM simulations. The resulting n-ports are incorporated into the overall circuit-level simulations. We further conducted experiments on waveguide decomposition, combining mode-matching with an FEM simulator.

Frequency Domain Adjoint Sensitivity Technique for Electromagnetic Solvers Sensitivity information is needed for (1) direct EM optimization, (2) space mapping EM optimization. We discovered that space-mapping models, for their ability to "resemble" actual circuit responses, are capable of providing sensitivity information, including higher order [21,46,53]. For direct optimization [18,43] our maximally flat quadratic formulation provides smooth, accurate gradient estimation, essential to efficient optimization. We store the results of expensive EM simulations in a dynamically updated data base system integrated with the interpolation technique. The automated EM design of optimal waveguide transformers and mitered bends exploits, for the first time, commercial finite element based 3D

EM simulators. We pursued these concepts rather than FAST because we enjoyed so much cooperation from EM software vendors. We continued work on distributed computation as an effective means of speeding up CPU intensive EM optimization.

Yield Optimization/Design Centering Algorithms developed within this project were subjected to the requirements of yield-driven design. For the first time, we presented new applications of aggressive space mapping to yield optimization using network theory, mode-matching and FEM simulation techniques [21,46,53]. Among important extensions of this work we envisage a highly efficient means for Monte Carlo analysis of microwave circuits carried out with the accuracy of FEM simulations.

Software Development Milestones: Software development took advantage of the open architecture of the commercial software systems OSA90/hope, Empipe and Empipe3D made available by Optimization Systems Associates Inc. Close collaboration with OSA was vital, offering timely validation and testing of new algorithms and ideas. Software development proceeded according to the original plan. Live demonstrations of our software have been made in Europe, Canada and in the US, both at international microwave symposia and in industry, including at a specially organized workshop at McMaster University directed at the Canadian user sector [80].

Spinoff Research: Several new research topics have emerged from our work on this project. We have initiated relevant research as we feel that the importance of those subjects is pressing. The most important area is developing robust space mapping algorithms and furthering the concept of space-mapped super-models for design of RF, wireless and microwave components and systems. We continue to believe that CAD and modelling of engineering devices, circuits and systems will reach a level of precision and computational efficiency previously undreamed of through the use of such novel techniques.

The Contribution of Each Co-Investigator: Close interaction between Bandler (the applicant) and Biernacki (co-investigator) resulted in a true "team effort" extremely beneficial to all parties and key to the overall success of our research. This scheme of cooperation included Dr. Chen, other research engineers, postdoctoral fellows and graduate students supervised by the co-investigators.

Scientific and Engineering Significance of the Results: Strong evidence of the significance of our contributions exists. Bandler was Guest Editor for two relevant special issues: (1) IEEE Trans. Microwave Theory and Techniques on Automated Circuit Design Using Electromagnetic Simulators, (2) Int. J. Microwave and Millimeter-Wave CAE on Optimization-Oriented Microwave CAD, both appearing in 1997 [75-78]. The only non-American to participate, 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." Bandler was invited to participate in the US DARPA Microwave and Front End Technology (MAFET) Principal Investigator and Design Review Meetings in 1996 and 1997. Bandler and Biernacki are members of the Micronet Network of Centres of Excellence since 1993 [66,79]. In 1997 we were invited to join TRIO and CITO. Bandler was Co-organizer and Co-chair (with Sorrentino) at the seminal Workshop on Automated Circuit Design Using Electromagnetic Simulators, IEEE MTT-S Int. Microwave Symp., Orlando, FL, 1995 [68]. Our colleague Dr. Chen reported on our work [68]. Bandler was Organizer and Moderator, Panel Session on Effective CAD: A Dilemma of Models!, IEEE MTT-S Int. Microwave Symp., San Francisco, CA, 1996 [73] and Co-organizer and Co-chair (with R.S. Snyder) and speaker on "EM optimization using space mapping," Workshop on State-of-the-Art Filter Design using EM and Circuit Simulation Techniques, IEEE MTT-S Int. Microwave Symp., Denver, CO, 1997 [81]. He will be Co-organizer and Co-chair (with M. Mongiardo) and speaker on "CAD with tolerances," Workshop on Computer-Aided Design for Manufacturability, IEEE MTT-S Int. Microwave Symp., Baltimore, MD, 1998 [87], and participate on the Panel on Research Directions in Microwave CAD [88]. Bandler will present "Space mapping optimization," at the Workshop on Microwave Filters and Multiplexers: Theory, Practice and CAD," 28th European Microwave Conf., Amsterdam, Netherlands, October 5-9, 1998 [89]. Our journal papers were mostly 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. NSERC research was a decisive factor in the election of Biernacki in 1996 to IEEE Fellow "For Contributions to the Theory and Implementation of Microwave and Analog CAD Technology". Bandler will become Co-chair of the IEEE MTT-S Society's Technical Committee on Computer-Aided Design from 1998. Our work is highly regarded by other

