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iCORE Research Report: Volume 1

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Alberta Informatics Circle of Research Excellence

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ALBERTA INFORMATICS CIRCLE OF RESEARCH EXCELLENCE

iCORE Research Report

VOLUME 1
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Introduction

During its first two years, the Alberta Informatics Circle of Research Excellence (iCORE) has attracted and supported ten new Alberta research teams in information science and engineering – including disciplines in computing science, electrical and computer engineering, mathematics, physics and other areas related to information and communications technology. These ten iCORE chairs and professors have attracted over 95 new graduate students, 12 new postdoctoral fellows, four new faculty members, and over twenty-five million dollars in new research funds.

This research report, the first in a regular series, outlines the activities and achievements of these iCORE research teams, which have been established in collaboration with Alberta universities and companies. Section One of this report outlines the progress of research teams that have completed their first full year supported by iCORE. Section Two introduces the newest award recipients, their plans, projects and early outcomes. As the inaugural issue, this volume attempts to convey the exceptional energy and calibre of iCORE-supported research in informatics.

The research outcomes achieved have been significant. They include new industrial partnerships with local, national and international companies, with government research organizations and with university research groups. The latter includes universities in Canada and elsewhere in the world – Finland, Bulgaria, Australia, Ireland, Wales, Italy, Netherlands, France, New Zealand, and the United States.

Industry and government partnerships fostered by iCORE researchers include relationships with: AT&T Labs, Bitonic, BioTools, BioWare, Brycol Consulting, Canadian Coast Guard, Canadian Space Agency, DALSA Inc., Department of National Defense, Electronic Arts, Ford Research Laboratories, Gennum Corp., Hitachi Ltd (Japan), Agency for Defense Development (South Korea), Hewlett Packard, IBM, LEICA Geosystems, Micralyne, National Institute of Standards and Technology, National Storage Industry Consortium, Network Photonics, Nokia Mobile Telephones, Nortel Networks, Philips Research Corporation, Raytheon Marine GmbH (Germany), *TR Labs* and the U.S. Navy.

With this emerging and ever-widening circle of research excellence – the university teams, expanding industry partnerships, and worldwide collaborations – Alberta is becoming known for stellar science and engineering. This research will almost certainly provide a significant boost to the information and communications technology (ICT) sector of Alberta's economy.

If you share the ambition of these exceptional research teams, we encourage your involvement in iCORE's activities to foster world-class research in information science and engineering. We also encourage your feedback and questions in response to this report.

Brian Unger
President, iCORE

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Section One: Annual Report Summaries

In its first year of operation, iCORE funded four iCORE Chairs and two iCORE Professors. This section presents summaries of their first annual research reports up to March 31, 2002, following one full year of iCORE funding. It includes reports from:

Dr Norman C. Beaulieu

WIRELESS COMMUNICATIONS LABORATORY

Electrical and Computer Engineering
University of Alberta

Dr Michael Brett and Dr Mark Freeman

NANOCORE: NANOSCALE ENGINEERING PHYSICS INITIATIVE

Electrical and Computer Engineering and Physics
University of Alberta

Dr Graham A. Jullien

ADVANCED TECHNOLOGY INFORMATION PROCESSING SYSTEMS LABORATORY

Electrical and Computer Engineering
University of Calgary

Dr Gérard Lachapelle

WIRELESS LOCATION RESEARCH

Geomatics Engineering
University of Calgary

Dr Jonathan Schaeffer

HIGH PERFORMANCE ARTIFICIAL INTELLIGENCE SYSTEMS

Computing Science
University of Alberta

DR NORMAN C. BEAULIEU

Wireless Communications Laboratory

iCORE CHAIR
ELECTRICAL AND COMPUTER ENGINEERING
UNIVERSITY OF ALBERTA

RESEARCH PROGRAM OVERVIEW

The overall research goal of this program is higher capacity in broadband wireless communication systems at lower cost. The primary thrust of this research is investigation into fundamental properties, limitations, and improvements in broadband wireless systems. Many researchers attack the problem through the use of error control coding. Although improvements in error control coding remain an important element in increasing the capacity of wireless systems, the research conducted under this iCORE Chair and Professor Establishment program is multifaceted and, taken overall, unique. In contrast to a focus only on the theory and technology of error control coding, it is believed that the sum of performance increases due to improvements in several wireless technologies will yield superior results at lower cost. Details of the four interrelated areas of research being investigated are outlined below.

RESEARCH PROJECTS

INTERFERENCE COMPENSATION IN WIRELESS NETWORKS

A fundamental limit to the capacity of *wireline* communication channels was established by Claude Shannon over 50 years ago. Recently, these results have been extended to the *wireless* channel. These new results are for a single user and predict quite reasonable capacity relative to the wireline results. However, wireline systems are single user systems whereas wireless systems are multi-

user systems. Hence, this reasonable channel capacity must be divided among many users, and consequently becomes unacceptably poor. However, with effective multi-user interference suppression, the single user capacity is restored. The two topics of the Theory of Quasi-Orthogonal Signalling and Wireless Receiver Designs for Interference Suppression and Cancellation are key to this work.

DIGITAL SIGNAL CLASSIFICATION

This is an important problem with extensive security and commercial applications,

message interception being an example of the former and digital repeaters for wireless and cable being an example of the latter. In the latter case, transmission overhead required for identifying signals is eliminated. Although some recent study has been devoted to this problem, signal classification is missing a fundamental underlying theory. It has many open problems, and offers enormous potential for industrially relevant new technologies. We are investigating two approaches to this problem: feature extraction and decision-theoretic design.

TRANSMITTER AND RECEIVER DIVERSITY FOR ENHANCED NETWORK CAPACITY

In order to achieve higher capacities on multi-user wireless channels approaching those of wireline channels, two major impairments must be controlled: interference and signal fading. The research detailed above on interference control aims to make a multi-user channel look more like a single user channel. The use of diversity techniques makes a fading channel look more like a channel without fading. We are carrying out comprehensive investigations into transmitter and combined transmitter/receiver diversity, and will integrate this approach with effective multi-user interference cancellation to obtain further capacity gains in broadband multi-service (voice, video, data) wireless network access.

WIRELESS CHANNEL STATE PREDICTION

It is well known that many wireless components and systems achieve enhanced performance by using channel state information. The potential of predicting future channel states and thereby greatly enhancing performance has recently been established by American researchers. Nonetheless, and not unusually, this early work

has a number of shortcomings, the most severe of which is a total reliance on the sum-of-sinusoids (SOS) wireless fading channel model. Work done by the Chair candidate and one of his students on SOS models of fading channels has discovered some heretofore unknown inaccuracies and limitations of the SOS models.

RESEARCH TEAM

FACULTY AND TEAM MEMBERS

- Dr Norman Beaulieu, Chair
- Dr Witold Krzymieñ, Professor, Department of Electrical and Computer Engineering
- Dr Ivan Fair, Associate Professor, Department of Electrical and Computer Engineering
- Dr Xiaodai Dong, Assistant Professor, Department of Electrical and Computer Engineering
- Dr M. O. Damen, Research Associate

Dr Witold Krzymieñ is a Professor in the Department of Electrical and Computer Engineering, University of Alberta, a principal investigator of the iCORE Wireless Laboratory at the University of Alberta, and an Adjunct Scientist with *TRLabs*. His current research activities are discussed in more detail below, with more emphasis given to those supported by and related to the iCORE Wireless Communications Laboratory.

Dr Krzymieñ's research activity presently includes the following principal topics.

- Single- and multi-carrier adaptive wireless transmission techniques for delay tolerant packet data services;

- Space-time processing and coding for future evolution of wireless Internet access;
- Multiple access interference (MAI) suppression;
- Long-term prediction of small-scale radio channel fading;
- Radio resource management to enable maximum advantage from adaptive transmission techniques and multi-user diversity.

Dr Ivan Fair is an Associate Professor in the Department of Electrical and Computer Engineering at the University of Alberta, where his research interests are focused on channel coding techniques for a variety of communication systems. He is also an Adjunct

Scientist with *TRLabs*. The two major research activities lead by Dr Fair that are currently being supported by the Wireless Communications Laboratory include:

- efficient implementation of iterative decoding techniques for turbo codes;
- development of codes for multiple-input multiple-output wireless systems.

Dr Xiaodai Dong is a recently appointed Assistant Professor in the Department of Electrical and Computer Engineering and a faculty iCORE Research Associate. The research focus of Dr Dong is on communication theory and its applications to wireless, optical and satellite communications systems.

PHD CANDIDATES

Kevin Altman: Symbol Synchronization in Small Signal-to-Interference Ratio Environments

Kareem Emile Baddour: Long Range Fading Channel State Prediction

Julian Cheng: Exact Performance Analysis of DS-CDMA

Ethan Davis: Signal Classification and Modulation Identification

Bo Hu: Novel Nonlinear Micro-Diversity Combining

Ge Li: Low Density Parity Check (LDPC) Codes for MIMO Wireless Systems

Pavel Loskot: Cochannel Interference Statistics of Angle Modulations

David Mazzaresse: Space-Time Turbo Coding for Wireless Packet Data Access with Hybrid ARQ and Adaptive Modulation/Coding

Geoffrey Messier: Techniques for Improved CDMA Forward Link Performance in Realistic Propagation Environments

Carlos Rentel: Performance Evaluation of High Bit Rate Cellular Packet Data Systems

Kathiravetpillai Sivanesan: Adaptive Receiver Designs for Multiuser Detection

Peng Tan: Interference Cancellation in OFDM

Yan Xin: High Order Spectral Null Multimode Codes

David Young: Novel Fading Models based on Physical Channels

Fengqin Zhai: Efficient Implementation of Turbo Codes

MSC CANDIDATES

Lingzhi Cao: Novel Signal-Plus-Noise Diversity Combining
 Christine Cheng: A Nakagami-M Fading Channel Simulator
 Laura Choy: Turbo Codes for High Capacity Wireless Access Systems
 Xiaofei Dong: Higher-Order Statistical Behaviour of Fading Channels
 Robert Elliott: Transmission Scheduling Algorithms for CDMA Packet Data
 Sasan Haghani: Hybrid Selection/Maximal Ratio Diversity for Two-Dimensional Signalling
 Wenyu Li: Optimal Pilot Symbol Assisted Modulation
 Qiong Xie: Minimax Wilkinson's Method for Lognormal Sums
 Zhaohui Zeng: ADSL over Ultra-Long Telephone Lines

POSTDOCTORAL FELLOW

Mohamed-Oussama Damen: Space-Time Codes

COMPLETED GRADUATE THESES SUPERVISED

- 1 Zhaohui Zeng, "Asymmetrical Digital Subscriber Line (ADSL) over Ultra-Long Telephone Lines," MSc Eng. Thesis, September 2000; subsequently employed by JDS Uniphase, Optical Network Solutions Group, Ottawa, ON.
- 2 Cuifen Cheng, "A Nakagami- m Fading Channel Simulator," MSc Eng. Thesis, November 2000; subsequently employed by Nortel Networks, Universal Mobile Telecommunication System (UMTS) RNC-IN Group, Ottawa, ON.
- 3 Xiaodai Dong, "Coherent Signalling and Receiver Diversity for Fading Channels," PhD Thesis, December 2000; subsequently employed by Nortel Networks, UMTS 3G Base Station Hardware Development Team, Ottawa, ON.
- 4 Xiaofei Dong, "Fading Statistics of Diversity Techniques," MSc Thesis, August 2001; subsequently employed by Gennum Corporation, IC Wireless Algorithms Design Engineer, Burlington, ON.
- 5 Yan Xin, "High Order Spectral Null Multimode Codes," PhD Thesis, January 2002; subsequently a Postdoctoral Fellow with Dr Ivan J. Fair.
- 6 Laura Choy, "Turbo Codes for High Capacity Wireless Access Systems," MSc Thesis, January 2002; subsequently employed by AGILENT, Vancouver, BC.

COLLABORATIONS

INTERACTION WITH ALBERTA INDUSTRY

- The iCORE Chair acted as a high technology consultant to CanAccord Capital Corporation of Edmonton, performing an assessment of intellectual property pertaining to a proposed issuance of Special Warrants of a start-up high technology company in Edmonton.
 - The iCORE Chair was appointed Director of the Corporation of Eleven Engineering, Edmonton, Alberta in March 2001. He has been actively involved in technology and product planning as well as the recruitment of highly qualified personnel in the reporting period.
 - Participated in a meeting to investigate collaborative research and educational opportunities with Siemens Canada in Calgary on May 10, 2001.
 - Participated in a meeting to investigate collaborative research and educational opportunities with Nortel Networks in Calgary on January 23, 2001.
 - Provided input to, and document review of, a proposal for collaboration with Siemens Canada. The proposal, made by the University of Alberta, is progressing.
- *New Jersey, US:* Research on hybrid selection/maximal ratio diversity combining digital receivers.
 - *Mobile and Portable Radio Research Group (MPRG), Virginia Tech, Blacksburg, Virginia, US:* Research on novel mathematical models for lognormal shadow fading.
 - *Electrical Engineering Department, University of L'Aquila, L'Aquila, Italy:* Research on new mathematical modeling of sums of lognormal random variables and applications to outage in slow frequency hopped time diversion multiple access (TDMA) spread spectrum (FHSS) cellular systems.
 - *Department of Engineering Science, University of Modena, Modena, Italy:* Research on efficient generation of cross-correlated fading amplitude sequences for simulation of correlated branch diversity systems.
 - *Department of Mathematics and Statistics, Queen's University, Kingston, Ontario:* Research on signal constellation mappings for non-uniform sources.

NATIONAL AND INTERNATIONAL

The iCORE Chair is actively collaborating with researchers nationally and internationally. Research collaborations include the following:

- *Wireless Systems Research Department, AT&T Labs – Research, Middletown,*

Dr Krzymieñ's interaction with industry includes:

- *Nortel Networks:* "Enabling Technologies for Future Wireless High Throughput Nomadic and Mobile Packet Data Access." CDMA System Research and Development,

Richardson and Spatial Processing Technology, Harlow Laboratories, UK.

- *Nortel Harlow Laboratories (UK)*: concerned with future wireless access involving MIMO spatial processing, adaptive transmission techniques and fading channel prediction.
- *Telus Mobility*: The project title is “Radio Planner: A Wireless Network Simulation for Real Environments”.
- *Ericsson Wireless Communications (CDMA Systems)*: Collaborative research work involving design and performance evaluation of very high bit rate wireless packet data systems employing adaptive modulation and turbo coding.

SPONSORSHIPS

The iCORE Chair has been very successful in obtaining funding from additional sources. Funding from sources in addition to the iCORE grant totals \$899,000. These grants with Dr Beaulieu as principal investigator include \$66,000 from NSERC for Wireless Communications and Digital Transmission, \$241,010 for the Steacie Memorial Fellowship in Wireless Communications Transmission and Modeling; \$350,000 for the CFI CRC in Wireless Communication Systems; and \$261,000 for the CITO Simulation Techniques and Tools for Correlated and Wideband Fading Environments Project. Dr Beaulieu is co-investigator with Principal Investigator Dr Peter McLane on an \$81,000 CITO project on Multi-User Detection and Interference Cancellation in Wireless Cellular Basestations for Coded DS-CDMA.

PUBLICATIONS

JOURNAL PUBLICATIONS

- 1 N.C. Beaulieu, “Bounds on Variances of Recovery Times of Decision Feedback Equalizers,” *IEEE Transactions on Information Theory*, vol. 46, Sep. 2000, pp. 2249-2256.
- 2 D.R. Pauluzzi and N.C. Beaulieu, “A Comparison of SNR Estimation Techniques for the AWGN Channel,” *IEEE Transactions on Communications*, vol. 48, Oct. 2000, pp. 1681-1691.
- 3 D.W. Paranchych and N.C. Beaulieu, “Performance of a Digital Symbol Synchronizer in Cochannel Interference and Noise,” *IEEE Transactions on Communications*, vol. 48, Nov. 2000, pp. 1945-1954.
- 4 C.C. Tan and N.C. Beaulieu, “On First-Order Markov Modeling for the Rayleigh Fading Channel,” *IEEE Transactions on Communications*, vol. 48, Dec. 2000, pp. 2032-2040.
- 5 J. Cheng and N.C. Beaulieu, “Maximum-Likelihood Based Estimation of the Nakagami- m Parameter,” *IEEE Communications Letters*, vol. 5, Mar. 2001, pp. 101-103.
- 6 M.F. Pop and N.C. Beaulieu, “Limitations of Sum-of-Sinusoids Fading Channel Simulators,” *IEEE Transactions on Communications*, vol. 49, Apr. 2001, pp. 699-708.
- 7 N.C. Beaulieu, C.C. Tan and M.O. Damen, “A ‘Better Than’ Nyquist Pulse,” *IEEE Communications Letters*, vol. 5, Sept. 2001, pp. 367-368.

