NEXT GENERATION OPTIMIZATION METHODOLOGIES FOR WIRELESS AND MICROWAVE CIRCUIT DESIGN

NSERC Strategic Grant No. STP0201832 FINAL REPORT

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Budget	Amount Awarded by NSERC	NSERC Expend. to Date	Total Cash by Partners	Total In-Kind by Partners
Year 1	$97,343	$97,343	$40,000	$149,800
Year 2	$105,100	$105,100	$5,000	$154,900
Year 3	$107,400	$107,400	$5,000	$154,900

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OBJECTIVES

Long-Term Objectives to create a reliable, efficient, cost-effective and robust CAE environment for specification driven top-down design of microwave and wireless circuits and one-pass design-build-test cycle. To this end we aspire to fully automating the entire design process, which requires dynamic integration of the various essential components. EM, thermal and mechanical models, physical simulation of active devices, circuit simulators, design optimization and analog diagnosis are to be smoothly united in a manner never before attempted in an automated fashion.

Short-Term Objectives to significantly advance the state-of-the art in automated EM design, through fully integrated tools, new design methodologies and corresponding algorithms.

Note The original proposal was designed by J.W. Bandler in collaboration with R.M. Biernacki. Dr. Biernacki left Canada to join Hewlett-Packard in California in late 1997. He was replaced by Q.J. Zhang in early 1998.

ACHIEVEMENT OF THE OBJECTIVES OF THE PROJECT

Highlights The novel Space Mapping Super Model concept has been expanded into the Generalized Space Mapping (GSM) Tableau approach [29], [43], [44], [49]. New Aggressive Space Mapping (ASM) algorithms enhanced by trust region methodology have been developed and implemented [3], [9], [12], [19], [26], [31], [38], [43], [48], [51], [59], [60], [66], [74], [75]. Hierarchical physical/geometrical macromodel structures based on Neural Network modeling technology have been successfully demonstrated [5], [10], [11], [17], [22], [30], [63]. Huber optimization effectively trains models from data subject to both large and small measurement errors [17], [18], [22]. Agilent ADS compatible physical macromodeling techniques and a prototype library of microstrip and stripline components have been developed [11], [22], [53]. Our original Space Mapping (SM) technology has been generalized and unified with knowledge based Artificial Neural Network (ANN) modeling (KBNN) [18], [25], [28], [33], [35], [37], [44], [47], [62], including K.C. Gupta's pre-existing EM ANN and Prior Knowledge Input (PKI) techniques. This provides attractive and physically intuitive choices to the user in extending empirical/equivalent circuit models far beyond original frequency and parameter limits with full-wave EM simulator accuracy.

Robust, Efficient *S*-Parameter Based EM Design An advantage of SM optimization algorithms is that they are knowledge-based [1], [5], [15], i.e., they exploit "coarse", empirical or "surrogate" models capable of fast physical representation of devices under consideration. We have developed a robust Aggressive Parameter Extraction (APE) algorithm for multi-point parameter extraction to address uniqueness of extracted models [20], [32]. We have created the robust Hybrid Aggressive Space Mapping (HASM) algorithm to handle severely misaligned models and improve robustness [19], [31]. HASM switches between SM optimization and direct optimization, defaulting to direct optimization if ASM fails. A novel lemma relates the response sensitivities between the two models [21]. It leads to a novel technique for SM based modeling of microwave and RF circuits. HASM is a major step towards full automation of the SM design process. The synthesis of coarse models is itself an important process [82], [83], [84], [85], [87], [92], [93], [94], [95]: coarse model construction is often straightforward, since there is an abundance of empirical and analytical approximations to discontinuities and structures in microwave and antenna theory and practice.

The most recent development in SM optimization is the Surrogate Model-based Space Mapping (SMSM) algorithm. SMSM formulates the design procedure as a general optimization problem of a surrogate model [38], [43], [48]. The surrogate is a convex combination of a mapped coarse model and a linearized fine model. The step taken in each iteration is confined to a region in which the surrogate model is trusted. SMSM utilizes a frequency sensitive mapping that allows it to overcome significant response shifts. We have thus strongly progressed towards the creation of an automated Space Mapping Optimization Engine. Our research version is called SMX [101], [104]. Its implementation is far from trivial. The SMX system currently features the SMSM algorithm. A user friendly interface allows the user to set the coarse and fine models, the simulation frequencies, etc. SMX utilizes the multi-thread capability of Windows operating system. The program interacts with the user during the optimization steps showing the improvement in the objective function.