researchers (see invited papers [5,6,11,12,16]) and promises a significant impact on the state of the art in automated CAD of RF, wireless and microwave circuits and systems. Our breakthroughs on EM optimization have opened up important avenues that will provide industry with extremely powerful new CAD tools. A highlight of our contributions is the acquisition in 1997 by HP-EEsof of OSA (Bandler, President, Biernacki, Vice President Research and Development).

**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.

Research Engineers: Dr. S.H. Chen significantly contributed to all aspects of the project as evidenced by many publications; Dr. Y.F. Huang contributed to microwave design applications [15,19,37,41,42,44].
Postdoctoral Fellows: Dr. Q. Wang and Dr. D. Omeragic substantially contributed to the parts of the project on EM theory and applications. Dr. Omeragic [18,21,43,46,53] became an NSERC Industrial Fellow working with OSA. Dr. Wang [40,47,50] joined Com Dev.
Ph.D. Students: P.A. Grobelny (OGS Scholar) [58] contributed significantly to software architecture. He is now with Newbridge Networks. Visiting student M. Dionigi from the University of Perugia [10] worked on mode-matching applications. M. Heaba Bakr (TRIO intern) contributes to space mapping. J. Sanchez started in 1997.
M.Eng. Students: R. Hemmers (NSERC Scholar) [59], now pursuing a Ph.D. at McMaster, contributed to EM optimization. I. Awad, P. Donahue, N. Lin [60], L. Wei, Y. Wei, C. Ying and X. Zhou also participated at various levels.
Summer Students. C. French contributed to reshaping our programming tools. S. Visram and R. Gangji 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 École Polytechnique. We take advantage of our software graphics and user-friendly features to attract students. New CAD research has been incorporated into graduate programs, and into our undergraduate curriculum, particularly into novel CAE laboratories.

**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, contracts and workshops [80], 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 recent releases of OSA's products (OSA90/hope, Empipe and Empipe3D). They provide an excellent vehicle for transfer to the user sector.

Canadian interactions include ABB (Ontario), Bell-Northern Research, ComDev, the Communications Research Centre, Gennum, Harris Farinon, MPB Technologies, Nanowave Technologies, Nortel, OptEM Engineering, Optotek, Quantic Laboratories, SFG Microwave, SPAR Aerospace and UniCAD. International interactions have included Andrew Antenna, Ansoft, Alcatel, AT&T, Daimler Benz, General Electric, GEC-Marconi Research, Hittite, HP-EEsof, Hughes, IBM, IMST, JPL, Loral, M/A-COM, Philips, Plessey, Raytheon, Rockwell, Siemens, Sonnet, Texas Instruments, Thorn-EMI, TriQuint, TRW, Watkins-Johnson and Westinghouse. In addition, during 1995-97 we have delivered talks at Aerospace Corp., Alcatel, Alenia Spazio, Ansoft Corp., AT&T Labs, BNR, CMC, ComDev, CRC,

HP-EEsof, Hughes (several), GEC-Marconi, IBM Watson Research Center, MAFET, Micronet, Mitre Corp., Motorola (AZ and IL), Northrop, NRAO, Qualcomm, Raytheon, Siemens, Space Systems Loral and Texas Instruments.