- 8 X. Dong and N.C. Beaulieu, "Average Level Crossing Rate and Average Fade Duration of Selection Diversity," *IEEE Communications Letters*, vol. 5, Oct. 2001, pp. 396-398.
- 9 X. Dong and N.C. Beaulieu, "Optimal Maximal Ratio Combining with Correlated Diversity Branches," *IEEE Communications Letters*, vol. 6, Jan. 2002, pp. 22-24.
- 10 J. Cheng and N.C. Beaulieu, "Accurate DS-CDMA Bit Error Probability Calculation in Rayleigh Fading," *IEEE Transactions on Wireless Communications*, vol. 1, Jan. 2002, pp. 3-15.
- 11 N.C. Beaulieu, "Introduction to 'Certain Topics in Telegraph Transmission Theory'," Invited Paper, *Proceedings of the IEEE*, vol. 90, Feb. 2002, pp. 276-279.
- 12 S. Kaiser, W.A. Krzymieñ, and K. Fazal, "SS-MC-MA systems with pilot symbol aided channel estimation in the asynchronous uplink," 2nd Special Issue on Multi-Carrier Spread Spectrum, the *European Transactions on Telecommunications*, vol. 11, no. 6, Nov./Dec. 2000, pp. 605-610.
- 13 S. Sun and W.A. Krzymieñ, "Hybrid ARQ and optimal signal-to-interference ratio assignment for high-quality data transmission in DS-CDMA," *European Transactions on Telecommunications*, vol. 12, no. 1, Jan./Feb. 2001, pp. 19-29.
- 14 Y. Xin and I.J. Fair, "Algorithms to Enumerate Codewords for DC2-Constrained Channels," *IEEE Transactions on Information Theory*, vol. 47, no. 7, Nov. 2001, pp. 3020-3025.
- 15 M.O. Damen, K. Abed-Meraim and S. Burykh, "Iterative QR Detection for BLAST," in *Wireless Personal Communications*, vol. 19, no. 3, Dec. 2001, pp. 179-191.
- 16 M.O. Damen, K. Abed-Meraim and J.-C. Belfiore, "Diagonal Algebraic Space-Time Block Codes," *IEEE Transactions on Information Theory*, vol. 48, Mar. 2002, pp. 628-636.
- 17 M.O. Damen, A. Tewfik and J.-C. Belfiore, "A Construction of a Space-Time Code based on Number Theory," *IEEE Transactions on Information Theory*, vol. 48, Mar. 2002, pp. 753-760.

JOURNAL PUBLICATIONS ACCEPTED

- 1 C.C. Tan and N.C. Beaulieu, "Transmission Properties of Conjugate-Root Pulses," accepted pending revisions for publication in *IEEE Transactions on Communications*.
- 2 X. Dong and N.C. Beaulieu, "New Analytical Probability of Error Expressions for Classes of Orthogonal Signals in Rayleigh Fading," accepted for publication in *IEEE Transactions on Communications*.
- 3 N.C. Beaulieu and M.L. Merani, "Generation of Multiple Rayleigh Fading Envelope Sequences with Specified Cross-Correlations," accepted pending revisions for publication in *European Transactions on Telecommunications*.
- 4 W.W. Choy, N.C. Beaulieu and M.O. Damen, "A New Technique for Estimating the Error Probability of Decision Feedback Equalization," accepted pending revisions for publication in *IEEE Transactions on Communications*.
- 5 D.J. Young and N.C. Beaulieu, "Quality Measures for Random Variates," accepted for publication in *IEEE Transactions on Information Theory*.
- 6 G. Takahara, F. Alajaji, N.C. Beaulieu, and H. Kuan, "Constellation Mappings for Two-Dimensional Signaling of Non-Uniform Sources," accepted pending revisions for publication in *IEEE Transactions on Communications*.

- 7 N.C. Beaulieu and C. Cheng, "Efficient Nakagami- m Fading Channel Simulation," accepted pending revisions for publication in *IEEE Transactions on Vehicular Technology*.
- 8 M.Z. Win, N.C. Beaulieu, L.A. Shepp, B.F. Logan and J.H. Winters, "On the SNR Penalty of MPSK with Hybrid Selection/Maximal Ratio Combining over IID Rayleigh Fading Channels," accepted pending revisions for publication in *IEEE Transactions on Communications*.
- 9 E. Davis, N.C. Beaulieu and M. Rollins, "A MAP Blind Bit-Rate Detector for Variable Gain Multiple Access Systems," accepted pending revisions for publication in *IEEE Transactions on Communications*.
- 10 S. Sun, W.A. Krzymieñ, Q. Shen, and B. Darian, "Rapid access protocols for discontinuous transmission in DS-CDMA systems," accepted for publication in *Wireless Personal Communications*.
- 11 R. Hang, W.A. Krzymieñ, and C.L. Despins, "Improved MAC protocol for reverse link packet data transmission in wideband DS-CDMA," accepted for publication in *IEEE Journal on Selected Areas in Communications: Wireless Communications Series*.

CONFERENCE PUBLICATIONS

- 1 N.C. Beaulieu and M.L. Merani, "Efficient Simulation of Correlated Diversity Channels," *IEEE Wireless Communications and Networking Conference WCNC*, Chicago, Sep. 26-29, 2000, pp. 207-210.
- 2 M.Z. Win, N.C. Beaulieu, L.A. Shepp, B.F. Logan and J.H. Winters, "Tight Simple Bounds on the Error Probability of Hybrid Diversity," *International Symposium on Information Theory and Its Applications (ISITA'00)*, Honolulu, Hawaii, Nov. 5-8, 2000, pp. 955-959.
- 3 B.R. Tomiuk and N.C. Beaulieu, "A New Look at Maximal Ratio Combining," *IEEE GLOBECOM*, San Francisco, Nov. 27-Dec. 1, 2000, pp. 943-948.
- 4 J. Cheng and N.C. Beaulieu, "Precise Bit Error Rate Calculation for Asynchronous DS-CDMA in Nakagami Fading," *IEEE GLOBECOM*, San Francisco, Nov. 27-Dec. 1, 2000, pp. 980-984.
- 5 X. Dong and N.C. Beaulieu, "Average Level Crossing Rate and Average Fade Duration of Diversity Methods," *Blakefest Workshop*, Victoria, Canada, June 7-8, 2001.
- 6 X. Dong and N.C. Beaulieu, "Average Level Crossing Rate and Fade Duration of MRC and EGC Diversity," *IEEE International Conference on Communications*, Helsinki, Finland, June 11-15, 2001, pp. 1078-1083.
- 7 J. Cheng and N.C. Beaulieu, "Estimation of the Nakagami- m Fading Parameter," *Wireless '01*, Calgary, Alberta, July 9-11, 2001, pp. 84-88.
- 8 J. Cheng and N.C. Beaulieu, "Moment-Based Estimation of the Nakagami- m Fading Parameter," *IEEE Pacific Rim Conference on Communications, Computers and Signal Processing*, Victoria, B.C., Aug. 26-28, 2001, pp. 361-364.
- 9 M.O. Damen, A. Abdi and M. Kaveh, "On the Effect of Correlated Fading on Several Space-Time Coding and Detection Schemes," in *Proceedings VTC-Fall*, Atlantic City, NJ, October 7-11, 2001, pp. 13-16.

- 10 M.O. Damen and N.C. Beaulieu, "A Study of Some Space-Time Codes with Rates Beyond One Symbol per Channel Use," *IEEE GLOBECOM*, San Antonio, Nov. 25-29, 2001, pp. 445-449.
- 11 M.O. Damen and N.C. Beaulieu, "Investigation of Two High-Rate Algebraic Space-Time Codes," *IEEE GLOBECOM*, San Antonio, Nov. 25-29, 2001, pp. 450-454.
- 12 M.O. Damen, N.C. Beaulieu and J.-C. Belfiore, "A Number Theory Based Dual Transmit Antennae Space-Time Code," *IEEE GLOBECOM*, San Antonio, Nov. 25-29, 2001, pp. 485-489.
- 13 K.E. Baddour and N.C. Beaulieu, "Autoregressive Models for Fading Channel Simulation," *IEEE GLOBECOM*, San Antonio, Nov. 25-29, 2001, pp. 1187-1192.
- 14 N.C. Beaulieu and C. Cheng, "An Efficient Procedure for Nakagami- m Fading Simulation," *IEEE GLOBECOM*, San Antonio, Nov. 25-29, 2001, pp. 3336-3342.
- 15 M.O. Damen and N.C. Beaulieu, "On Diagonal Space-Time Code Using Algebraic Rotations," *Proceedings European Wireless*, Florence, Italy, Feb. 26-28, 2002, pp. 877-883.
- 16 X. Dong and N.C. Beaulieu, "Average Level Crossing Rate of Maximal Ratio Diversity in Unbalanced and Correlated Fading Channels," *IEEE Wireless Communications and Networking Conference WCNC2002*, Orlando, Florida, March 17-21, 2002, pp. 762-767.
- 17 M. Jamil, W.A. Krzymieñ, D. van Wyk, "Performance Analysis of Constant Envelope Quadriphase Sequences for CDMA," in the *Proc. IEEE Sixth Intl. Symposium on Spread Spectrum Techniques & Applications (ISSSTA2000)*, Parsippany, NJ, USA, September 6-8, 2000, pp. 212-215.
- 18 L.F. Choy, I.J. Fair, W.A. Krzymieñ, "Complexity-Performance Trade-offs in Turbo Codes for IMT-2000," in the *Proc. 2000 IEEE Vehicular Technology Conference (VTC2000-Fall)*, Boston, USA, September 24-28, 2000, pp. 2568-2575.
- 19 K. W. Ang, W.A. Krzymieñ, "Effects of Different Configurations of RAKE Receivers on the Performance of an Interference Cancellation Scheme in Frequency Selective Channels," in the *Proc. 7th IEEE Singapore Intl. Conf. on Communication Systems*, Singapore, November 20-24, 2000.
- 20 G.G. Messier, W.A. Krzymieñ, "An Indoor IS-2000 Transmit Diversity Evaluation using Propagation Measurements," in the *Proc. 2001 Semi-Annual Vehicular Technology Conference (VTC2001-Spring)*, Rhodes, Greece, May 6-9, 2001, pp. 423-427.
- 21 G.G. Messier, J.S. Nielsen, W.A. Krzymieñ, "CDMA Forward Link Performance Evaluation using Propagation Measurements," in the *Proc. 2001 Intl. Conference on Communications (ICC2001)*, Helsinki, Finland, June 11-15, 2001, pp. 2995-2999.
- 22 R. Novak, W. A. Krzymieñ, "A Downlink OFDM-F/TDMA Packet Data System Employing Multi-User Diversity," in the *Proc. 2001 3rd Intl. Workshop on Multi-Carrier Spread-Spectrum & Related Topics (MC-SS 2001)*, Sept. 26-28, 2001, pp. 181-190, Kluwer Academic Publishers 2002.
- 23 M. Yavuz, D. Paranchych, G. Wu, Ge Li and W. A. Krzymieñ, "Performance Improvement of the HDR System Due to Hybrid ARQ," in the *Proc. IEEE 2001 Semi-Annual Vehicular Technology Conference (VTC2001-Fall)*, Atlantic City, NJ, USA, October 7-11, 2001, pp. 2192-2196.
- 24 F. Zhai, I.J. Fair, "Improved Performance of Error Detection in Turbo Decoding by Incorporating a Short CRC with the Mean-Sign-Change Criterion," *Proceedings of the 2001 IEEE International Symposium on Information Theory*, Washington, DC, June 24-29, 2001, p. 143.

- 25 Y. Xin, I.J. Fair, "A New Metric for Comparing Performance of High-Order Spectral-Null Codes," *Proceedings of the 2001 IEEE International Symposium on Information Theory*, Washington, DC, June 24-29, 2001, p. 143.
- 26 G.G. Messier, W.A. Krzymieñ, and J.S. Nielsen, "Impact of Propagation Environment and Transmit Diversity on CDMA Forward Link Performance," to appear in the *Record Intl. Workshop on Wireless Communications & Networking: 3G and Beyond*, Istanbul, Turkey, May 11, 2001.
- 27 R. Novak and W. Krzymieñ, "Cellular Performance of a Multi-service OFDM-CDMA System with Spatially-dependent Rate Assignment and Power Control," in the *Proc. 2000 Intl. Conf. on Wireless Communications (Wireless2000)*, Calgary, Canada, July 10-12, 2000, pp. 448-459.
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DR MICHAEL BRETT AND DR MARK FREEMAN

NanoCORE: Nanoscale Engineering Physics Initiative

iCORE PROFESSORS
ELECTRICAL AND COMPUTER ENGINEERING AND PHYSICS
UNIVERSITY OF ALBERTA

RESEARCH PROGRAM OVERVIEW

The NanoCORE program has enabled principal researchers Michael Brett (Electrical and Computer Engineering) and Mark Freeman (Physics) to provide strong leadership and pursue activities related to promotion and growth of nanotechnology research. These include leadership in establishment and funding of the extensive (6000 square foot) University of Alberta Micromachining and Nanofabrication Facility (NanoFab), which is open to any user and has now provided micro and nanofabrication research services to over 250 users from over 50 research groups. Not only are these users academic researchers from seven universities, a number of new Alberta companies rely on the NanoFab for product development research. A strong relationship is expected with the newly established National Institute for Nanotechnology in Edmonton.

The NanoCORE research program funds core research activities in the fields of nanostructured thin films and devices (Brett), and nanoscale magnetics and ultrafast microscopy (Freeman). Also funded are staff central to the NanoFab – a nanolithography specialist and a fabrication technician. These personnel support not only the direct research of NanoCORE but also the nanofabrication efforts of researchers across the province. In order to create maximum impact and support professors with emerging research programs, NanoCORE also supports targeted nanotechnology research of six other professors in Engineering and Physics. Key research achievements of 2001 include: development of new photonic band gap materials for the next generation of photonic devices; the first ultrafast imaging of nanoscale magnetic dynamics necessary to understand the ultimate storage and speed limits of magnetic disk drives; and development of a process to enable simple non-lithographic manufacture of nanostructure arrays.

RESEARCH PROJECTS

NanoFab Establishment: Drs Brett and Freeman have played the key leadership roles in establishing, equipping, and securing continued funding support for the very successful University of Alberta Micromachining and Nanofabrication Facility (NanoFab). This open access facility has extensive capability and specific processes unique in Canada. To date it has been used (hands-on) by 254 researchers from seven universities, 54 research groups, and 11 industries. The NanoFab is established in a new 600 m² clean room in the new Electrical Engineering building on campus, and has a staff of seven with an annual operations budget over \$700K.

Micralyne/NSERC Chair: Dr Brett holds the Micralyne/NSERC Senior Industrial Research Chair in Thin Film Engineering, which sponsors research developing device applications of nanostructured thin film materials.

Centre for Nanoscale Physics: Dr Freeman led the creation of this centre, intended to promote the department's nanoscience research effort.

Canadian Institute for Advanced Research: Dr Freeman is an affiliate with the recently formed CIAR in Nanoelectronics.

Designated Area of Research Excellence: Drs Brett and Freeman were co-authors of the joint Engineering/Science document that led to the designation of NanoScience and Technology as one of a handful of areas of research excellence at the University of Alberta.

University of Alberta NanoCouncil and NINT: Drs Brett and Freeman both serve on the University of Alberta NanoCouncil, which is intended to help coordinate nanotechnology activities across the campus. In this role they have worked to support the creation of the National Institute of Nanotechnology, and have provided input to define the research focus of NINT.

Photonic Band Gap Materials: Unique square spiral photonic crystal structures have been fabricated, following a new geometry for ideal large band gap materials proposed by theoretician Sajeed John of University of Toronto. The journal *Science* recently listed this work in their prestigious section "Editor's Choice - Highlights of the Recent Literature" (*Science* 294, 2001: p. 1793). Photonic crystals may lead to a new generation of optical and communications devices, and potentially optical computation.