Concurrent Optimization with Multiple EM Simulators and Active Devices Five powerful SM based neuromodeling techniques have been developed [62], [18], [25], [28], [89], [90], [91]: Space Mapped Neuromodeling (SMN), Frequency-Dependent Space Mapped Neuromodeling (FDSMN), Frequency Space Mapped Neuromodeling (FSMN), Frequency Mapped Neuromodeling (FMN) and Frequency Partial-Space Mapped Neuromodeling (FPSMN). They exploit the vast set of empirical models already available, decrease the number of fine model evaluations needed for training, improve generalization ability and reduce the complexity of the ANN topology w.r.t. the classical neuromodeling approach. Frequency-sensitive neuromappings expand available quasi-static empirical models. FMN effectively aligns frequency-shifted responses. Partial mappings for the physical parameters make more efficient use of the implicit knowledge in the coarse model. As an original alternative to the classical backpropagation algorithm, Huber optimization has been employed to efficiently train neuromappings, exploiting its robust characteristics for data fitting [17], [18], [22]. SM based neuromodels of some microstrip passive components have been verified and implemented within *NeuroModeler* Version 1.2b (1999); they can be entered into Agilent ADS (1999) as library components through an ADS plugin module. A new concept called Generalized Space Mapping (GSM) enhances existing empirical models of microwave devices and significantly extends validity regions [29], [43], [44], [49]. GSM exploits few relevant full-wave EM simulations to build a mapping from the fine model parameters and frequency to the coarse model parameters and frequency, thus aligning the two models. Its simplicity makes GSM an attractive CAD tool. A novel criterion can discriminate between different coarse models of the same device.

A powerful new optimization method exploits SM-based neuromodeling in an efficient Neural Space Mapping (NSM) algorithm, including frequency mapping [37], [45], [47]. A coarse model is used not only as source of knowledge that reduces the amount of learning data and improves the generalization performance, but also as a means to select the initial learning base points through sensitivity analysis. A novel procedure does not require parameter extraction to predict the next point. The SM-based neuromodels are developed without using testing points: their generalization performance is controlled by gradually increasing their complexity starting with a 3-layer perceptron with 0 hidden neurons. NSM optimization was applied to several practical microstrip circuits using Sonnet's ***em*** simulator.

A new algorithm for EM-based design of microwave circuits was developed: Neural Inverse Space Mapping (NISM) optimization [102]. This is the first SM algorithm that explicitly makes use of the inverse of the mapping from the fine to the coarse model parameter spaces. NISM follows an aggressive formulation by not requiring a number of up-front fine model evaluations to start building the mapping. An innovative yet simple procedure for parameter extraction avoids the need of multipoint matching and frequency mappings. A neural network whose generalization performance is controlled through a network growing strategy approximates the inverse of the mapping at each iteration. NISM step simply evaluates the current neural network at the optimal coarse solution. This step is equivalent to a quasi-Newton step while the inverse mapping remains essentially linear.

We expanded the original SM technique [103] by allowing preassigned parameters (not used in optimization) to change in some components of the coarse model. We refer to those components as "relevant" components and we present a method based on sensitivity analysis to identify them. As a result, the coarse model can be calibrated to align with the fine model. We developed an algorithm that establishes a mapping from some of the optimizable parameters to the preassigned parameters of the relevant components. This mapping is updated iteratively until we reach the optimal solution.

<u>Electromagnetic (EM) Design and Modeling Benchmark Problems</u> In consultation with industry we selected microwave or RF structures, both planar and 3D, to be used in this project to test new theories and corresponding algorithms: (1) a six-section H-plane waveguide passband filter [92], (2) a microstrip double-folded stub (DFS) stopband filter [93] (*Sonnet*), (3) a waveguide bandpasss waffle-iron filter *(ComDev)*, (4) microstrip and stripline models for signal integrity modeling *(Nortel Networks)*, (5) microstrip via and laser diode neural models *(Nortel Networks)*, (6) a low-radiation balanced microstrip passband filter [87], [94] (*Nortel Networks*), (7) a microstrip-fed rectangular patch antenna [95], (8) a three-section rounded edge waveguide transformer (*Hughes*), (9) H-plane waveguide filters *(Hughes)*, (10) a high-temperature superconducting (HTS) four pole quarter-wave parallel coupled-line microstrip filter (*Westinghouse*), (11) standard waveguide transformers, (12) various microstrip bends and T-junctions (*M/A COM*), (13) a library of microstrip and stripline models, (14) coplanar waveguide (CPW) components [36], [50], and (15) a library of FET models. We research coarse models (fast empirical or equivalent-circuit models) of waveguide filters and impedance transformers, microstrip filters and transformers, T-junctions [16], [82], [83], [84], bends, microstrip antennas [95], [98], [99], etc. We construct coarse models sometimes by simply utilising a full-wave EM simulation on a very coarse space-time discretization grid, and sometimes through circuit decomposition.