Scientific Interactions We chaired sessions: on Nonlinear Devices and Circuits, IEEE MTT-S Int. Microwave Symp., Orlando, FL, 1995, on CAD and Modelling of Nonlinear Circuits, 25th European Microwave Conf., Italy, 1995, on Advanced CAD Methodologies, IEEE MTT-S Int. Microwave Symp., Denver, CO, 1997, on Device Modelling, European GaAs Symp., Italy, 1997 and on Simulation at MW+RF, England, 1995 and 1996 [63-65,84,85]; lectured at international workshops, meetings and short courses [66-68,71,72,74,79-82,83,87-89], including the one-day mini workshop "Automated direct optimization-driven electromagnetic design of high-frequency and high-speed circuits," held by the Simulation Optimization Systems Research Laboratory, McMaster University, Hamilton in 1997 (speakers were Bandler, Biernacki and Dr. S.H. Chen) [80].

Bandler has served on Technical Program Committees of the IEEE MTT-S Int. Microwave Symposia (Orlando, 1995, San Francisco, 1996, Denver 1997 and Baltimore 1998), and MW+RF, London, England, 1995 and 1996 [69,70] and is on the Organizing Committee, 8th Biennial IEEE Conf. on EM Field Computation, 1998. Biernacki has served on the Technical Program Committee of IEEE MTT-S Int. Microwave Symposia [86]. We delivered talks during 1995 to 1997 at U. of Bologna; U. of Leeds; U. of Kent; Carleton U.; TU Delft; U. of Duisburg; McMaster U.; UWO; IEEE, Toronto Section; U of T Micronet; IEEE MTT/AP, NJ Chapter; CNAM/ESCPI; UC, Dublin; Queen's Belfast; UMIST; York U.; King's College London; IEEE MTT/AP, PA/NJ Chapters; IEEE AP-S Chapter, LA.

In Canada we continue interacting with ComDev, CRC, Gennum, OptEM, Quantic, Dr. Hoefer (Univ. of Victoria), Drs. Zhang and Nakhla (Carleton) [24,31,39], Drs. Conn and Litva (McMaster's CRL), Dr. Ghannouchi (École Polytechnique), as well as with Micronet, TRIO and CITO. We have visited ComDev, CRC, Gennum, Harris Farinon, MPB Technologies, SPAR and UniCAD. Drs. Zhang and Nakhla (Carleton) have made breakthroughs in VLSI interconnect yield optimization through our innovations [24,31,39]. International interactions include Dr. Adalbert Beyer (Duisburg). We continue our fruitful collaboration with Dr. Kaj Madsen (Denmark) [4,9,22,25,30,33,56,57], including visits. We have collaborated with Dr. F. Arndt (Bremen) using his waveguide library [18,21,43,46,53], Drs. M. Dionigi, M. Mongiardo, R. Sorrentino [10] (Perugia), W.J. Getsinger (consultant) and S.H. Talisa (Westinghouse) [7,26], D.G. Swanson (Watkins-Johnson) [2] and L.W. Hendrick (Hughes) [18,43].

**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 [66]. 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.

The technology we have developed will have an impact on increased design automation in the electronics manufacturing industries. Availability of a 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. ComDev (as always, ahead if its competitors) realized the potential of the space mapping concept: Drs. R. Mansour and S. Ye of adapted it to ComDev's design process.

Viability and competitiveness of the high tech Canadian industry in the global market is the most important benefit. Our results have found their way into both software and hardware production in Canada, all substantially export-directed. Our goal is to create CAD methodology for first-pass success in circuit design to reduce the design cycle and related cost. Our close link with Optimization Systems Associates Inc. enhanced our posture.

**PUBLICATIONS**

Our research resulted in 25 refereed or invited papers already published or accepted for publication in the most reputable journals and conferences [1-25]. The work has been documented in 32 internal reports [26-57] and

constituted substantial parts of 3 graduate theses [58-60]. Many other forums for dissemination of our technology were available, including the ones listed here [61-89].

Refereed Journal Papers and Conference Contributions


[1] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Integrated harmonic balance and electromagnetic optimization with Geometry Capture," *IEEE MTT-S Int. Microwave Symp. Digest* (Orlando, FL, 1995), pp. 793-796.

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[14] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Parameterization of arbitrary geometrical structures for automated electromagnetic optimization," *IEEE MTT-S Int. Microwave Symp. Digest* (San Francisco, CA, 1996), pp. 1059-1062.

[15] J.W. Bandler, R.M. Biernacki, S.H. Chen and Y.F. Huang, "Aggressive space mapping with decomposition: a new design methodology," *MR96 Microwaves and RF Conf.* (London, UK, 1996), pp. 149-154.

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