Manufacturable Nanostructures: The first fabrication of sub-micrometer periodic arrays of helices or other nanostructures was demonstrated using arrays of seeds to nucleate growth. Manufacturability of this technique was shown by avoiding lithography entirely, and using an embossed plastic process to generate submicron seed arrays. Thus these techniques give rise to a fully non-lithographic, simple two step fabrication of periodic arrays of precisely engineered helical, spiral or post nanostructures. Such a process might be crucial to reducing the fabrication cost of nanostructures used in photonic band gap materials, and photonic or other devices.

Thermal Barriers: Thermal barrier coatings of Yttria stabilized Zirconia (YSZ) are used extensively on turbine blades (particularly in aircraft engines) to provide insulation of the metal blade from heat. A new multilayer semi-porous YSZ nanostructure has been developed that has been measured by the National Institute for Standards and Technology (USA) to possess a thermal property ten times better than conventional YSZ barriers.

Nanopatterning: We have demonstrated the use of the transmission electron microscope for electron beam lithography to create patterns of 20nm size or smaller. This technique has been initially utilized to produce triangular arrays of magnetic permalloy bits.

Ultrafast Magnetization Reversal Dynamics: Ultrafast microscopy has been exploited to elucidate the long-standing problem of magnetization reversal dynamics in magnetic microstructures. Numerous groups worldwide have adopted this approach to studies of magnetization dynamics.

RESEARCH TEAM

Research funded by iCORE is listed below, organized by principal investigator:

Michael Brett

The primary research program has involved development of nanostructured thin films and devices using the Glancing Angle Deposition technique invented at the University of Alberta. Ten graduate students and three postdoctoral fellows were active in the research team in 2001. Devices developed

using nano-structured coatings include: hybrid liquid crystal/ nanostructured film coatings for optical display applications; humidity sensors using porous nanostructures; resonators constructed from nanosprings; nanostructured titania solar cells; porous coatings for microchromatography; three-dimensional periodic nanostructures for photonic band gap materials; nanostructured carbon electrodes; and new porous thermal barrier materials. One of the key hires utilizing NanoCORE funds has been Dr Jim Broughton, who joined the group after six years of industry experience. He is developing commercial applications of nanostructured films in the solid electrode field.

Mark Freeman

Primary research programs involve ultrafast phenomena and studies of nanoscale magnetism, and his group numbered 12 researchers in 2001. Development of new processes and specialized tools includes: construction of a low temperature cryostat to measure spatiotemporal dynamics of magnetization; achieving nanofabrication of 20nm structures in permalloy for studies of nanoscale magnetism; and exploiting ultrafast microscopy to image the magnetic reversal process in small magnetic domains. Key hires are Dr Mirwais Aktary and Dr Marek Malac, who have developed techniques using electron beam lithography and lithography in the TEM to reproducibly fabricate sub-50nm structures.

Chris Backhouse (ECE)

Through graduate student Jay Sulima, research is directed towards development of quantum tunnel diode devices that could

enable extremely high speed communications and be advantageous in remote sensing applications. The devices are intended to be integrated with MEMS actuators to produce a complete system on a chip.

Steven Dew (ECE)

Postdoctoral fellow Maria Stepanova is studying the effects of sputter target nanostructure on the resultant uniformity and yield of the sputter deposition process. This work is fundamental to optimizing sputter deposition, which is a critical tool in nanofabrication processes.

Ray Egerton, Al Meldrum (Physics)

Graduate student Peng Li is attempting to improve the light emission efficiency of phosphors by engineering specific crystal grain sizes and compositions. TEM studies are used to characterize the phosphor nanostructures.

Frank Hegmann (Physics)

Summer research assistant Joseph Ngai has developed femtosecond laser ablation techniques. This process may prove useful for machining materials on very small size scales, since the laser pulse is so short that there is little time for diffusion of heat (and hence damage) to other areas of the material not irradiated.

Frank Marsiglio (Physics)

Graduate students Simona Verga and Lucian Covaci are investigating the phenomena of nanoscale superconductivity. This research involves understanding the theory of transitions to a superconducting state and the effects of nanoscale ordering on superconductor properties.

PHD CANDIDATES

Greg Ballantine: Ultrafast Scanning Tunneling Microscopy

Wayne Hiebert: Magnetization Reversal Dynamics

Brian Dick: Nanostructure Fabrication

Barb Djurfors: Nanostructure Characterization

Ken Harris: New Nanomaterials Fabrication

Scott Kennedy: Photonic Crystal Fabrication

Mary Seto: Characterization of Microsprings

MSC CANDIDATES

Miroslav Belov: Developing Nanolithography Processes

Mike Colgan: Solar Cells Based on Nanoporous Materials

Lucian Covaci: Researching Nanoscale Superconductivity

Martin Jensen: Photonic Crystal Devices

Peng Li: Transmission Electron Microscopy Analysis of Nanostructures

Z. Liu: Ultrafast Microscopy Analysis of Nanoscale Magnetics

Aaron Slepkov: Nonlinear Organic Optical Materials
Jay Sulim: Nanoelectronic Devices
Simona Verga: Researching Nanoscale Superconductivity Issues
Peter Hrudey: Optical Films and Devices
Anastasia Elias: New Nanostructured Materials
Andy van Popta: Liquid Crystal Impregnated Nanostructures

POSTDOCTORAL FELLOWS

Mark Roseman: Spatiotemporal Dynamics of Magnetization
Ludmila Shepelev: Magnetic Domain Structures

RESEARCH ASSOCIATES

Mirwais Aktary: Nanolithographic Process Development
Jim Broughton: Supercapacitor Development
Byoung-Chul Choi: Studying Nanoscale Magnetic Domains
Greg Kiema: Nanobiotechnology Applications
Marek Malac: Permalloy Structures, Transmission Electron Microscope
Maria Stepanova: Atomic Interactions in Sputtering
Doug Vick: Nanostructure Growth and Models

SUMMER STUDENTS

Peter Hrudey: Electrochemical Processing of Porous Materials
Rahim Janmohamed: Sophisticated Auto-centering and Auto-focusing Programming
Allowing Unattended Data Acquisition
Kim Mervyn: Scanning Tunneling Microscope Tip Fabrication and Molecular Electronics Research
Joseph Ngai: Femtosecond Laser Ablation
D. Inglis (undergraduate): Low Temperature Scanning Tunneling Microscope

LABORATORY SUPPORT

Stephanie Bozic: NanoFab Technician and Supervisor
David Fortin: Administrative and Technical Laboratory Support
Karin Hayward: Administrative Support
Albert Huizinga: Electronics Support

COLLABORATIONS

The need to stay state-of-the-art in expensive nanotechnology processes and equipment requires collaboration with external universities and corporations. In particular, when research reaches the stage of demonstrating commercial applications it is advantageous to solicit corporate input. Interactions and collaborations have included:

- Research with Dr Dick Broer of the Philips Research Corporation (Eindhoven, The Netherlands) on development of new flat panel display technology utilizing hybrid devices of liquid crystals embedded in nanostructured thin films.
- Testing of new high insulation nanostructured thermal barrier coatings at the National Institute of Standards and Technology (Gaithersberg, USA) with Dr Eduardo Gonzales.
- Continuing studies of ultrafast magnetic phenomena in nanostructures in collaboration with magnetic storage firms Read-Rite, Quantum, and Seagate, and interaction with the National Storage Industry Consortium.
- Development of a non-lithographic embossing process for mass fabrication of nanostructure arrays with Dr Cees Bastiaansen of the Technical University of Eindhoven, The Netherlands.
- Collaboration with Dr Tom Smy at Carleton University, in development

and verification of a simulator for nanostructure fabrication.

- Collaboration with Dr Sajeew John of the University of Toronto to fabricate a new geometry of photonic crystal – an array of square spiral nanostructures.
- Pursuing a commercialization process with Micralyne for the Glancing Angle Deposition technology for engineering thin film nanostructure.

SPONSORSHIP

In addition to the iCORE grant, the NanoFab facility was funded through a \$1.89 million grant from the Alberta Science and Research Authority, and by a recent \$8.3 million CFI Innovation Fund Award for nanofabrication equipment. Drs Brett and Freeman have also recently been awarded an NSERC Major Facilities Access grant (\$122,000/yr) for NanoFab operating funding. Other major funding, in addition to the federal and provincial infrastructure awards, includes \$538,000 from the Canada Foundation for Innovation, \$93,000 from the MicroSystems Technology Research Institute, Dr Freeman's \$200,000 Canada Research Chair, and \$252,000/yr for the Micralyne/NSERC Senior Industrial Research Chair held by Dr Brett.

PUBLICATIONS

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- 3 B.C. Choi, G.E. Ballentine, M. Belov, and M.R. Freeman, "Bias Field Dependence of the Spatiotemporal Evolution of Magnetization Reversal in a Mesoscopic Ni₈₀Fe₂₀ element," *Phys. Rev. B*, vol. 64, 2001, p. 144418.
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- 7 M.J. Colgan and M.J. Brett, "Field Emission From Carbon and Silicon Films with Pillar Microstructure," *Thin Solid Films*, vol. 389, 2001, pp. 1-4.
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- 11 K.D. Harris, K.L. Westra, and M.J. Brett, "Fabrication of Perforated Thin Films with Helical and Chevron Pore Shapes," *Electrochemical and Solid State Letters*, vol. 4, no. 6, 2001, pp. C39-42.
- 12 B. Dick, M.J. Brett, T.J. Smy, M. Belov and M.R. Freeman, "Periodic Submicrometre Structures by Sputtering," *J. Vacuum Science and Technology*, vol. B19, 2001, pp. 1813-1819.
- 13 M.W. Seto, B. Dick, and M.J. Brett, "Mechanical Response of Microsprings and Microcantilevers," *J. Micromechanics and Microengineering*, vol. 11, 2001, pp. 582-588.

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CONFERENCE PROCEEDINGS

- 1 B.C. Choi, G.E. Ballentine, M. Belov, W.K. Hiebert, and M.R. Freeman, "Ultrafast Magnetization Reversal Dynamics on a Micrometer-Scale Thin Film Element Studied by Time Domain Imaging," *Mat. Res. Soc. Symp. Proc.*, vol. 648, 2001, p. 4.9.
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BOOK CHAPTERS

- 1 B.C. Choi and M.R. Freeman. "Time Domain Optical Imaging of Ferromagnetodynamics," to appear in Springer volume on "*Magnetic Microscopies of Nanostructures*," H. Hopster and H.P. Oepen, editors, Springer Verlag, (2001).
- 2 Marek Malac, Ray Egerton, and Michael Brett, "Thin Films Deposited at Glancing Incidence and Their Applications," *Vacuum Technology and Coating*, vol. 2, no. 7, July 2001, pp. 48-53. (Invited article to trade magazine).

DR GRAHAM A. JULLIEN

Advanced Technology Information Processing Systems Laboratory

iCORE CHAIR
ELECTRICAL AND COMPUTER ENGINEERING
UNIVERSITY OF CALGARY

RESEARCH PROGRAM OVERVIEW

The Advanced Technology Information Processing Systems (ATIPS) Laboratory at the University of Calgary is focused on the development of real-time information processing systems technology, which uses advanced sensing, signal processing theory and hardware architectures for a variety of application domains. The philosophy behind ATIPS is to develop fundamentally new models and technologies that are required to solve problems in specific application areas. The laboratory adopts a vertical approach to real-time systems design being involved in all aspects of algorithms, architectures, arithmetic and VLSI circuits. The laboratory is currently exploring the evolving System-on-Chip (SoC) design paradigm, and is one of the lead clients in the Canadian Microelectronics Corporation (CMC), SoC Research Network. Our thrust for the period of tenure of the iCORE Chair, is to extend our collaborations from the signal processing community, where we have many established links, to wider research areas. We plan to exploit the synergism of our expertise in application specific signal processing systems, with the expertise of new collaborators to generate novel devices and techniques in those complementary disciplines. Current target areas, with specific projects, are:

SYSTEM-ON-CHIP

These projects are a mix of continuing and new projects based on our involvement with the CMC SoC Research Network.

- 1 IP Blocks and generators for high throughput rate fault tolerant modulus replication architectures;
- 2 Embedded DRAM generators for systolic array video-rate multi-dimensional logarithmic filters;
- 3 A video coder using a mix of IP blocks using new compression techniques;
- 4 Integrating novel RF wireless front-end circuitry with the Tality Bluetooth core;
- 5 Very low-power adiabatic circuits and module generators for hearing-aid architectures.

BIOTECHNOLOGY

The first two projects are new, and are based on our recently established collaboration with Dr K.V.I.S. Kaler of the BioElectrics Laboratory, and Dr M.P. Mintchev of the Bio-Instrumentation Laboratory, at the University of Calgary.

- 1 Lab-on-Chip micro-diagnostic systems using lelexel and plexel arrays;
- 2 Bio-chip - implantable micro-stimulators for colonic motility repair;
- 3 Acoustic beam-steered hearing aid sensors and processors.

REAL-TIME SIGNAL PROCESSING SYSTEMS

These projects reflect our current interests in application specific real-time signal processing systems. Much of this research is aimed at exploring alternative number representation techniques for performance driven implementations.

- 1 Algebraic integers for discrete cosine and discrete wavelet transforms, with applications to multi-media data streaming and compression;
- 2 Optimum base multi-dimensional logarithmic number system filter architectures with applications in video processing and very low-power hearing instrument processors;
- 3 Analog arrays for very low noise digital arithmetic in mixed signal applications;
- 4 Development of tools and techniques for building plenoptic (complete view) camera systems using lenticular arrays and CCD sensors;
- 5 Machine vision algorithms for CCD time-delay and integration (TDI) camera systems;
- 6 Development of adaptive filters for an asymmetrical wireless LAN.

EMERGING TECHNOLOGIES

A completely new thrust is the application of our design expertise to emerging technologies. Our initial research efforts have been directed towards Quantum-dot Cellular Automata (QCA) that was pioneered at Notre Dame University. Our contributions centre around design and simulation tools and building blocks for new QCA architectures.

- 1 Design tools for Quantum Cellular Automata (QCA). This project is involved with the development of the first comprehensive CAD tool for this promising emerging technology. Using our design tool, we are developing new structures for some of the basic components required to build QCA computational architectures.

RESEARCH PROJECTS

Continuing ProjectsALGEBRAIC INTEGERS FOR
IMPLEMENTING DSP TRANSFORMS

We have developed novel approaches for computing real-valued discrete transforms such as the discrete cosine transform (DCT), the discrete Hartley transform (DHT), and most recently DAUB-4 and DAUB-6 wavelet transforms. This approach is yielding considerable reduction in hardware and power compared to conventional techniques. Application areas include data compression for streaming multimedia.

FIR DIFFERENTIATORS AND PREDICTORS

This work presents a novel method for designing polynomial FIR predictors (PFP) and polynomial predictive FIR differentiators (PPFD) for fixed-point environments. This work is carried out in collaboration with the Helsinki University of Technology.

HYBRID DISTRIBUTED-NEURON
ANN ARCHITECTURES

In this work we explore a useful self-scaling property of a hybrid (analog/digital) artificial neural network architecture based on distributed neurons. In conventional sigmoidal neural networks with lumped neurons, the effect of weight quantization errors becomes more noticeable at the output as the network becomes larger. This work is carried out in collaboration with the Research Centre for Integrated Microsystems (RCIM), University of Windsor.

A NUMBER SYSTEM WITH CONTINUOUS
VALUED DIGITS

This work introduces a novel number system based on signed continuous valued digits. Arithmetic operations in this number system are performed using simple analog circuitry, in contrast to the conventional implementation of arithmetic units by Boolean or multiple-valued logic circuits. This technique has advantages in low-noise arithmetic used for mixed-signal applications. This work is carried out in collaboration with RCIM.

RNS ALGORITHMS FOR COMPUTATIONAL
GEOMETRY PROBLEMS

A new and efficient number theoretic algorithm for evaluating signs of determinants is investigated. The algorithm uses computations over small finite rings for significant reduction in hardware costs.

DATA PROCESSING FOR TIME DELAY AND
INTEGRATION (TDI) CAMERAS

Time Delay Integration (TDI) is a technology used in line-scan cameras to improve moving image quality. Charge transfer between wells in each of the rows is synchronized to the velocity of the moving image in order to improve contrast and reduce noise in low illumination environments. This project addresses in-camera processing systems to provide self-synchronizing of the charge clock and real-time defect detection techniques for Web-based manufacturing processes. This work is carried out in collaboration with RCIM.