<u>Advances in Device Modeling Technology Exploiting Artificial Neural Networks</u> Our systematic work on neural networks gained international recognition [22], [34], [53]. Neural networks are fast and flexible alternatives in microwave modeling and design. Continued work in the area has led to new developments in training algorithms, modeling structures and applications. To address certain key challenges in developing RF/microwave neural models, a set of automatic training algorithms have been developed [17], [27], [41], [46]. An iterative multi-stage (IMS) approach including a macro-level process and a stage-level process is proposed. At the macro-level, the IMS decomposes the complicated original task into several simpler sub-tasks or stages; and at the stage-level, the IMS utilizes a variety of neural network structures and effective training techniques,

including several existing techniques and a new Huber quasi-Newton (HQN) technique. The proposed HQN allows the IMS approach to model only smooth portion of the problem behavior in one of the training stages, ignoring sharp/sudden variations. A neural network training-driven adaptive sampling algorithm is developed for efficient generation of training and test data for neural based microwave modeling. The approach makes microwave data generation an integral part of model development/training. For user-specified model accuracy, the algorithm periodically communicates with the neural network training process and automatically determines the number of samples required and their distribution in the model input space. The work is applied to transmission line and FET modeling, improving model training efficiency over standard training approaches.

For the first time, a discrete recurrent neural networks (RNN) is trained to learn the dynamic responses of nonlinear microwave circuits [39]. The training data are large-signal waveforms of the circuit inputs and outputs. A quasi-Newton training algorithm with gradient information based on backpropagation through time is developed. Once being trained, the RNN macromodel retains the full analog behavior of the original nonlinear microwave circuits, and can be used as fast and accurate representation of the circuit for high level simulation and optimization. It has been applied to the modeling of FET devices, and power amplifier and mixer circuits.

<u>Interfaces to Various CAD Simulators</u> The incorporation of *NeuroADS* into *NeuroModeler* follows our tradition of easy interoperability between disjoint software packages. *NeuroADS* allows seamless and unified integration of KBNN and SM device modeling with Agilent ADS, allowing users the freedom to use a resulting model as easily as a circuit library component. Our ongoing research is aimed at easy integration of today's popular software with Space Mapping and other optimization techniques. We successfully investigated engineering user-friendly interfaces that allow Agilent EDA products to be driven externally, allowing for automated Space Mapping, Neural Network training and other tasks. (Our capability of handling any specific syntax of a given simulator has been previously demonstrated using ***em***, HFSS and SPICE).

Our research has progressed beyond original expectations [51]. Key steps have been typically carried out manually or by MATLAB: the ASM process needs to be friendly and automated. To this end we created the world's first Space Mapping Optimization engine. Called SMX [101], [104], it is an object oriented research system written in C and C++. It can be linked with OSA90 and Agilent Momentum. We initiated with Dr. K. Madsen's group (TU Lyngy, Denmark) a comprehensive theoretical investigation of optimality conditions and convergence properties of ASM optimization [26] from a mathematical point of view. We are also collaborating in developing and testing CAD tools.

<u>Software Development Milestones</u> We took advantage of open architecture software systems OSA90/hope and Empipe provided by Optimization Systems Associates Inc. (now part of Agilent Eesof EDA). Agilent generously provided HFSS, Empipe3D, ADS (with Momentum), Series IV and IC-CAP, while Sonnet Software, Inc. provided ***em***. Software development proceeded according to 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 specially organized workshops at McMaster University directed at the Canadian user sector.