GENETIC ALGORITHMS FOR FILTER ARCHITECTURE DESIGN

This work presents new algorithms that use genetic programming in the design of filter architectures. We have introduced techniques both for eliminating common sub-expressions in hardware implementation of fixed coefficient multiplier filter architectures and for optimizing the pipeline structure of recursive filters. This work is carried out in collaboration with RCIM.

New Projects

HIGH PERFORMANCE ADAPTIVE FILTERS

Using the Modulus Replication Residue Number System (MRRNS) mapping technique, we are able to compute over identical channels using modular arithmetic. This approach is being applied to an adaptive equalizer for the *TRLabs* Gigabit Wireless LAN project. A major feature of the architecture is the ability to implement complex arithmetic, over a large number of pipelined taps, without any interaction between the real and imaginary parts of the data. The aim of the project is to be able to compute over 400 billion arithmetic operations per second in a single SoC chip.

MULTI-DIMENSIONAL LOGARITHMIC NUMBER SYSTEMS

A recently introduced double-base number representation has proved to be successful in improving the performance of several algorithms in cryptography and digital signal processing. The index-calculus version of this number system can be regarded as a two-dimensional extension of the classical logarithmic number system. For signal processing applications, we are applying this

technique both to low-power filterbanks and compressors for hearing-aids as well as to very high throughput rate video filters. For cryptography applications, we have developed new procedures for decreasing the processing time of several crypto protocols.

ADIABATIC SWITCHING TREES

This new project builds on some earlier work from the Research Centre for Integrated Microsystems, University of Windsor, and some recently published work from Prof. A. Salama's group at the University of Toronto. By replacing cascaded logic functions with minimized transistor trees, we are able to produce large fan-in logic that lends itself to the implementation of adiabatic systems. Since many of our arithmetic architectures use small blocks of read-only memory, these are easily converted to high fan-in trees and may lead to some new techniques for very low-power arithmetic processors.

LEXEL AND PLEXEL ARRAYS FOR BIO-ANALYSIS

In a joint project with Dr K.V.I.S. Kaler, Director of the BioElectrics Laboratory, University of Calgary, we are investigating the implementation of arrays of electric field elements (Lexels) and CMOS imaging arrays to applications in dielectrophoretic (DEP) control of cells in fluids. The array structure will allow the generation of arbitrary electric field waveforms on a grid structure, and will increase the flexibility of applying the DEP effect. The aim of our work on plexel arrays is to combine pixels and lexels to both control and monitor cell motion under the control of non-linear electric fields.

COLONIC STIMULATORS

This joint project with Dr M.P Mintchev, Director of the Bio-Instrumentation Laboratory, University of Calgary, is associated with the development of a MEMS (Micro-Electro-Mechanical System) implantable neural stimulation device. The target area is repair of colonic motility functions where one of the major hurdles is the requirement for large stimulation power from implantable, wireless devices.

locally connected quantum-dot cellular automata (QCA). *QCADesigner* is a layout and simulation tool developed in the ATIPS laboratory that allows the design and simulation of QCA architectures. Based on a variety of in-house and custom code, provided by collaborating laboratories involved in QCA research, it is capable of QCA design layout and simulation. There have been over 100 downloads of the tool since it was placed on the ATIPS Web site.

DESIGN TOOLS FOR QUANTUM CELLULAR AUTOMATA (NEW)

The use of quantum-dots is a promising emerging technology for implementing digital systems at the nano-scale level, and recently studied computational paradigms for quantum-dot technology include the use of

QCA ARCHITECTURAL COMPONENTS (NEW)

Using *QCADesigner*, members of the ATIPS laboratory are producing new design techniques for the basic building blocks that may be used to develop arithmetic, logic and memory units for this emerging technology.

RESEARCH TEAM

FACULTY AND TEAM MEMBERS

Dr Graham Jullien, Director, ATIPS Laboratory
 Dr W. Badawy, Director, Video-Processing Laboratory
 Dr Vassil S. Dimitrov, Associate Professor
 Dr J.W. Haslett, Director, RF Circuits Group
 Dr Laurent Imbert, Postdoctoral Fellow
 Dr Wenjing Zhang, Postdoctoral Fellow
 Dr Peiyu Zhang, Postdoctoral Fellow
 Mr J. Eskritt, MAsc, BAsc ATIPS Laboratory Manager
 Mr Paul Horbal, BAsc, ATIPS Administrative Research Assistant

COLLABORATING TEAM PARTNERS

Dr K.V.I.S. Kaler, Director, Bio-electrics Laboratory, University of Calgary
 Dr M. Minchev, Director, Bio-instrumentation Laboratory, University of Calgary
 Dr M. Ahmadi, Research Centre for Integrated Microsystems, University of Windsor
 Dr W.C. Miller, Director, Research Centre for Integrated Microsystems, U. of Windsor

PHD CANDIDATES

J. Eskritt: Multidimensional Logarithmic Systems
 C. Baykal: Data Stream Algorithms for TDI CCD Cameras
 M. Fu: Algebraic Integers for Error Free DSP Computations
 Y. Ibrahim: Analog Arrays using Cellular Neural Networks
 S. Makki: Acoustic Beam Steering Hearing Aid Algorithms
 R. Muscedere: Difficult Operations in 1 and 2 -Digit DBNS

MSC CANDIDATES

M. Alam: A Pipelined Threads Architecture for AES Encryption (in cooperation with Dr W. Badawy, Video Processing Laboratory)
 J. Doherty: Implantable Bio-Chips (in cooperation with the Bio-Instrumentation Laboratory, Dr M. Minchev, Director)
 P. Horbal: Adiabatic Circuits for Switching Trees
 J. Keilman: SoC Based Lxel Arrays for Lab-on-Chip Applications (in cooperation with the Bio-Electrics Laboratory, Dr K.V.I.S. Kaler, Director.)
 K. Wahid: IP Cores for Algebraic Integer DWT Video Stream Compressors
 K. Walus: CNNs and Quantum Dot Computers
 J. Yeboah: Analog Circuits for Low Noise Digital Arithmetic
 M. Amtoun: 3D Image Recovery from a Plenoptic Camera
 J. Li: Low-Power Hearing Aid Processor
 A. Razavi: Plenoptic Camera Simulator
 J. Wu: Asynchronous Hearing Aid Processor Architectures
 M. H. Zheng: Fault Tolerant MRRNS Processor

COLLABORATIONS

ATIPS laboratory members made several visits to sponsoring industries during 2001. Included in these visits were numerous interactions with DALSA Inc. where our research team demonstrated research progress on a variety of projects associated with machine vision camera systems. These include the first demonstration of self-synchronization of a CCD Time-Delay and Integration (TDI) camera system and several new algorithms for defect detection on Web inspection systems. Initial work on using a single camera for 3D imaging was also presented. A team of faculty and students also visited Genum Corp., where presentations were made relating our work on video-rate processors and hearing aid architectures and processors. Genum is very interested in testing and applying our technology in their next generation products, and we have recently submitted test integrated circuit designs to the Canadian Microelectronics Corporation for this purpose. As part of the research on next generation hearing instruments, a MEMS acoustical array and supporting socket structure, with a beam forming array of microphones, was presented. This work was carried out in co-operation with our collaborating team at the University of Windsor. Two major projects are also being carried out in collaboration with *TRLabs*, Calgary. These are related to the Gigabit Wireless LAN project and include work on new RF front-end circuitry and a high throughput rate adaptive digital filter for the base station.

The ATIPS laboratory has established strong collaborations with several university

laboratories in Alberta, Canada and worldwide. These include the Bio-Electrics, Bio-Instrumentation and Video Processing laboratories at the University of Calgary; the Research Centre for Integrated Microsystems at the University of Windsor; the VLSI Research Group, University of Toronto; the Center for Advanced Computer Studies, University of Louisiana, Lafayette; the Electronic Materials and Devices Laboratories, Department of Electrical Engineering, University of Notre Dame, Indiana; Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier; Department of Electrical and Communication Engineering, Helsinki University of Technology; Communications and Information Technology Research Group, University of Cardiff; Department of Computer Engineering, Technical University of Sofia, Bulgaria; Electrical Engineering Department, Macquarie University, Sydney, Australia; and School of Electrical and Electronic Engineering, Queen's University, Belfast. The collaborations include visits of students and scholars between the research groups, joint projects, and mutual development of software tools and integrated circuit designs.

SPONSORSHIPS

In the very successful first year of operation, research grants of more than \$580,000 were awarded to members of the ATIPS laboratory in addition to the iCORE award. Micronet awarded two grants of \$220,000 and \$40,000 to a team from the University of Calgary and the University of Windsor for Phase III, Year IV, of the network; these grants included components of industrial funding. NSERC installments were made to

Dr Jullien for *Alternative High Performance Arithmetic Structures for Data-stream Digital Signal Processing* (\$58,905); Dr Dimitrov for *Implementation of Cryptography Algorithms* (\$26,000), and to Dr Haslett for *Semiconductor Devices, Circuits, and Instrumentation* (\$37,860). Dr Jullien was awarded a \$50,000 Research Excellence Envelope (REE) grant from the University of Calgary. The Canadian Microelectronics Corporation awarded the ATIPS laboratory a joint test equipment

loan for \$80,000. Dr Haslett was awarded a design equipment loan worth \$82,000 from CMC, and \$25,000 from TR Labs for infrastructure support of a research project on *RF Wireless IC Design*. There were also several integrated circuit awards totalling more than \$25,000. In addition to these cash and equipment awards, the University of Calgary contributed significantly to the ATIPS laboratory infrastructure within the new ICT building.

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DR GÉRARD LACHAPELLE

Wireless Location Research

iCORE CHAIR
GEOMATICS ENGINEERING
UNIVERSITY OF CALGARY

RESEARCH PROGRAM OVERVIEW

This iCORE grant focuses on research related to outdoor and indoor wireless location, navigation and positioning using satellite and ground-based RF techniques, and fusion with self-contained sensors with a focus on availability, accuracy and reliability.

Highlights:

- Chair awarded a Canada Research Chair in April 2001;
- New faculty member in support of the Chair, Dr R. Klukas;
- Visiting professors from South Korean universities.

Partnerships with numerous federal government, Calgary-based and foreign-based public and industrial organizations were renewed or put in place. Partners and sponsors included the Department of National Defence, Canadian Coast Guard, Canadian Space Agency, NovAtel Inc, Nokia, Ericsson, SiRF, Raytheon, U.S. Navy and Hitachi.

Significant results were achieved in the following areas: (1) analysis of navigation satellite signals for location in degraded signal environments, such as urban canyons and inside private residences in partnership with Ericsson USA and SiRF, CA, (2) analysis of the impact of the European Union Galileo satellite navigation system on Canada, in partnership with the Canadian Space Agency, (3) study of tactical indoor positioning systems in partnership with the Department of National Defence, (4) estimation of precise relative aircraft motion in partnership with the U.S. Navy, (5) GPS-based attitude determination in partnership with the Department of National Defence and companies based in Germany and South Korea, and real-time kinematic positioning with GPS in partnership with a Calgary-based and a Tokyo-based company.

Spinoffs included the graduation of two MSc students, the training of two internship

students, the publication of numerous papers, and the licensing of software programs that encapsulate some of the above research to 15 organizations via University Technologies International; the value of these license transactions was \$550,000.

The research activities in 2001 focused on four objectives, namely:

- enhancement of ground and satellite-based RF location systems;
- system integration, algorithms and software implementation;
- super accurate real-time location services;
- performance analysis of combined GPS/Galileo.

RESEARCH PROJECTS

Research was initiated related to the use of navigation satellite signals in degraded environments, namely a study on GPS signal fading properties and an assessment of a stand alone high sensitivity receiver for use under foliage, in urban canyons and in a mild indoor environment. These activities were conducted in cooperation with Ericsson and SiRF, U.S.A. Research was conducted on the impact of the European Union planned Galileo navigation satellite system. Part of the study was conducted in collaboration with NovAtel Inc, Calgary; MDA, Vancouver; Galileo Industries, France; and the Canadian Space Agency. A technical component focused on the availability, accuracy and reliability enhancements of the combined GPS/Galileo system for Canada.

The research team completed a Tactical Indoor Positioning System Option Study under sponsorship from the Department of National Defense with colleagues from Geomatics Engineering to assess the feasibility of high accuracy (2 metre) indoor positioning.

We pursued the enhancement and testing of an advanced multiple reference station RTK (Real-Time Kinematic) DGPS positioning method and software in cooperation with Robertson Enterprises, Calgary, and Hitachi Corporation/DX Antenna, Japan.

The performance assessment of various military and civilian GPS receiver technologies was conducted with the sponsorship of the Department of National Defense and the Department of Fisheries and Oceans.

Research was continued on the use of GPS for high accuracy aircraft buffeting estimation with the sponsorship of the U.S. Navy Naval Air Warfare Center.

Research was continued in the use of low cost GPS receivers for attitude determination using a multi-antenna configuration.

RESEARCH TEAM

FACULTY MEMBERS AND VISITING EXPERTS

Dr Gérard Lachapelle, Chair
Dr Richard Klukas, Assistant Professor
Dr M.E. Cannon, Professor, Department of Geomatics Engineering
Dr S. Skone, Assistant Professor, Department of Geomatics Engineering
Dr Naser El-Sheimy, Assistant Professor, Department of Geomatics Engineering
Dr Yang Gao, Associate Professor, Department of Geomatics Engineering
Dr Ken Fyfe, Department of Mechanical Engineering, University of Alberta
Professor C.W. Jeon, Soonchunhyang University, South Korea
Professor O. Salychev, Moscow State Technical University
Professor G. Jee, Konkuk University, South Korea

PHD CANDIDATES

S. Ryan: Global Navigation Satellite System Reliability Analysis
M. Petovello: Real-Time Fusion of GPS and Inertial Sensors
E. Fonseca: Estimation of Ionospheric Activities in Brazil Using Continuous GPS Measurements
K. O'Keefe: Investigations of Satellite Navigation on Mars Using the Proposed Mars Network Constellation
P. Alves: Real-Time Kinematic Multi-Reference Station Differential GPS
C. Ma: Study of Time-Based Wireless Location Techniques for W-CDMA Cellular Phone Network
G. Pugliano: Performance Analysis of a Multi-Reference Station Approach for High Performance Positioning in Italy
U. Dogan: Study of the Tectonically Active Marmara Region, Turkey, Using GPS (visiting PhD student)

MSC CANDIDATES

G. Liu: Impact of the Ionosphere on GPS Carrier Phase Ambiguity Resolution
G. MacGougan: GPS Signal Interference Analysis
Y. Lu: Vehicular Navigation in Urban Canyons
C. Basnayke: Vehicular Traffic Modelling Using Precise Satellite-Based Navigation
K. Lap Siu: GPS Signal Interference Testing (internship student, BSc Electrical Eng candidate)
D. Langen: Assessment of Multiple Reference Station RTK Methods (internship student BSc Geomatics Eng candidate)
V. Hoyle: GPS-based Attitude Estimation Hardware and Software Testing (research assistant BSc Geomatics Eng candidate)
Chaochao Wang: Kinematic Platform Attitude Determination Using Low-Cost GPS Receivers

J. Angelo: GPS Signal Measurement Performance Analysis (part-time MSc)
 A. Wang: Impact of RF Interference on GPS Aeronautical Applications (MSc)
 L. Dong: Electrical Engineering, Xian, China (MSc)
 A. Jakab: Quality Monitoring of GPS Signals (part-time MSc)
 R. Stirling: Use of MEMS Inertial Sensors for Motion Detection and Location
 O. Julien: Galileo Signal Performance Evaluations

COLLABORATIONS

Collaboration was established with Professor Ken Fyfe, Dept of Mechanical Engineering, University of Alberta, to investigate the fusion of RF location and self-contained MEMS sensors for personal location, navigation and guidance. An immediate outcome of this collaboration is the co-supervision of a University of Alberta-based graduate student.

SPONSORSHIPS

A five-year sponsorship agreement with Nokia Mobile Telephones, starting 1 May 2001, was put in place.

A \$300,000 grant from CFI and ISRIP was secured to establish a 16-station GPS reference station network in Southern Alberta to conduct RTK GPS positioning and navigation experiments and investigate the applicability of GPS for atmospheric studies.

Short-term research sponsorship, consisting of targeted research support, was received from the following agencies: Canadian Coast Guard, Department of National Defense, Canadian Space Agency, U.S. Navy/Naval Air Warfare Center, Raytheon Marine GmbH (Germany), Hitachi Ltd (Japan), Agency for Defense Development (South Korea).

Long-term research sponsorship was received or secured from the following external agencies: National Centre of Excellence AUTO 21, NSERC (Operating research grant and strategic grants), CFI, and IIPP.

Thanks to the success of the Chair in securing external sponsors for his research activities, another \$1.4 million was raised in funding, in addition to the iCORE grant of \$0.5 million. Much of the above \$1.5 million was million raised in collaboration with faculty members from the Chair's department and includes grants from NSERC, CFI, IIPP, ISRIP, and other grants and contracts from domestic and foreign sources. The amount pro-rated to the Chair was \$0.95 million. The initial objective to use the iCORE grant to leverage additional funds has been exceeded.

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DR JONATHAN SCHAEFFER

High Performance Artificial Intelligence Systems

iCORE CHAIR
COMPUTING SCIENCE
UNIVERSITY OF ALBERTA

RESEARCH PROGRAM OVERVIEW

This report represents a summary of the first year of the iCORE Chair in High Performance Artificial Intelligence Systems. Our group now consists of two professors, one research associate, two programmer/analysts, one secretary, 11 graduate students co-supervised by the Chair, and six other students who are involved in the research for their thesis studies.

Our research into games has two dimensions:

- 1) Developing new algorithms to explore large search spaces. In general, it is not possible to search to the end of the game, given the real-time constraints that game-playing programs operate under (typically a minute or less per move). The search algorithms need to be “smart” enough to make decisions that attempt to maximize the information gained in the given time allowed.
- 2) These programs need to manipulate knowledge to be able to differentiate desirable from undesirable states. Selecting the knowledge to use, acquiring it, deciding on how to represent it, testing it, and evaluating it are all hard problems.

Rather than explore each component in isolation, our group prefers to build working systems that demonstrate how all the components can be integrated to create a high-performance system.

RESEARCH PROJECTS

This section summarizes research for the first year of the iCORE Chair award. Note that in the following report, parallel computing research is included, even though iCORE

funds were not used to support this work. Parallel computing represents 25 per cent of research time for this team. iCORE indirectly benefits from this work by increasing research time for the Chair and by freeing up NSERC funds.

GAMES

We work on many different games, each of which offers different aspects of the search/knowledge problem to explore. In the past year we have worked on games with a large branching factor (lots of legal moves). For these games, deep search (as in *Deep Blue*) is not possible. Hence you need “smarter” search strategies and better-quality knowledge. Examples from the group include the work of the following researchers:

- Theo Tegos’ Amazons program *Antiope* tied for first place in the Jenazon Cup, the premier computer Amazons tournament.
- Martin Mueller’s *Explorer* is one of the strongest Go programs in the world.
- We have developed the two strongest Lines of Action programs in the world. Lines of Action is a relatively new game that has attracted a large following. At the 2001 Computer Olympics, Yngvi Bjornsson’s program *YL* won the gold medal.
- Darse Billings’ program *MONA* won the world correspondence championship against all the top human players.
- Awari is a well-known African game played on a 2 x 6 board, starting with 48 pebbles (12 a side). Humans think they can play well, but computer analysis shows that they play quite poorly. Thus we have a game where there is little in the way of useful knowledge about how to play well. Jack van Rijswijck is working on using data mining techniques to discover human-understandable patterns that are correlated with success.
- Poker is a challenging problem because of missing information – you do not know your opponent’s cards. Dealing with imperfect/unknown information is an important problem with numerous real-world applications. Here you need to infer probabilities about likely outcomes. Our group (including Darse Billings, Aaron Davidson, and Neil Burch) has concentrated on opponent modeling, detecting patterns in the opponent’s play that can later be exploited. Humans do this all the time. When you buy a used car, through experience you quickly learn a model of a used car salesman. Such a model allows you to infer that everything the salesman says may not be completely correct! Our research has led to the development of *Poki*, the world’s strongest poker program for Texas Hold’em (the most strategically challenging poker variant that is widely played; it is used in the annual World Series of Poker).
- Post’s Correspondence Problem (PCP) is a well-known problem used to show NP Completeness. Because PCP is NP Complete, researchers have not built computer solvers for this application. Ling Zhao has developed the best PCP solver in the world, finding optimal solutions that are hundreds of moves long. This research has resulted in new search techniques.
- A few years ago researchers discovered

that the search techniques that are useful for puzzles can be applied to planning system, such as scheduling. Adi Botea is building a new planning system that does technology transfer from the games/puzzles literature.

TOOLS

We are working on several tools that can facilitate the development of high-performance search applications.

Many search applications use similar algorithms and algorithm enhancements. Analysis of numerous programs shows that the “winning combination” of algorithms plus enhancements is a function of the search space properties (e.g., Is the search space a tree or a graph? Are there cycles?). Markian Hlynka is building a tool that analyzes the properties of the search space built by an application. The tool then builds a functional search program for that application. The tool experiments with this new program, collects experimental data, decides whether the results are good and, if not, iterates by modifying the generated program. In this way, the tool automatically builds a program to solve your problem, giving respectable performance. Of course, there is a difference between “respectable” and “high” performance, and we are working on closing this gap.

Many applications need performance beyond what is possible on a single processor. Akihiro Kishimoto has done research on new strategies for distributing the work in a search to parallel processors. His new algorithms are comparable with the best in the literature and, with many ideas yet to try, we expect to do even better.

SOLVING GAMES

For many years, we have been interested in “solving games” – building a perfect game-playing system. With *Chinook*, our checkers-playing program that became the first program to win a human world championship, we built a very strong, but not perfect program. There are four projects involved here.

Domineering is a tile game played on a board. The search space for a 10 x 10 board is an astronomical 10^{40} — roughly as large as chess. We can use knowledge to dramatically prune provably irrelevant parts of the search. Nathan Bullock’s software can solve nine times nine domineering in less than a day, and the 10 times 10 proof is currently running. This research has led to new insights into how to use knowledge to eliminate search.

The search space size for the game of Awari is 10^{12} , not all that large by today’s standards. In 1999, we started a project to solve this game. In 2001, we accelerated this work, in part because of access to Multimedia Advanced Computational Infrastructure (MACI) resources. This problem has turned out to be deceptively difficult, since the proofs can be hundreds of moves in length. We have made substantial progress towards solving this game, but it will take considerable intellectual and computing efforts to reach our goal (Neil Burch, Darse Billings, Jack van Rijswijck).

Whereas the previous two games can be solved by search-based means, these techniques do not apply to poker. Poker is a game of imperfect information. Instead we

have set up a set of equations that when solved will produce a game-theoretic optimal strategy for two-player Texas Hold'em. Unfortunately, the set of equations is too large for full poker (10^{18}), but we have used the system to solve simpler variants. We are working on a new system that produces a nearly optimal solution using considerably fewer equations. Our initial results are very encouraging. This work, if successful, would form part of our poker-playing program *Poki* (Darse Billings, Neil Burch, Aaron Davidson, Duane Szafron).

Although solving games may not sound particularly interesting, the techniques that are used are quite useful. Solving large combinatorial search spaces (as in Awari and checkers) is a challenging problem and requires the development of new optimization algorithms, data management tools, parallel algorithms, and data compression algorithms. Solving poker is particularly interesting, because the ideas have applicability to other imperfect-information domains, such as combinatorial auctions.

APPLICATIONS IN SEQUENCE ALIGNMENT

Our expertise in single-agent search is being applied to the problem of computing optimal sequence alignments, a fundamental operation in computational biology. Biologists want to take multiple DNA or protein strands and align them to maximize the similarities between the strands. For example, this analysis can be used to identify differences in strands that might be indicators of genetic defects. The same technology that is used to solve the Rubik's Cube can be used

to address the problem of sequence alignment.

For two sequences, the alignment problem is well understood and heavily researched. Nevertheless, we have made some innovations here, including a new space-efficient algorithm *FastLSA* and a new algorithm for pruning irrelevant parts of the search space (Aaron Davidson). For more than two sequences, the alignment problem becomes much harder. If one has n sequences of average length m , the computational complexity of an optimal alignment is $O(m^n)$. Using single-agent search (A^*) and new heuristic techniques that we have developed, we can optimally solve hard problems with six sequences of average length 300. This problem of size $300^6 \approx 10^{15}$ can be solved in one hour on a slow Sun computer with two GB of RAM. Matt McNaughton is working on new techniques to improve the capabilities of our algorithm.

COMMERCIAL GAMES

Over the past three years, our research group has been moving away from the classic board and card games to the challenging domain of commercial games. John Laird (University of Michigan) calls commercial games "AI's killer app," and an excellent testbed for creating "human-level AI". We have entered into agreements with Electronic Arts (the world's largest manufacturer of computer games) and BioWare (an Edmonton-based games-company with an international reputation) that gives us research funds and access to their source code.

We currently have two projects underway with our partners. First, path-finding represents a large computational component of many commercial games. Peter Yap has developed novel algorithms for dramatically improving the search. Conventionally, path-finding implementations use a grid of tiles (much like a city map). Peter has proved that a hex-shaped topology is exponentially better. However, it is hard to design maps using hexes. Instead, the “tex” topology is introduced. Texus look like a wall of bricks. They preserve almost all of the search savings of hexes but are easy to work with. Both Electronic Arts and BioWare have shown a lot of interest in this work.

Second, we are working on a new design of the artificial intelligence in Electronic Arts’ FIFA soccer game. Jack van Rijswijck is spending eight months at Electronic Arts working on this project. This is a daunting project because it means working with a large legacy code application. At this point we have completed our learning curve and are working on the new design and implementation.

PARALLEL PROGRAMMING SYSTEMS

For over 15 years, we have worked on building high-level tools to simplify the task of writing parallel programs. Parallel programming is harder than sequential programming; the parallel programmer has to worry about communication, synchronization, load balancing, deadlock, granularity, etc., in addition to all the complexities of sequential programming. In the 1980s, I noticed that I reused parallel code in different applications; the application changed but the type of

parallelism did not. In effect I discovered design patterns (they did not get this name until the early 1990s). From 1987 to 1990 we built our first generation parallel programming tool, *Frameworks*, that took design patterns, specified by a simple graphical interface, and converted them to code. The user had to insert parallel constructs into their code. From 1991 to 1995, we worked on *Enterprise*. Here the onus on the user was simpler. From a design pattern we would use a compiler to modify the user’s sequential code to insert the parallelism. Since 1997, we have worked on our third generation system, *CO₂P₃S* (Correct Object-Oriented Pattern-based Parallel Programming System). The user selects the design pattern, and the system generates a code framework that correctly implements the parallel semantics. The user supplies sequential hook methods to get a complete running application. This work has been done by Steve MacDonald and extended by Kai Tan.

RESEARCH TEAM

FACULTY AND TEAM MEMBERS

- Jonathan Schaeffer, Chair
- Tony Marsland, Professor
- Martin Mueller, Associate Professor
- Neil Burch, Programmer/Analyst
- Kimberly Doring, Programmer/Analyst
- Yngvi Bjornsson, Postdoctoral Fellow
- Louise Whyte, Administrative Assistant

PHD CANDIDATES

Darse Billings: Reasoning with Imperfect Information
Adi Botea: Planning
Markian Hlynka: Learning to Search Efficiently
Jack van Rijswijk: AI Architectures for Sports Games
Peter Yap: Pathfinding
Steve MacDonald: Parallel Programming Environments
Ehud Sharlin: Tangible User Interfaces

MSC CANDIDATES

Nathan Bullock: Solving Domineering
Aaron Davidson: Opponent Modelling
Dan Hein: Computer Hex (Summer Student)
Akihiro Kishimoto: Parallel Alpha-Beta Search
Matt McNaughton: Optimal Multiple Sequence Alignment
Theodore Tegos: Combinatorial Game Theory
Ling Zhou: Posts Correspondence Problem
John Anvik: Pattern-based Parallel Programming
Steve Bromling: Designing Meta-Patterns
Kai Tan: Distributed Memory Parallel Patterns
Vanessa Yaremchuk: AI Approaches to Migraines

POSTDOCTORAL FELLOW

Yngvi Bjornsson: AI in Commercial Computer Games

COLLABORATIONS

Numerous sponsorships and collaborations have been announced in addition to iCORE funding.

WestGrid — Canada Foundation for Innovation, \$12 million (over 2 years)

WestGrid — ASRIP, \$6 million (over 2 years)

The above applications are large collaborative efforts. The first has five co-Principal Investigators including Jonathan Schaeffer and Brian Unger (plus 250 researchers). The second is a provincial application, which has two co-Principal Investigators (Drs Schaeffer and Unger) plus roughly 125 researchers.

SPONSORSHIPS

Additional funding comes from various sources. BioWare has donated \$500,000 US in software, and a research grant of \$10,000 per year for three years. Electronic Arts is funding a PhD student. PENCE (Protein Engineering Network Centre of Excellence) is funding an MSc student to do whole-proteome analysis. A CRC Chair position adds an additional \$20,000 per year in research funds, while the current NSERC operating grant is \$46,000, pending renewal. A grant for \$472,000 over three years from IRIS (Institute for Robotics and Intelligent Systems) Centre of Excellence has just been announced. Several faculty members have been involved in our projects, and their commitment will increase in the coming year because of the IRIS project. These include Russ Greiner, Rob Holte, Paul Lu, and Duane Szafron (University of Alberta) and Joerg Denzinger (University of Calgary).

PUBLICATIONS

BOOKS

J. Schaeffer and J. van den Herik. *Chips Challenging Champions: Games, Computers, and Artificial Intelligence*, Elsevier Science Publishers B.V., 2002 (in press).

REFEREED JOURNALS AND CONFERENCE PROCEEDINGS

- 1 J. Romein, H. Bal, J. Schaeffer, and A. Plaat, "A Performance Analysis of Transposition-Table-Driven Scheduling," *IEEE Transactions on Parallel and Distributed Systems* 2002 (in press).
- 2 J. Schaeffer, "Technology Transfer from One High-Performance Search Engine to Another," *International Computer Games Association Journal*, vol. 24, 2001, pp. 131-145.
- 3 D. Billings, A. Davidson, J. Schaeffer, and D. Szafron, "The Challenge of Poker," *Artificial Intelligence*, 2002 (in press).
- 4 J. Schaeffer, "A Gamut of Games," *AI Magazine*, vol. 22, no. 3, 2001, pp. 29-46.
- 5 J. Schaeffer, M. Hlynka, and V. Jussila, "Temporal Difference Learning Applied to a High-Performance Game-Playing Program," *International Joint Conference on Artificial Intelligence (IJCAI)*, 2001, 529-534.

- 6 M. Mueller, "Computer Go," *Artificial Intelligence*, vol. 134, nos. 1-2, 2002, pp. 145-179.
- 7 U. Globus and M. Hlynka, "The Butterfly and the Board: {A} Preliminary Look at Chaos Theory as a Model for Robust Go Algorithms," *Game Informatics2001-GI-5*, 2001, p. 28.
- 8 M. Mueller, "Partial Order Bounding: A New Approach to Evaluation in Game Tree Search," *Artificial Intelligence*, vol. 129, nos.1-2, 2001, pp. 279-311.
- 9 M. Mueller, "Solving 5x5 Amazons," *The 6th Game Programming Workshop* (GPW 2001), Hakone (Japan), IPSJ Symposium Series, vol. 14, 2001, pp. 64-71.
- 10 A. Davidson, "A Fast Pruning Algorithm for Optimal Sequence Alignment," *2nd IEEE International Symposium on Bioinformatics & Bioengineering* (BIBE' 2001) 2001, pp. 49-56.
- 11 J. van den Herik and J. Uiterwijk, and J. van Rijswijck, "Games Solved," *Artificial Intelligence*, 2002 (in press).
- 12 J. Anvik, S. MacDonald, D. Szafron, J. Schaeffer, S. Bromling, and K. Tan, "Generating Parallel Programs from the Wavefront Design Pattern," *7th International Workshop on High-Level Parallel Programming Models and Supportive Environments* 2002 (in press).

Section Two: Reports for Recent Awards

In our second year of operation, we recruited one iCORE Chair and three iCORE Professors. In the following section, recent award recipients present their research program overviews, preliminary descriptions of the research projects, introduction to the research teams and collaborations that are under way.