<u>The Contribution of Each Co-Investigator</u> Close interaction between Bandler (the applicant) and Zhang (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. Natalia Georgieva, research engineers, postdoctoral fellows and graduate students supervised by the co-investigators.

<u>Scientific and Engineering Significance of the Results</u> Strong evidence of the significance of our contributions exists. Two Special Issues of the *Int. J. RF and Microwave CAE on Applications of Artificial Neural Networks to RF and Microwave Design* (Q.J. Zhang and G. Creech, Co-Eds. [23], Q.J. Zhang, M. Mongiardo and R. Perfetti, Co-Eds. [52]) afford significant exposure. Q.J. Zhang, panelist, spoke on "A neural network paradigm

for high-frequency component modeling, simulation and optimization" [70]. The significance of the area and our contribution to it is evidenced by our organization and contributions to many international workshops, in particular *The First International Workshop on Surrogate Modelling and Space Mapping for Engineering Optimization* (Bandler and Madsen, Co-organizers), Lyngby, Denmark, November 2000. There large number of delegates at this successful workshop covered many disciplines, including optimization and several branches of engineering.

We delivered invited presentations in 1998 at CRC (Ottawa), Nortel (Ottawa), Univ. of Victoria, Spar Aerospace, Com Dev, Univ. of Limoges, Dalhousie Univ. and HP EEsof (Santa Rosa, CA); in 1999 at Com Dev, Univ. of Waterloo, Carleton Univ., Washington Univ. (St. Louis), CRC, EMS Technologies, Univ. of Manitoba and the Technical Univ. of Denmark; in 2000 at Imperial College London, BAE Systems (UK), Univ. of Cyprus, ETH Zurich, Univ. of Paris VI, Helsinki Univ. of Technology, Motorola (Phoenix), Siemens (Germany), Nokia (UK). Q.J. Zhang was the only non-US invited contributor to the private Motorola Symp. on Simulation and Modeling, Ft. Lauderdale, 1999 [65].

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. Our work is highly regarded by other researchers (see invited papers [15], [25], [34], [35], [40], [42], [43], [63], [65], [75]) 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. Our work on this project has resulted in more than 50 refereed papers already published or accepted for publication in reputable journals and conference proceedings, and several papers submitted for 2001.

International workshop contributions include: Research Directions in Microwave CAD (J.W. Bandler, panel member, IEEE MTT-S IMS, Baltimore, 1998); CAD for Manufacturability (J.W. Bandler and M. Mongiardo, Co-organizers and Co-chairs, J.W. Bandler, lecturer, IEEE MTT-S IMS, Baltimore, 1998); Microwave Filters and Multiplexers: Theory, Practice and CAD (J.W. Bandler, invited speaker, 28th European Microwave Conf., Amsterdam, 1998) [61]; Novel Methodologies for Device Modeling and Circuit CAD, (J.W. Bandler and Q.J. Zhang, Co-organizers and Co-chairs, J.W. Bandler, lecturer, Q.J. Zhang, lecturer [63], IEEE MTT-S IMS, Anaheim, CA, 1999), Advances in Mixed Electromagnetic Field and Circuit Simulation, (J.W. Bandler, invited speaker, IEEE MTT-S IMS, Anaheim, CA, 1999); CITO/MMO Workshop on Modelling and Simulation for Electronic Systems (J.E. Rayas-Sánchez, speaker [68], Mississauga, ON, 1999), Automated Circuit Optimization Using Electromagnetic Simulators, (J.W. Bandler and D.G. Swanson, Jr., Co-organizers and co-chairs, J.W. Bandler, lecturer [74], Q.J. Zhang [73], lecturer, IEEE MTT-S IMS, Boston, 2000), Application of ANNs to RF and Microwave Design, (K.C. Gupta and Q.J. Zhang, Co-organizers and Co-chairs, Q.J. Zhang, lecturer [72], IEEE MTT-S IMS, Boston, MA, 2000), 1st Int. Workshop on Surrogate Modeling and Space Mapping for Engineering Optimization, (J.W. Bandler and K. Madsen, co-organizers, J.W. Bandler, keynote speaker [43], Q.J. Zhang, keynote speaker [42], Lyngby, Denmark, 2000), CITO Research Review Meeting (Q.J. Zhang, presenter, Ottawa, 2000), Micronet Annual Workshops (J.W Bandler and Q.J. Zhang, presenters, Ottawa, 1998, 1999 and 2000). Several international workshops are already planned for 2001.