Dr Guenther Ruhe

INDUSTRIAL RESEARCH IN SOFTWARE ENGINEERING

Computer Science and Electrical and Computer Engineering
University of Calgary

Dr Christian Schlegel

HIGH CAPACITY DIGITAL COMMUNICATIONS TECHNOLOGIES

Electrical and Computer Engineering
University of Alberta

Dr Hugh Williams

ALGORITHMIC NUMBER THEORY AND CRYPTOGRAPHY

Mathematics
University of Calgary

Dr Carey Williamson

BROADBAND WIRELESS NETWORKS

Computer Science
University of Calgary

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DR GUENTHER RUHE

Industrial Research in Software Engineering

iCORE PROFESSOR
COMPUTER SCIENCE AND ELECTRICAL AND COMPUTER ENGINEERING
UNIVERSITY OF CALGARY

Start Date: July 2001

RESEARCH PROGRAM OVERVIEW

The need for further development of software engineering practices within companies adds to the demand for systematic knowledge and skill management in combination with active usage of this knowledge to support decision-making at all stages of the software lifecycle. With continuous technological change, globalization, business reorganizations, e-migration, etc. there is a continuous shortage of the right knowledge at the right place at the right time. The process of software development and evolution in particular is an ambitious undertaking involving a huge number of variables under dynamically changing requirements, processes, actors, stakeholders, tools and techniques. Very often, this is combined with incomplete, imprecise, fuzzy or inconsistent information about all the involved artifacts. Knowledge management in software engineering is concerned with actively identifying (discovering), evaluating, securing (documenting), disseminating, and systematically deploying knowledge throughout the software development organization. The knowledge mainly comes from former projects and from experiences of the outside world.

Why do we need advanced decision support for software development and evolution? The current state-of-the practice reveals the reasons:

- Decision problems are often poorly understood and/or described;
- Decisions are often carried out ad hoc and are made at the last moment;
- Decisions are typically not based on empirically evaluated models and best knowledge/experience;
- Decisions are made without taking into account the perspectives of all involved stakeholders who may have conflicting interests;
- Violation of (main) constraints is often detected too late;
- Impact and consequences of decisions are not well understood.

The need for decision support covers the complete life cycle. For the requirements, analysis, design, construction, testing and evolution phases, decision makers need support to describe, evaluate, sort, rank, select or reject candidate products, processes or tools. For example, decisions might be concerned with:

- Requirements: Which functional and non-functional requirements should be chosen according to given budget and time constraints?
- Design: Should we make or buy products or any other software components?
- Maintenance: What is the break-even point to develop a new product or have another release to fix defects or to adapt to new requirements?
- Project planning and control: How will we react to budget, time or resource shortages?
- Verification and validation: Which technique is most appropriate? Which people? Which artefacts should be investigated? When should we terminate?
- Risk management: What is the appropriate trade-off between risk and potential benefit?

Software Engineering Decision Support (SEDS) considers the software planning, development and evolution process as a continuous problem solving and decision making activity. The expected result is a better understanding, management and control of software processes, products, resources, tools, and technologies. The tremendous impact of software on products and services makes SEDS a critical activity. The more intelligent support based on sound methodology, empirically validated models, and best knowledge and experience can be offered, the more likely good decisions can be made. Good solutions are characterized by the feature that they satisfy most of the inherent objectives and constraints, that they are reasonable to implement, cost-effective and that, in addition, they provide a way for post-mortem impact analysis. Typically, these solutions are hard to find. The challenge is to provide sound methodological support for enabling good decisions about processes and products, risks and bottlenecks as well as for selection of tools, methods and techniques.

RESEARCH PROJECTS

SOFTWARE ENGINEERING DECISION SUPPORT ENVIRONMENT (SEDESU)

The reporting year was mainly devoted to launch methodological research for developing a Software Engineering Decision Support Environment (SEDESU) and to activate the environment with first concrete prototypes. Therein, horizontal layers represent the three infrastructure components. Vertical

components represent packaged models, experience and knowledge of the related research topics as input for operating the environment. We created both the horizontal layers (including a definition of their interaction) and are starting to develop vertical layers with concrete instances for the model.

ALBERTA RESEARCH CENTRE FOR INNOVATIVE SOFTWARE ENGINEERING TECHNOLOGIES

The Alberta Research Centre for Innovative Software Engineering Technologies (AASET) has been designed to be a unique and world-leading research centre for emerging Software Engineering technologies. One of the goals of the development of this research centre is to leverage the existing reputations of several internationally known software researchers to create both interest and respect among software engineering scholars and thereby enable an aggressive recruiting program to attract many of the best software engineers who will further grow this industry.

AASET's research approach is highly interdisciplinary and is based on the complementary competence in software engineering technologies, empirical software engineering, human-computer interaction, software engineering knowledge management and decision support, as well as software technology absorption and dispersion.

Technological, organizational, managerial and empirical research components fit together to achieve synergies for the core technological software engineering research.

- The purpose of software engineering knowledge management and decision support is to offer on demand, in time and in a context-sensitive way relevant technological knowledge and to support human decision-making under constraints and conflicting interests.
- Software quality and predictability is using the concept of empirical research to better understand, estimate, control,

and improve the different facets of software quality and to substantially improve predictability of software.

- Human-computer interaction, groupware, and usability methodologies are aimed at offering support for collaboration between humans in team based software engineering as well as for the interaction with the computer during development, evolution, and use of software.
- Methodological and empirical research in software technology absorption and dispersion will help researchers, businesses, government agencies, investors and end customers of new software engineering technologies to better understand the issues involved in maximizing the benefit gained from their activities in the software supply chain.

The research challenges for AASET are to: develop and enhance the theoretical foundations of these technologies; better understand the preconditions and constraints for context sensitive and efficient use of the technologies; and integrate technological software engineering research as part of the a more comprehensive effort to develop predictable and reliable software as part of our daily products and services.

QUANTITATIVE WIN/WIN – A NEW METHOD FOR DECISION SUPPORT IN REQUIREMENTS NEGOTIATION

Defining, prioritizing, and selecting requirements are problems of tremendous importance. A new approach called Quantitative WinWin for decision support in requirements negotiation is studied. The

difference to Boehm's WinWin groupware-based negotiation support is the inclusion of quantitative methods as a backbone for better and more objective decisions. Like Boehm's original WinWin, Quantitative WinWin uses an iterative approach, with the aim to increase knowledge about the requirements during each iteration.

DECISION-MAKING FOR COTS SELECTION

Integration of commercial off the shelf (COTS) products as elements of larger systems is a promising new paradigm. COTS-based development allows organizations to focus on their key business area, and to rely on outside sources for other functions. Another fundamental motivation for use of COTS software is its expected impact on timely maintenance as well as on flexibility and on ease of modernization of computer-based systems. An NSERC research proposal was approved to develop and evaluate an innovative methodology to support multi-criteria decision-making for COTS selection as essential part of CBS. A novel aspect of the approach is that COTS-related make-or-buy decisions will be based on the investigation of their related consequences for the complete CBS lifecycle.

FIRST INTERNATIONAL WORKSHOP ON SOFTWARE ENGINEERING DECISION SUPPORT (SEDECS'2002)

The first International Workshop on Software Engineering Decision Support was held in conjunction with the 14th International Conference on Software Engineering and Knowledge Engineering SEKE'2002 in Ischia, Italy. Ten high quality papers were finally accepted after a peer review process. A special issue of the Journal on Software En-

gineering and Knowledge Engineering will be edited with advanced and improved versions of the four to five best papers of the workshop.

INTRODUCTION TO THE RESEARCH TEAM

The research team consists of researchers from both the Department of Computer Science and Department of Electrical and Computer Engineering. It covers individual researchers with a broad range of topics. The main emphasis is to integrate those topics having a close relationship to Software Engineering Decision Support. Simultaneously, iCORE support is being used to attract further researchers from all over the world to join the group. Currently, most intensive collaborations are with Dr Maurer and Dr Denzinger from the Department of Computer Science, Dr Eberlein, Dr Far, and Dr Moussavi from the Department of Electrical and Computer Engineering and with Post-doc Dr Des Greer from the University of Belfast, who is visiting the lab for six months. During Winter 2002, a Killam Research Fellowship was successfully applied for Dr Rainer Unland. He visited the University of Calgary for four months in the first quarter of 2002.

A team of six to ten graduate and PhD students is expected to start in September 2002. Amandeep (a Masters Student from University of New Brunswick) will start in September 2002 as a research assistant to coordinate the design and development of a Software Engineering Decision Support Environment.

COLLABORATIONS

NATIONAL COLLABORATIONS

National collaborations mainly cover the Alberta Software Engineering Research Consortium ASERC. The centre is composed of faculty and graduate students from the University of Alberta and the University of Calgary that are engaged in applied research in software engineering and partner companies that currently participate or intend to participate in collaborative research with the academic members. In addition to the above, informal collaborations were and will be launched especially with the groups of Dr Khaled El-Emam (NRC Canada), Dr Lionel Briand (Carleton University, Ottawa), and Dr Ronald Reifer (applied for CRC Chair at University of Victoria).

INTERNATIONAL COLLABORATIONS

The Software Engineering Research Group at the University of Calgary successfully applied to become a member of the International Software Engineering Research Network ISERN. This gives us excellent opportunities to further extend collaboration with leading researchers and research institutions all over the world. For a list of the 33 member organizations from both industry and academia, see http://www.iese.fhg.denetwork/ISERN/pubisern.list_of_members.html.

In accordance to the Academic Cooperation Research Exchange between the University of Calgary and the Fraunhofer Institute for Experimental Software Engineering ("Fh IESE"), the Laboratory for Software Engineering Decision Support, a joint venture between the Department of Computer Science and the Department of Elec-

trical and Computer Engineering at the University of Calgary ("SEDS") and Fh IESE agreed to a collaborative research and personnel exchange.

Informal collaborations were launched especially with the groups of Dr Ross Jeffrey (University of New South Wales, Sydney, Australia), who visited the lab in June 2002 and gave a presentation on recent research results. Future collaborations are planned with the groups of Dr Vic Basili (Fraunhofer Center Maryland, USA), Dr David Raffo (University of Portland, Oregon, USA), and Dr. Goivanne Cantone (University of Rome, Italy).

INDUSTRIAL COLLABORATIONS

To attract industry, a professional Web site was launched, see also: <http://www.seng-decisionsupport.ucalgary.ca/>. As part of preparing the AASET proposal, several industrial partners were contacted. AASET recognizes that it needs to be aligned with Alberta industry and has formed an Industry Advisory Board (IAB). The IAB of AASET's will include eight high profile representatives from large, mid-size and small ICT companies:

- Marcos Lopez, President and CEO, Bitonic
- Brian Shultz, CEO, Brycol Consulting
- Joe Wigglesworth, Manager Centre for Advanced Studies, IBM
- Dave Reid, Strategic Planning, LEICA Geosystems
- Peter McCurdy, Senior Manager, CDMA Base Station Software Development, Nortel
- Roger Peterson, Chief Operating Officer, TRILabs

- Oleh Hniatuk, President and CEO, University Technologies International
- Ramesh Uppal, VP Technology and Data, Wi-Lan

PUBLICATIONS

PRESENTATIONS

- 1 Keynote at “Software Engineering Decision-Making – Methodology and Applications” at CONQUEST’2001 conference, Nuremberg/Germany, October 2001.
- 2 Software Engineering Decision-Making: Methodology and Applications, National Research Council, IIT, Ottawa, Canada, October 18, 2001.
- 3 Research Profile, University of Edmonton, October 2, 2001.
- 4 Advanced Decision Support in Software Engineering – Methodology and Application, University of Edmonton, November 23, 2001.
- 5 Software Engineering Research at University of Calgary (application for membership), ISERN annual meeting, University of Strathclyde, Scotland, August 20, 2001.
- 6 Advanced Decision Support in Software Engineering – Methodology and Application, Keynote at ASERC Workshop on Quantitative and Soft Computing Based Software Engineering, Banff, February 2002.
- 7 Advanced Decision Support for Requirements Negotiations, CUSEC conference, Montreal, March 2002.
- 8 Advanced Decision Support for Requirements Negotiations, Sunshine Village, U of C Software Engineering Workshop, April 2002.
- 9 Quantitative WinWin – A New Method for Decision Support in Requirements Negotiation, 14th International Conference on Software Engineering and Knowledge Engineering (SEKE’2002), Ischia, July 2002.

PUBLICATIONS

- 1 G. Ruhe, “Learning Software Organisation,” *Handbook of Software Engineering and Knowledge Engineering*, S.K. Chang, ed., World Scientific Publishing Co., Inc. 2001.
- 2 D. Pfahl, M. Klemm M, G. Ruhe G, “A CBT Module with Integrated Simulation Component for Software Project Management Education and Training,” *The Journal of Systems and Software*, vol. 59, 2001, pp 283-298.
- 3 D. Pfahl, N. Angkasaputra, C. Differding, G. Ruhe: “CORONET-Train: A Method for Web-Based Collaborative Learning in Software Organisations,” *Proceedings of LSO Workshop PROFES 2001*, Kaiserslautern, Germany.
- 4 D. Pfahl, N. Koval, G. Ruhe: “An Experiment for Evaluating the Effectiveness of Using a System Dynamics Simulation Model in Software Project Management Education,” In: *IEEE Computer Society: 7th International Software Metrics Symposium*, Metrics’01 - Proceedings Los Alamitos : IEEE Computer Society, 2001, pp 97-109.

- 5 D. Pfahl, G. Ruhe: "System Dynamics as an Enabling Technology for Learning in Software Organisations," in: *13th International Conference on Software Engineering and Knowledge Engineering, SEKE'2001* Skokie: Knowledge Systems Institute, 2001, pp 355-362.
- 6 I. Gruetzner, D. Pfahl, G. Ruhe: "Systematic Courseware Development Using an Integrated Engineering Style Method," *Proceedings of the Networked Learning Conference*, Berlin, May 2002.
- 7 D. Pfahl, O. Laitenberger, J. Dorsch, G. Ruhe, "An Externally Replicated Experiment for Evaluating the Learning Effectiveness of Using Simulations in Software Project Management Education." *submitted and IESE-Report* 004.02/E, January 2002.
- 8 G. Ruhe, A. Eberlein, D. Pfahl, "Quantitative WinWin – A New Method for Decision Support in Requirements Negotiation," in: *14th International Conference on Software Engineering and Knowledge Engineering, SEKE'2002* Skokie: Knowledge Systems Institute, 2002, pp 355-362.
- 9 I. Gruetzer, G. Ruhe, D. Pfahl, "Systematic Courseware Development Using an Integrated Engineering-Style Method," *IESE Report*, 067.01/E, March 2002.
- 10 I. Gruetzer, D. Pfahl, G. Ruhe, "Cost-Benefit Analysis of Courseware Development Using IntView, *IESE-Report*, 068.01/E, October 2001.

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DR CHRISTIAN SCHLEGEL

High Capacity Digital Communications

iCORE PROFESSOR

ELECTRICAL AND COMPUTER ENGINEERING, UNIVERSITY OF ALBERTA

Start Date: January 2002

RESEARCH PROGRAM OVERVIEW

Research will focus on new applications and methodologies of error control coding, concentrating on the statistical behavior of iterative error control decoders and the study and design of low complexity, implementable coding and decoding structures; the integration of iterative error control coding techniques into the joint detection in multiple access channel situations such as CDMA; the study and design of efficient, scalable space-time communications systems; the development of error control coding algorithms and space-time communications systems and demonstration of proof of concept prototypes; and the study and prototyping of high-complexity analog error control decoding algorithms and proof of concept studies.

RESEARCH PROJECTS

ERROR CONTROL CODING TECHNOLOGY

In applications, the integration of error control into a communications system environment is essential and will lead the way to future highly efficient data communications systems. Dr Schlegel's team has done much of the early work in the integration of error control coding into joint detection for multiuser systems, and the HCDC continues these efforts. His team has proposed and analyzed iterative joint detectors for CDMA systems and other interference channels. They have also proposed linear preprocessing systems which generate error control

metrics for decoupled single channel error control decoders and have shown that such an approach has excellent performance as well as manageable complexity requirements.

Furthermore, the team has pioneered a hardware implementation of an iterative receiver design based on the Gauss-Seidel iterative matrix inversion method.

The HCDC is extending this recent work in computationally efficient error control decoders to spearhead new architectures for high-speed decoders with an emphasis on implementations in field programmable gate

arrays (FPGAs) as well as extending research in the analysis of the dynamical behavior of iterative decoders to understand the inevitable complexity performance tradeoffs and the most efficient decoding strategies.

MULTIPLE ANTENNA SYSTEMS

Regardless of advanced coding techniques channel capacity remains an unmovable barrier, and data rates beyond these limits can only be possible by increasing the capacity of the transmission channel itself. This can be accomplished by sophisticated transmitter and receiver systems design. A central technique for this is the use of multiple transmit and receive antennas. Such systems can theoretically increase capacity by up to a factor equaling the number of transmit and receive antennas in the array. However, operation over multiple antenna systems will require scalable technologies that can be operated on channels which may consist of 100 or more correlated subchannels. The information theoretic capacity of multiple antenna systems and data communications techniques which exploit that potential have been studied recently by a number of authors, who report dramatic increases in supportable data rates.

The HCDC is studying the multiple antenna channel and its inherent capacity potential as well as ways and means of exploiting this potential via error control coding techniques in conjunction with space-time layering. We have already achieved initial results for concatenated error control coding and differential space-time modulation for a dual-antenna system, in which we achieve a performance only

1.5dB away from the theoretical multi-antenna channel capacity. These encouraging results point us in the right direction and intensive research in combining error control coding with space-time modulation is likely to generate systems at the verge of the theoretical limit of performance. The obvious way to extend these space-time coding principles to larger antenna arrays is to investigate serially concatenated structures using larger differential space-time codes.

INTERFERENCE CONTROL AND MITIGATION TECHNOLOGIES

While multiple antenna systems can raise the capacity limit of a channel, the theoretical capacity of a wireless network is automatically increased by adding more users to the system as a function of the total system power which increases with each user. However, a proliferation of uncoordinated wireless links without advanced coordinated joint receiver processing will simply increase interference, and interference limitation is a serious problem of current systems. System capacities can be increased if individual data links can be separated from each other in efficient, non-destructive ways. Interference cancellation techniques which are optimally integrated into the error control and multiple antenna systems are among the most promising methods under investigation.

We have pioneered linear iterative cancellation techniques that are computationally superior to the usually required matrix inversion methods, in particular for scenarios where the interference signal changes rapidly such as random CDMA, or large carrier frequency

shifts as occurs with high-speed mobile transmitters. Our research group has implemented an iterative linear cancellation system using the Gauss-Seidel iterative method and applied it to a CDMA system. An FPGA implementation is currently under evaluation.

HIGH-SPEED, LOW COMPLEXITY VLSI IMPLEMENTATIONS

The platform for the realization of these high-data rate transmission systems are modern VLSI implementations of the circuits and subsystems required to operate a data link. The advances of VLSI technology makes it possible today to implement systems with a complexity requirement of hundreds of million of transistors. The efficient design of such large VLSI systems will pose a major challenge for the communications industry, as evidenced by the continued shortfall of well educated designers.

The mainstay of current implementation work focuses on the efficient design of FPGA cores. These are modules which execute particular functions such as decoding, demodulation, synchronization etc. With the availability of large FPGA platforms, the most difficult and time consuming component of the system core design efforts has migrated to the efficient design of the algorithm on some software platform (VHDL, C, C++), and thus the implementation of system cores has become an ideal domain for academic research.

For the past five years Dr Schlegel has worked with L3 communications (Salt Lake City, UT) on efficient FPGA implementation of error control decoding algorithms. L3

communications is a company specializing in high-speed data links, primarily for the US military.

ANALOG CIRCUIT IMPLEMENTATION OF DIGITAL SYSTEMS

With the success of Turbo coding interest has grown in the design of efficient maximum a posteriori (MAP) decoders for the component codes of such systems. Recently it has been demonstrated that MAP decoders can be built using analog computational units. While all current implementations have been built in BiCMOS technology, the research group at the University of Utah has completed a design of an analog extended Hamming decoder which is an all CMOS implementation, the world's first of its kind.

Our proof of concept implementation in CMOS technology demonstrates the capability of robust, low power operation. A speed of 20 Mbps is achieved for an [8,4,4] extended Hamming code. Currently we are working on extending this design to a larger product turbo code. Since such a code exhibits massive parallelism, an analog core computation speed of only a MHz is required for a throughput of more than 1 Gbps. However, many circuit related issues have to be studied before this larger design becomes feasible, among it the high-speed input and output of signals, intermediate short-term storage and distribution of the analog inputs to the analog processing core.

INTRODUCTION TO THE RESEARCH TEAM

The High Capacity Digital Communications team will consist of two research associates, postdoctoral fellows, several graduate students,

and visiting researchers. Extensive collaboration with existing faculty members and researchers in the Department of Electrical and Computer Engineering is already under way.

This year's visiting researchers are: Dr Alex Grant, University of South Australia, an expert in information theory and applications; Dr Lance Perez, University of Nebraska, an expert on turbo coding; and Drs Gianluca Lazzi and Brian Hughes, North Carolina State University, in the area of unified space-time communications. The HCDC team further works with Drs Chris Meyers and Reid Harrison, University of Salt Lake City, who, together with Dr Schlegel are known for their contribution of the world's first CMOS implementation of an analog error control decoder. Strong ties also exist with L3 Communications, a Salt Lake City based defense contractor through and Dr Ayyoob Abbaszadeh and Mr Zackary Bagley, both principal staff engineers at L3 Communications specializing in VLSI system design.

In addition to iCORE Chair Dr Beaulieu, close collaboration is under way with Dr Ivan Fair, whose expertise in the design and implementation of error control coding techniques is directly related to Schlegel's Professorship. Furthermore, Dr Witold Kryzmiński is an active and invaluable member of the HCDC team bringing in his expertise in transmission systems.

COLLABORATIONS

Dr Alex Grant: Senior Lecturer at the University of South Australia has worked with Dr Schlegel on space-time modulation systems and multiple user systems. They are working on a joint research monograph "Coordinated

Multiple User Communications" to be published next year. He has visited the HCDC in the summer of 2002.

Dr Lance Perez: An Associate Professor at the University of Nebraska at Lincoln, Dr Perez, an expert in turbo coding, has visited the HCDC this summer and works with Dr Schlegel on their new book *Trellis and Turbo Coding*, to be published soon.

Dr Vincent Gaudet: Dr Gaudet is a recent hire at the University of Alberta from Toronto and works with the HCDC on analog implementations of error control codes.

Drs Gianluca Lazzi and Brian Hughes: Assistant Professor Lazzi and Professor Hughes from the North Carolina State University have worked with Dr Schlegel on space-time modulation and antenna design for multiple antenna communications channel. Dr Lazzi and Dr Hughes have joint NSF grants with Dr Schlegel in the area of united space-time communications.

Drs Chris Meyers and Reid Harrison: Associate Professor Myers and Assistant Professor Harrison from the University of Salt Lake City have worked with Dr Schlegel on the world's first CMOS implementation of an analog error control decoder. Joint NSF grants supported this work.

Dr Ayyoob Abbaszadeh: Dr Abbaszadeh is a staff engineer at L3 Communications specializing in VLSI system design. He has worked with Dr Schlegel on the implementation of turbo coding decoders and associated projects.

PUBLICATIONS

- 1 C. Schlegel and Z. Bagley, "Efficient Processing for High-Capacity MIMO Channels," submitted to *IEEE J. Selected Areas Commun., Special Issue: MIMO Systems*, May 2002.
- 2 B. Farhang-Boroujeny and C. Schlegel, "Efficient Multicarrier Realization of Full-Rate Space-Time Orthogonal Block Coded Systems," submitted to *IEEE J-SAC*, April 2002.
- 3 Z. Bagley and C. Schlegel, "Pair-Wise Error Probability for Space-Time Codes under Coherent and Differentially Coherent Decoding," submitted to *IEEE Trans. Commun.*, January 2002.
- 4 C. Schlegel and A. Grant, "Differential Space-Time Turbo Codes," submitted to *IEEE Trans. Inform. Theory*, December 2001.
- 5 C. Schlegel and A. Grant, "Concatenated Space-Time Coding," *Proc. Symposium on Personal, Indoor and Mobile Radio Communications*, PIMRC 2001, pp. 139-143, Sept. 30 - Oct. 3, San Diego, CA.
- 6 A. Grant and C. Schlegel, "Differential Turbo Space-Time Coding," *Proc. IEEE Information Theory Workshop* 2001, pp. 120-122, Cairns, September 2001.
- 7 Z. Bagley and C. Schlegel, "Classification of Correlated Flat Fading MIMO Channels (Multiple Antenna Channels)," *CIT* 2001, June 3-6, Vancouver, BC.

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DR HUGH WILLIAMS

Algorithmic Number Theory and Cryptography

iCORE CHAIR
MATHEMATICS, UNIVERSITY OF CALGARY

Start Date: September 2001

RESEARCH PROGRAM OVERVIEW

Over the last several years the need to ensure privacy has increased exponentially, particularly in such areas as: confidentiality in Internet communication; transfer of electronic funds; sending of military, diplomatic, corporate or even personal email messages; and the filing of personal medical records in large databases. Consequently, cryptography is an essential component of any installation in which secure communication is needed.

The security of almost all commercially available cryptosystems is based on the presumed difficulty of certain mathematical problems, for example the integer factorization problem. The difficulty of these problems is usually established anecdotally through frequent and unsuccessful attempts by specialists to provide solutions to them. Indeed, several problems thought to be very difficult, such as the integer factorization problem, have been shown to be somewhat less to considerably less intractable than previously believed. Such results have usually been discovered as the result of intense numerical experiments performed through the implementation of special purpose algorithms on large-scale computing devices. This is essentially what our research is all about — the investigation and possible implementation of hard mathematical problems as a source of secure communication systems. This includes all aspects of this sort of work from abstract theory to the fabrication of special-purpose computing devices.

In particular, the discrete logarithm problem (DLP) in function fields has proved so far to be very resistant to attack by all known methods. Indeed, the *elliptic curve system*, a special case of function field based schemes, is widely used in commercial applications. For example, *Certicom*, a Canadian company, sells several cryptographic products based on elliptic curve systems which are used in secure mobile phones, pagers and fax machines. As the study of the DLP in algebraic number fields and, particularly, in function fields is still very much in its infancy, there is much research that has yet to be done to provide an acceptable level of confidence in schemes that are based on these algebraic structures in order for them to be adopted by institutions such as banks, securities firms and the insurance industry.

RESEARCH PROJECTS

IMPROVED IMPLEMENTATION

In the case of our protocol involving real quadratic fields, we have developed a new representation for the ideals being considered, which has allowed us to considerably lower the precision needed at the expense of increasing the complexity of a second communication round. However, it turns out that in practice this second round proved to be no real problem as it is very rarely needed and executes very rapidly in those cases where it is required.

DETERMINATION OF OPTIMAL DISCRIMINANTS

One of the advantages of using number fields for cryptographic purposes is that we have some freedom in the selection of a certain parameter, the discriminant. However, this parameter needs to be chosen optimally with respect to both security and efficiency of implementation. We are currently developing a low cost, high speed special computing device called a number sieve to assist in determining optimal selections.

BENCHMARKING

As there is no rigorous mathematical proof of the security of our (or almost any other) cryptosystem, the only way we can certify its security and effectiveness is to test it extensively. Thus, it will be necessary to conduct very large scale numerical experiments in order to acquire the data needed to determine accurately the security of our cryptographic schemes. We plan to use a Beowulf cluster consisting of components from Dell as the hardware configuration on which to conduct this testing. The cluster requested consists of 43 Dell PowerEdge 1550 dual processor servers, each of which contains two 866 MHz Intel Pentium III processors.

UNCONDITIONAL DETERMINATION

OF THE REGULATOR

Another important consideration in this work is the question of whether a given instance of the DLP is actually solvable. This brings us to the problem of testing an ideal for principality. To do this we need to know the regulator. Unfortunately, the regulator that the fastest algorithm currently available determines is conditional on the GRH. It is of great interest to find the regulator unconditionally. The conditional algorithm should at least compute an integral multiple of the regulator, and this is something that can be checked very quickly. Having made this determination, the next problem is to establish that the integral multiplier of the regulator in the conditional regulator is one. There are two phases of doing this. The first is to establish that the regulator must exceed some predetermined bound. The next is to prove that for no integer less than a certain amount can we have the regulator being conditional one divided by that integer. It is interesting that both of these phases can be parallelized.

VERIFYING THE COHEN-LENSTRA HEURISTICS

The security of these schemes is dependent upon the number of reduced principal ideals in the quadratic number field (or function field) and the difficulty of solving the DLP in the field. The first of these problems is easily handled by use of the Cohen-Lenstra heuristics on the distribution of the odd part of the class number. However, as the Cohen-Lenstra heuristics are not rigorously established, it is essential that they be thoroughly tested numerically.

INVARIANTS IN FUNCTION FIELDS

Dr Scheidler's research focuses on the development and implementation of algorithms for computing invariants of cubic function fields as well as the exploration of these fields for cryptographic applications. Jointly with Dr Yoonjin Lee of the University of Delaware (USA), she has developed an algorithm for computing the fundamental units and the regulator of a purely cubic function field of unit rank two. Work on generalizing this technique to arbitrary cubic fields is in progress.

INTRODUCTION TO THE RESEARCH TEAM

The Algorithmic Number Theory and Cryptography research group includes senior team member Renate Scheidler, a researcher whose current work on secure key exchange systems and protocols using various mathematical devices is considered to be leading the field.

An additional ten faculty members, several postdoctoral fellows and up to fifteen graduate students from mathematics and statistics, computer science and electrical engineering at the University of Calgary, as well as from local industry partners, are expected to be added to the team.

Drs Scheidler and Williams, along with U of C math professor Richard Mollins, have developed three new undergraduate courses, Introduction to Cryptography, Cryptography — the Design of Ciphers, and Advanced Cryptography and Cryptanalysis for second, third and fourth year students, respectively.

The team began with three masters students

in the fall and has since attracted two more to the program, one of whom holds an NSERC Post Graduate Scholarship A.

MSC CANDIDATES

Richard Cannings: Quantum Computing and Cryptography
 Brendan Oseen: Computation of the Cardinality of the Isogeny Class of an Elliptic Curve over a Finite Field
 Kjell Wooding: Development of a High-Speed Numerical Sieving Device

POSTDOCTORAL FELLOWS

Filip Saidak: Analytic and Probabilistic Number Theory
 Safuat Hamdy: Number Field Cryptography
 Siguna Mueller: Public Key Cryptography and Primality Testing

COLLABORATIONS

CENTRE FOR INFORMATION SECURITY AND CRYPTOGRAPHY (CISAC)

One of the main (non research) objectives of the iCORE Chair in Algorithmic Number Theory and Cryptography is to establish a centre of excellence for information security at the University of Calgary using the iCORE Chair as the core and involving team members and other individuals from both inside and outside the University.

DISTINGUISHED VISITORS PROGRAM

We have also inaugurated our proposed Distinguished Visitors Program. We have done this by establishing a Discrete Mathematics Seminar within the Department of Mathematics and Statistics.