J.W. Bandler was Technical Program Committee Member and Session Chair, IEEE MTT-S IMS, 1998, 1999 and 2000; Technical Program Committee Member, IEEE MTT-S Int. Topical Symp. on Technologies for Wireless Applications, Vancouver, 1999; Organizing Committee Member, 8th Biennial IEEE Conf. on EM Field Computation, 1998; and Co-Chair, IEEE MTT-S Technical Committee MTT-1 on CAD. J.W. Bandler became Associate Editor of the new journal Optimization and Engineering, Kluwer Academic Publishers. He is currently a Member, Applied Science and Engineering Division Fellowship Review Committee, Royal Society of Canada (1998, 1999, 2000). J.W. Bandler was Ph.D. Examiner, University of Paris VI, France, Oct. 9, 2000. In 2000 J.W. Bandler became Thrust Leader for "Optimization and Computer-aided Design" on McMaster's successful Canada Foundation for Innovation Infrastructure Project "Communication Technology Research Centre" headed by Dr. Max Wong. Including matching funds the amount awarded is $6.6M. Finally, J.W. Bandler is active within Bandler Corporation (J.W. Bandler, President).

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 Mr. S. Porter contributed to various software aspects of the project. He left to co-found the high-tech start-up Distributed Science Inc. with international collaboration and funding and located in Hamilton.
Postdoctoral Fellows Five postdoctoral fellows included Dr. M.H. Bakr, Dr. N. Georgieva (NSERC Postdoctoral Fellow), Dr. F. Guo, Dr. M. Yagoub, Dr. Fang Wang (Ph.D. student who won the Senator Medal from Carleton University [54]) and Dr. S. Wang. Dr. Georgieva, Dr. Guo and Dr. Bakr substantially contributed to the parts of the project on EM theory and applications. Dr. M.H. Bakr became an NSERC Postdoctoral Fellow and is now working at the University of Victoria under Dr. W.J.R. Hoefer on electromagnetics. Dr. Guo [97], [98], [99] joined Mitec in Montreal. Dr. Fang Wang is now with IBM, West Palm Beach, FL. Dr. S. Wang is now with PMC-Sierra, Ottawa. Dr. Georgieva progressed to become a faculty member at McMaster University and is a recipient of an NSERC University Faculty Award.
Ph.D. Students Five Ph.D. students included M.H. Bakr [58] (TRIO intern, OGS Scholar), V. Devabhaktuni (OGS Scholar), M.A. Ismail, J.E. Rayas-Sánchez (funded by the Mexican Government and OGS Scholar) and J.J. Xu. M.H. Bakr contributed significantly to theory and software design and is now NSERC Posdoctorate Fellow. J.E. Rayas-Sánchez was instrumental in development of joint neural network modeling methodology.
M.Eng. Students M.Eng. students included Y. Cao, B. Chattaraj, T. Chen [57], Qingsha Cheng, X.L. Ding (Nortel Scholarship), Y. Fang, H. Feytzbakh [56], L. Lin, C. Xi [55]and X. Xu. P. Donahue joined Com Dev. C. Xi is now with Infocam, Montreal. H. Feytzbakh and Lei Lin are now with Nortel, Ottawa. T. Chen is now with Motorola in Chicago.
Visiting Personnel Dr. T. Gunel (Visiting Professor, Istanbul Technical University) worked with us on CAD of microwave and antenna structures. Visiting scholar J. Søndergaard from the Technical University of Denmark assisted with the development of theory and algorithms for space mapping.

Many other Canadian students and researchers utilize our developments for their courses and as a vehicle in graduate level research, not only at McMaster University but also at Victoria and Carleton. New CAD research has been incorporated into graduate and undergraduate programs, particularly into novel CAE laboratories. Several new graduate students joined us in 2000. We take advantage of our comprehensive commercial software and the very successful *NeuroModeler* to attract students.

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, 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. We welcomed Canadian exploitation and collaboration. We brought together the expertise and resources of both Carleton and McMaster. Co-investigator Q.J. Zhang's *NeuroModeler* provides an excellent vehicle for transfer to the user sector: it is used by Com Dev and Nortel Networks. It was featured in 1998, 1999 and 2000 in the Carleton Univ. booths at the IEEE MTT-S IMS and Exhibition. We held a full day workshop on "Next generation optimization methodologies for wireless and microwave circuit design" at McMaster Univ., June 28, 1999, attended by 40 people coast to coast (guest speakers: P. Leach (CITO), R.