PUBLICATIONS

- 1 R.A. Mollin, "Continued Fractions and Class Number Two," *Int. J. Math. and Math. Asc.*, Vol. 27, 2001, pp. 565 -571.
- 2 R.A. Mollin, "Criteria for Simultaneous Solutions of $X^2 - DY^2 = c$ and $x^2 - Dy^2 = -c$," *Canadian Math. Bulletin*, to appear.
- 3 R.A. Mollin, "A Brief History of Factoring and Primality Testing B.C. (Before Computers)," *Math. Magazine* (to appear).
- 4 R.A. Mollin, "The Diophantine Equation $AX^2 - BY^2 = C$ and Simple Continued Fractions," *Int. Math. J.* vol. 2, 2002, pp. 1-6.
- 5 R.A. Mollin and K. Cheng, "Continued Fraction Beepers and Fibonacci Numbers," *Math. Rep. Acad. Sci. Canada* (to appear).
- 6 R.A. Mollin, "Ideal Criteria for Both $X^2 - DY^2 = m_1$ and $x^2 - Dy^2 = m_2$ to have Primitive Solutions for any Integers m_1, m_2 Prime to $D > 0$ " (in press).
- 7 R.A. Mollin, "New Prime-Producing Quadratic Polynomials Related to Class Number One and Two" (in press).
- 8 F. Lemmermeyer and R.A. Mollin, "On the Tate-Shafarevich Groups of $y^2 = x(x^2 - 2)$ " (in press).
- 9 R.A. Mollin, "Pellian Polynomials and Period Lengths of Continued Fractions" (in press).
- 10 R.A. Mollin, "Period Lengths of Continued Fractions Involving Fibonacci Numbers" (in press).
- 11 R.A. Mollin, "The Diophantine Equation $AX^2 - BY^2 = C$ Solved via Continued Fractions" (in press).
- 12 R.A. Mollin, "Infinite Families of Pellian Polynomials and their Continued Fraction Expansions" (in press).
- 13 R.A. Mollin, "Perron and Continued Fractions" (in press).
- 14 R.A. Mollin and K. Cheng, "Families of Long Continued Fractions Revisited" (in press).
- 15 R.A. Mollin and K. Cheng, "Beepers, Creepers and Sleepers" (in press).
- 16 A.J. van der Poorten, H.J.J. te Riele, and H.C. Williams, "Computer verification of the Ankeny-Artin-Chowla Conjecture for All Primes Less than 100 000 000 000," *Mathematics of Computation*, vol. 70, 2001, pp. 1311-1328.
- 17 R. Scheidler, "Ideal Arithmetic and Infrastructure in Purely Cubic Function Fields," *Journal de Theorie des Nombres de Bordeaux*, vol. 13, 2001, pp. 609-631.
- 18 R. Scheidler, "Cryptography in Quadratic Function Fields", *Designs, Codes and Cryptography*, vol. 22, 2001, pp. 239-264.
- 19 J. A. Sellers and H. C. Williams, "On the Infinitude of Composite NSW Numbers," *Fibonacci Quarterly* (to appear).
- 20 M. J. Jacobson, Jr. and H. C. Williams, "New Quadratic Polynomials with High Densities of Prime Values," *Mathematics of Computation* (to appear).
- 21 M. J. Jacobson, Jr. and H. C. Williams, "Modular Arithmetic on Elements of Small Norm in Quadratic Fields," *Designs, Codes and Cryptography* (to appear).

REFEREED CONFERENCE PROCEEDINGS

- 1 H. C. Williams, "Solving the Pell Equation," *Proc. Millennial Conference on Number Theory*, A. K. Peters, M.A. Natick (to appear).
- 2 M. Jacobson, Jr., R. Scheidler, and H. C. Williams, "The Efficiency and Security of a Real Quadratic Field Based Key Exchange Protocol," *Public Key Cryptography and Computational Number Theory*, Walter de Gruyter, Warsaw, 2001, pp. 89-112.

BOOKS AND BOOK CHAPTERS

- 1 K. Alster, J. Urbanowicz, and H.C. Williams, eds., *Public-Key Cryptography and Computational Number Theory*, Proceedings of the International Conference organized by the Stefan Banach International Mathematical Center, Warsaw, Poland, Sep. 11-15, 2000, Walter de Gruyter, Berlin, 2001, 331 pages.

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DR CAREY WILLIAMSON

Broadband Wireless Networks

iCORE PROFESSOR

COMPUTER SCIENCE, UNIVERSITY OF CALGARY

Start Date: July 2001

RESEARCH PROGRAM OVERVIEW

The research program is centered on unifying wireless technologies and the Web, exploiting the full benefits of each. The research program is applied in nature, with a strong focus on experimental computer systems performance research.

The general goals of the research program are:

- identify performance problems and bottlenecks in the design and operation of protocols in wireless/Web-based communications systems;
- propose and evaluate creative solutions to these performance problems;
- promote larger-scale deployment of wireless Internet/Web infrastructure at the University of Calgary

RESEARCH PROJECTS

This section provides four examples of specific projects under way in the research group.

WIRELESS TRAFFIC CHARACTERIZATION

Three of the most exciting and fastest-growing Internet technologies in recent years are the World Wide Web, multimedia streaming, and wireless networks. The Web has made the Internet available to the masses, through its TCP/IP

protocol stack and the principle of layering: Web users do not need to know the details of the underlying communication protocols in order to use network applications. Multimedia streaming provides desktop access to real-time and on-demand audio and video applications for educational and entertainment purposes at home, office, and school. Wireless technologies have also revolutionized the way people think about networks, by offering users freedom from the constraints of physical wires.

All three of these technologies are available today, in desktop or handheld form, at relatively modest cost. Mobile users are interested in exploiting the functionality of the technology at their fingertips, as wireless networks bring closer the “anything, anytime, anywhere” promise of mobile networking. In this project, we explore the convergence of these technologies by studying multimedia streaming applications for mobile Internet users in a wireless local area network (WLAN) environment. We focus on the RealMedia multimedia streaming application, delivering audio and video content from a wired-Internet RealMedia server to a mobile client (laptop or PDA) on an in-building IEEE 802.11b WLAN in the Department of Computer Science at the University of Calgary.

Our study has three objectives. First, we seek to characterize the network traffic workload generated by the RealMedia streaming application, in order to study the impact on the WLAN. Such a characterization is useful in capacity planning studies for the design, deployment, and evolution of larger WLANs. Second, we seek to understand the relationship between wireless channel characteristic (i.e., channel error rate, packet loss, retransmission, delay) and the user-perceived quality of a video stream. We do this using a wireless “sniffer” to capture and analyze the WLAN traffic for a mobile user at a variety of physical locations in our WLAN environment. This portion of the study offers a subjective assessment of video quality as a function of channel error characteristics, with attendant explanations for the performance degradations based on network-level effects. Third, we attempt to understand the impacts

of competing Internet TCP/IP packet traffic on the quality of a RealMedia streaming session. Again, we use WLAN traffic measurements to ascertain the behaviour of RealMedia streaming in the presence of bandwidth-hungry TCP traffic flows.

Ongoing work is extending the wireless network traffic measurement and characterization study to the wireless Internet classroom, where the purpose is to understand the user behaviours, application usage, network bandwidth demands, and protocol performance for more general Internet usage.

CONTEXT-AWARE TCP/IP

One of the primary challenges in the wireless Internet context is “performance transparency”: providing an end-user Internet experience that is (hopefully) no worse than that in the traditional wired-Internet desktop environment. In this project we focus on the role of “awareness” in the Internet protocol stack, and its influence on network protocol performance. We use the Web application as the primary motivating example.

The Web relies primarily on three communication protocols: IP, TCP, and HTTP. The Internet Protocol (IP) is a connection-less network-layer protocol that provides global addressing and routing on the Internet. The Transmission Control Protocol (TCP) is a connection-oriented transport-layer protocol that provides end-to-end data delivery across the Internet. Among its many functions, TCP has flow control, congestion control, and error recovery mechanisms to provide reliable data transmission between sources and

destinations. The robustness of TCP allows it to operate in many network environments. Finally, the Hyper-Text Transfer Protocol (HTTP) is a request-response application-layer protocol layered on top of TCP. HTTP is used to transfer Web documents between Web servers and Web clients (browsers).

Several interesting protocol interactions occur when TCP is used to transfer Web documents. For example, TCP's flow and congestion control algorithms are (arguably) designed to optimize throughput for long-lived bulk data transfers. The TCP slow-start phase is used initially to probe the network capacity, and steady-state is typically reached in the congestion avoidance phase. For small documents, however, the steady-state congestion avoidance phase is not always reached before the transfer terminates. Unfortunately, the extra round-trip times incurred during TCP slow-start add to the transfer times for Web users.

Our work is motivated by three observations. First, not all packet losses are created equal. Some TCP packet losses incur a coarse-grain timeout and retransmission at the sender; others incur only a fast retransmit to recover the missing packet. The effect on Web document transfer time can be dramatically different depending on which of these two scenarios occurs. Second, TCP sources have relatively little control over packet loss within the Internet. In particular, they have little control over how a packet loss affects them. Third, IP routers have a significant role to play in how packet losses affect the transfer times for individual TCP flows.

A question follows naturally from the above

observations: can we make the TCP/IP protocols “smarter” about the specific job (i.e., Web document transfer) that they are trying to do? As a possible answer, we propose a “goal-oriented” transport-layer protocol called the Context-Aware Transport/Network Internet Protocol (CATNIP). CATNIP is based on the TCP protocol, but changes the sender's TCP/IP protocol stack to get information, such as Web document size, from the application layer. Based on this information, CATNIP sources can make informed decisions about flow and congestion control, so as to reduce traffic burstiness, avoid packet losses in small windows, and improve Web document transfer times. Similarly, CATNIP routers can make informed packet discard decisions when Internet congestion occurs.

Ongoing work is extending the CATNIP idea to the wireless domain.

WEB SERVER BENCHMARKING

Web server performance plays a central role in the user-perceived “Internet experience,” and thus has been the focus of a lot of recent research. Many different Web server architectures have been proposed, and evaluated on a wide range of platforms. Many implementation optimizations have been proposed for Web servers as well, particularly in regards to communication protocol handling, request scheduling, and reducing system overhead.

One of the challenges in comparing and evaluating Web servers is the sensitivity of Web server performance to a broad set of system-level and application-level configuration parameters. For example, some Web

servers are process-based, some are not; some Web servers use memory-mapped files, some do not; some Web servers are highly optimized for static content retrieval, while others are not. Understanding the performance tradeoffs between these configuration choices is complicated. In addition, the characteristics of the workload presented to the Web server can have a dramatic effect on the observed performance. In fact, fundamentally different server behaviours can result for different workloads, depending on whether the primary system bottleneck is the CPU, the network bandwidth, or the network latency.

This project focuses on building an experimental environment for the benchmarking of Web servers and Web proxy caching appliances. For simplicity, we focus only on the LAN environment in this work, though a companion project considers Wide Area Network (WAN) emulation. The approach relies on relatively fine-grain reporting of performance data for a broad set of system-level performance metrics. Graphical visualization of these performance indices helps to identify the primary system bottleneck in each configuration studied.

HIGH-PERFORMANCE NETWORK EMULATION

Network emulation is a hybrid performance evaluation methodology that combines aspects of experimental implementation with aspects of simulation (or even analytical) modeling. This approach has received increasing research attention in recent years as researchers address large, complex, and challenging Internet performance problems.

The network emulation approach offers a flexible, controllable, and reproducible environment for performance experiments. It enables controlled experimentation with end-user applications (e.g., Internet gaming, video streaming) without facing the transient behaviours of the Internet. More importantly, emulation enables experimentation with a wide range of network and workload configurations. It is well known that the properties of a Wide-Area-Network (WAN) can have significant impact on Internet protocol behaviours and Web server performance. Testing in a wide range of WAN scenarios can provide greater confidence in the robustness of a server or application prior to Internet deployment.

In this project, we focus on Web server benchmarking using the Internet Protocol Traffic and Network Emulator (IP-TNE) developed by Rob Simmonds and others at the University of Calgary. The IP-TNE is built using a parallel discrete-event simulation (PDES) kernel, enabling high-performance WAN emulation. The IP-TNE provides a detailed simulation model of an arbitrary IP internetwork WAN topology. Internet hosts can send IP packets to other hosts, whether real (on the Internet) or virtual (within the simulated WAN), via the emulator. Similarly, virtual hosts within the emulator can send (real) IP packets to other (real) hosts on the Internet. The translation of packets between real and simulated Internet environments is accomplished through a technique similar to “IP masquerading,” carefully implemented to provide high-performance packet reading and writing at Gigabit Ethernet rates.

The purpose of the project is to demonstrate the capability of parallel network emulation using the IP-TNE. We use Web server benchmarking as a case study, for three reasons. First, it demonstrates the packet-handling and throughput capabilities of the IP-TNE as a Web server workload generator. Second, it serves to validate prior results in the literature highlighting the impacts of WAN conditions on Web server performance. Third, our study demonstrates that WAN emulation using a single computer is feasible for Web server benchmarking.

INTRODUCTION TO THE RESEARCH TEAM

Current members of the research team are:

- Martin Arlitt: Senior Research Associate with expertise in Web workload characterization, Web performance, and Web server benchmarking.
- Guangwei Bai: Postdoctoral Fellow with expertise in Internet traffic modeling.
- Tianbo Kuang: Research Associate with expertise in wireless networks, video compression, and network traffic measurement.
- Nayden Markatchev: System/Network Administrator for the research lab who also does research on network simulation, traffic modeling, and graphical user interfaces.

- Qian Wu: Research Associate with expertise in TCP/IP protocols and network simulation.

This research team has a broad set of skills and expertise, including Internet protocols, wireless networks, network traffic measurement, network simulation, and performance evaluation. Four MSc students are part of the team as well: Mingwei Gong, Yujian (Peter) Li, Kehinde (Kenny) Oladosu, and Fang (Shelly) Xiao. Four more graduate students are scheduled to arrive in September 2002.

Key collaborators are:

- Dr Rob Simmonds, University of Calgary
- Dr Brian Unger, University of Calgary

COLLABORATIONS

We were awarded \$1.2 million from the Canada Foundation for Innovation (CFI) to build the Experimental Laboratory for Internet Systems and Applications (ELISA). Matching funds from the Province of Alberta and the Province of Saskatchewan will enable procurement of equipment for the ELISA laboratory in the near future. The ELISA lab is a geographically-distributed experimental Internet testbed between the University of Calgary and the University of Saskatchewan. It will be used for the testing, measurement, and evaluation of new and emerging Internet applications. Research at the University of Calgary end will focus on wireless networks, Web performance, network traffic measurement, and network emulation. Research at the University of Saskatchewan will focus on media streaming, multicast, and mobile computing applications.

PUBLICATIONS

At least one paper has been co-authored with each research staff members this year. This reflects well on the expertise and research ability of my research staff, and has made for a productive first year in my position at the University of Calgary. In my opinion, two of these papers are of particular significance. First, the IP-TNE paper [1] significantly advances the state of the art for WAN emulation. Better yet, we have only explored the “tip of the iceberg” with the IP-TNE so far. We look forward to further research collaborations with Rob Simmonds and Brian Unger as we see what IP-TNE can do. Second, the CATNIP paper [6], establishes a new research theme on the role of “awareness” in protocol performance, which will be central to ongoing work on wireless Web performance. Both of these papers make nice contributions to the literature and lay the groundwork for further research.

RECENT PUBLICATIONS

- 1 C. Williamson, R. Simmonds, and M. Arlitt, “A Case Study of Web Server Benchmarking Using Parallel WAN Emulation,” *Proceedings of IFIP Performance 2002*, Rome, Italy, September 2002.
- 2 T. Kuang and C. Williamson, “A Measurement Study of RealMedia Audio/Video Streaming Traffic,” *Proceedings of SPIE ITCOM 2002*, Boston, MA, July 2002.
- 3 G. Bai and C. Williamson, “Time-Domain Analysis of Web Cache Filter Effects,” *Proceedings of International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS’02)*, San Diego, CA, July 2002.
- 4 T. Kuang and C. Williamson, “RealMedia Streaming Performance on an IEEE 802.11b Wireless LAN,” *Proceedings of IASTED Wireless and Optical Communications Conference (WOC 2002)*, Banff, AB, July 2002.
- 5 M. Busari and C. Williamson, “ProWGen: A Synthetic Workload Generation Tool for Simulation Evaluation of Web Proxy Caches,” *Computer Networks*, vol. 38, no. 6, pp. 779-794, June 2002.
- 6 C. Williamson and Q. Wu, “Context-Aware TCP/IP,” *ACM Performance Evaluation Review*, vol. 29, no. 4, pp. 11-23, March 2002.
- 7 C. Williamson, “On Filter Effects in Web Caching Hierarchies,” *ACM Transactions on Internet Technology*, vol. 2, no. 1, pp. 47-77, February 2002.
- 8 C. Williamson, “Internet Traffic Measurement,” *IEEE Internet Computing*, vol. 5, no. 6, pp. 70-74, November/December 2001.

PAPERS IN SUBMISSION

- 1 M. Arlitt and C. Williamson, “Understanding Web Server Configuration Issues: Principles, Pitfalls, and Performance.”
- 2 G. Bai and C. Williamson, “Workload Characterization in Web Caching Hierarchies”
- 3 N. Markatchev and C. Williamson, “WebTraff: A GUI for Web Proxy Cache Workload Modeling and Analysis.”
- 4 C. Williamson and N. Markatchev, “Multi-Variate Analysis of Mobility Models for Network Protocol Performance Evaluation.”



Notes