Biernacki, and D. Swanson).

Changes and Deviations An unprecedented number of changes has occurred: CRC has reorganized: Michel Cuhaci and Malcolm Stubbs have taken over from Rene Douville as contacts; Nanowave Technologies is now part of Remec (US owned); the Spar Aerospace group is now part of EMS Technologies (US owned); Harris has reorganized: Philip Mambo is now with Advanced Microwave Technologies, Inc.; Ying Shen has left Canada; Nortel has reorganized: Dr. John Sitch and Chris Falt are now part of the Microelectronics Group; former coinvestigator Radek Biernacki is now at Agilent EEsof EDA (US); supporter Q.J. Zhang (Carleton Univ.) became officially coinvestigator.

Industrial Interactions We maintained close co-operation with each other through many mutual visits, meetings and regular phone and email contacts, leading to joint publications of research results. Q.J. Zhang continues close collaboration with Nortel through meetings and presentations with R. Sheffield, J. Williamson, D. Goulett, G. Wilson, D. Montuno and J. Aweya. Several conference papers jointly with Nortel have been presented in international conferences [6], [7], [8]. We visited C. Falt of Nortel, delivered a seminar, and discussed high-frequency modeling and optimization tasks. C. Falt visited McMaster, and delivered a seminar on Nortel's efforts in device modeling and EM optimization. Collaboration focussed on high-frequency modeling and EM optimization [87], [94].

With several graduate students we made several visits and presentations to Com Dev (R. Mansour, S. Peik, S. Ye and Ke-Li Wu) in 1998 and 1999. Interaction continued with Com Dev in 2000 through C. Kudisa and Ming Yu. We visited CRC (M. Cuhaci, M. Stubbs, V. Szwarc, K. Verver and A. Laneve) in 1998 and 1999, presenting joint seminars. M. Cuhaci gave a seminar at McMaster in 1999 on CRC's work. We visited G. Moss, V. Keresteciyan and B. Stoute (EMS, Montreal) in 1998 and 1999, giving seminars. Technical interactions are maintained. We visited Harris Farinon, and discussed passive and active device modeling and optimization.

There have been many other visits or exchanges including Gennum (David Lynch, Denis Salvador, Jim Kendall), Remec Nanowave (Hien Do Ky, Dr. Ali Rahal), Harris (Fabio Concilio), Nortel (John Sitch, Chris Falt, R. Sheffield, D. Goulette), Quantic (Al Wexler), CRC (Malcolm Stubbs, Michel Cuhaci, Valek Szwarc), Carleton Univ. (Michel Nakhla), Univ. of Manitoba (Lot Shafai), Univ. of Victoria (Wolfgang Hoefer). In addition, we have had visits and presentations from CRC (Michel Cuhaci and Neil Simons), CITO (Peter Leach), Com Dev (Ming Yu, Raafat Mansour), Nortel (Chris Falt), M/A COM (Dan Swanson), Sonnet Software (Jim Rautio), Agilent EEsof EDA (Radek Biernacki[2], [3], [9], [12], [13], [14], [77], [80]), Wolfgang Hoefer (Univ. of Victoria), M. Nakhla (Carleton Univ), Kaj Madsen and Jacob Søndergaard (TU Denmark). J.W. Bandler visited Ansoft Corporation and Sonnet Software, Inc. in 2000.

Scientific Interactions Contact has been made with Dr. Raafat Mansour and Dr. S. Safavi-Naeini (Univ. of Waterloo) and with Dr. David Kennedy (Optotek, Ottawa). We held a meeting with Dr. Megid Saad (Scientific Microwave Corp., Montreal). Q.J. Zhang explored European links with Dr. Rolf Jansen (Aachen, Germany). He developed collaboration with Dr. K.C. Gupta (Univ. of Colorado) [53], [67], [72]. J.W. Bandler explored European links (P.E. Frandsen, Denmark) with the "PUNQ" project funded by the European Commission. Dr. Kaj Madsen with Ph.D. student Jacob Søndergaard (TU Lyngby, Denmark) continues to actively collaborate on Space Mapping optimization. We have had visits and presentations from both. Possible collaborations with Dr. V. Rizzoli's group (Bologna, Italy) were explored. Collaboration with Dan Swanson (M/A-COM, now with Bartley RF Systems) [16], [84] and Chris Falt (Nortel Networks) [87], [94] has been active. In 1999 we embarked on various collaborative projects with N. Georgieva at McMaster University.

Q.J. Zhang visited Dr. Z. Chen of Dalhousie Univ. (Halifax) and the Univ. of Limoges (France) in 1998, and delivered seminars on neural based modeling for microwave design. In Canada we continue interacting on EM simulation and optimization with Com Dev, CRC, Gennum, Nortel, OptEM, Quantic, Dr. Hoefer and Poman So (Univ. of Victoria), Dr. Nakhla (Carleton), Dr. Shafai (Univ. of Manitoba), as well as with Micronet and CITO. We visited Com Dev, CRC, Gennum, Harris Farinon, Remec Nanowave, Nortel Networks, Spar (EMS Technologies) and Scientific Microwave Corporation.

BENEFITS TO CANADA AND THE NON-ACADEMIC PARTICIPATING ORGANIZATIONS

Our results are finding 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. In a number of important niche areas, our algorithms far exceed those offered in prevailing US products. Furthermore, this project helps us maintain our internationally recognized position in CAD. Viability and competitiveness of the high tech Canadian industry in the global market is the most important benefit. Developments in wireless telecommunications pushes frequencies to higher and higher bands. Advanced research is already under way for developing hardware for wireless telecommunication services at frequencies as high as 20-30 GHz. Here, novel types of transmission lines are used, such as multilayer printed coplanar and slot lines. These require the development of a whole new generation of passive and active devices, such as coplanar/slot junctions, bends, power dividers, couplers, radiating elements, etc. The development of sufficiently accurate models for reliable analysis and design is of great importance to the telecommunication industry in the years ahead. Our work opens up new opportunities for significant advances. It addresses the long term goal of a fully integrated CAD system, enabling virtual prototyping and concurrent design. Advances in wireless technologies are placing demands on the CAD environment and simulation tools to handle increased circuit miniaturization and complexity. Further innovative designs may be achieved using powerful 3D full-wave EM simulators in conjunction with sophisticated optimizers. This requires robustizing and expanding the SM technology and seamless integration of a variety of EM simulators with optimization software.

PUBLICATIONS

Our research resulted in 52 refereed or invited publications already published or accepted for publication in the most reputable journals and conferences [1-52] and one book [53]. The work has been documented in over 100 internal reports and constituted substantial parts of 5 graduate theses [54-58]. Many other forums for dissemination of our technology were available, including the ones listed here [59-75].

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

[1] F. Wang and Q.J. Zhang, "Knowledge based neural models for microwave design," <u>IEEE Trans. Microwave Theory Tech.</u>, vol. 45, 1997, pp. 2333-2343.

[2] Q.J. Zhang, F. Wang, M.S. Nakhla, J.W. Bandler and R.M. Biernacki, "Signal integrity optimization of highspeed VLSI packages and interconnects," <u>Proc. 48th ECTC Electronic Components and Technology Conf.</u> (Seattle, WA, 1998), pp. 1073-1076.

[3] M.H. Bakr, J.W. Bandler, R.M. Biernacki, S.H. Chen and K. Madsen, "A trust region aggressive space mapping algorithm for EM optimization," <u>IEEE MTT-S IMS Dig.</u> (Baltimore, MD, 1998), pp. 1759-1762.

[4] F. Wang, V. Devabhaktuni and Q.J. Zhang, "A hierarchical neural network approach to the development of library of neural models for microwave design," <u>IEEE MTT-S IMS Dig.</u> (Baltimore, MD, 1998), pp. 1767-1770.

[5] F. Wang and Q.J. Zhang, "Incorporating combined functional/structural knowledge in library of neural models," <u>Proc. IEEE Int. Conf. Neural Networks</u> (Anchorage, AK, 1998), pp. 363-366.

[6] J. Aweya, Q.J. Zhang and D. Montuno, "A neural network based congestion control scheme based on fuzzy parameter adaptation for computer networks," <u>Proc. IEEE Int. Conf. Fuzzy Syst.</u> (Anchorage, AK, 1998).

[7] J. Aweya, Q.J. Zhang and D. Montuno, "A direct adaptive neural controller for flow control in computer

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