

2005 Research Report

NORMAN BEAULIEU**APRIL 2004 - MARCH 2005**

This document is an excerpt from the 2005 iCORE Annual Research Report. For information or copies, please contact iCORE.

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A man with a beard and glasses, wearing a dark suit, a light blue shirt, and a yellow patterned tie, stands in front of a building with large windows. The text 'WIRELESS COMMUNICATIONS LABORATORY' is overlaid in large, bold, yellow letters on the right side of the image.

WIRELESS COMMUNICATIONS LABORATORY

Ultra-wide bandwidth systems (UWB), multiple-input multiple-output systems (MIMO), and wideband orthogonal frequency division multiplexing (W-OFDM) are “hot” new solutions being investigated in the iCORE Wireless Communications Laboratory.

NORMAN C. BEAULIEU

iCORE Chair

Electrical and Computing Engineering, University of Alberta

<http://www.ece.ualberta.ca/~iwcl/>

Each year the iCORE Wireless Communications Laboratory team undergoes renewal as the important areas of wireless evolve and as excellence and productivity drive the membership.

Dr Norman C. Beaulieu has held the iCORE Wireless Communications Laboratory Chair and Professorship since 2000. University of Alberta faculty members Dr Witold Krzymien, Dr Chintha Tellambura and Dr Vincent Gaudet, as well as University of Calgary faculty member Dr Abraham Fapojuwo and new recruit, iCORE Junior Chair Masoud Ardakani, form the iCORE Wireless Communications Laboratory Team.

Dr Xiaodai Dong was recruited as iCORE Junior Chair and iCORE Research Associate from September 2000 to December 2004. The iCORE Wireless Communication Laboratory thanks Dr Dong for her past participation with the team.

EXECUTIVE SUMMARY

The overall goal of the iCORE Wireless Communications Laboratory (iWCL) research program is to create new engineering science and technologies that will lead to higher capacities in broadband wireless communication systems at lower cost. Having established an internationally recognized program of scholarly research to meet this goal, the iCORE Chair is now building an intellectual property portfolio while maintaining its scholarly activities.

The research activity of Professor Krzymień and his graduate students is focused on broadband high throughput packet data access to the Internet for mobile and nomadic users, employing orthogonal frequency division multiplexing (OFDM) and spread spectrum signalling, and multiple-input multiple-output (MIMO) antenna techniques. The work includes physical link layer issues such as adaptive modula-

tion and coding, space-time coding, multiple access interference cancellation and long range channel state prediction, as well as medium access control (MAC) and radio resource management questions, such as hybrid ARQ (Automatic Repeat reQuest) and packet transmission scheduling algorithms.

Dr Fair and his graduate students are investigating efficient channel coding techniques for wireless communication systems. The three main areas of work include development of efficient turbo decoding techniques, new codes for MIMO systems, and coding techniques to reduce the peak-to-average power ratio in OFDM systems.

Dr Tellambura's research interests are focused on multi-carrier techniques and wireless fading channel communications. Particular focus is on techniques for the design of high rate, high reliability wireless networks that integrate OFDM and space-time coding.

Dr Fapojuwo and his graduate students are investigating efficient protocols and algorithms for high performance wireless communication networks. The goal is to propose, develop and analyze the performance of new and efficient protocols at the data link, transport and network layers of the open system interconnection (OSI) reference model to achieve enhanced capacity and performance in future generation wireless wide area (cellular) networks (WWANs), wireless local area networks (WLANs), and mobile ad hoc networks (MANETs).

These collaborations have resulted in an unprecedented number of successful journal and conference papers. Nineteen refereed journal papers appeared in the reporting period, all in leading international journals. A further 15 refereed journal papers were accepted in the reporting period, again all in leading international journals. In addition, 38 conference papers were presented by the iCORE Chair and his research trainees in the reporting period. A further

twenty conference papers were accepted for presentation in May, June, August, and September 2005. In addition, one invited paper was presented at a major international conference in Spain.

The iWCL has also been successful in obtaining external funding: bringing \$1,411,706 of other research funding to the program. Additionally, research trainees in the program have received \$293,329 in external awards.

In consequence of the achievements, awards, recognition and growth of the first forty-three months, the iWCL is now well known in the international communications research community and is increasing international and national awareness of Alberta, iCORE and the University of Alberta.

RESEARCH PROGRAM OVERVIEW

To reach the wireless communications goal of higher capacity at lower cost, new engineering science must be put into action in the development of new technologies for real world systems. In order to provide higher data transmission rates to more users without sacrificing the integrity of the received information, advances must be made in the transmission system designs and components.

The primary thrust of the iWCL research is investigation into fundamental properties, limitations, and improvements in broadband wireless systems. A secondary thrust is the application of the research results to present and future systems. To that end, the team is investigating a number of scientifically important and industrially relevant topics.

RESEARCH PROJECTS

BEAULIEU: RESEARCH PROJECTS

1) Ultra-Wide Bandwidth (UWB) Communications Systems

UWB refers to new systems and technologies that are envisioned to provide short range, high data rate services to multiple users in an unlicensed transmission format. UWB systems are attracting great scientific and industrial interest. These systems are unconventional in that they spread the information signal over an extremely wide bandwidth, occupying many gigaHertz of spectrum. Correspondingly, the signals have an extremely small power spectral density and appear as noise to existing users. Further, unlike conventional wireless communication systems that are carrier-

based, an UWB system is a carrier-less system, which transmits the digital information without translating it to a carrier frequency. As an emerging technology, UWB offers great potential as an area where one can make fundamental theoretical contributions and at the same time develop technology that can lead to socio-economic benefits for the supporting community. Our team has derived the only mathematical solution for predicting the bit error rate (BER) in a multiple access environment due to the multi-user interference, that is accurate for all regions of signal-to-noise ratio (SNR). Using this solution, we have undertaken the first accurate BER comparison of time-hopping (TH) UWB systems employing pulse position modulation (PPM) and binary phase shift keying (BPSK). Our team is well positioned to conduct further research on UWB receiver design, building on our past research and on the effects of quantization on signal detection. In this work, we expect to find new non-coherent receiver designs, possibly leading to intellectual property.

2) Orthogonal Frequency Division Multiplexing (OFDM) Systems

OFDM is a transmission aimed for high speed wireless data communication, and is also relevant to digital audio and video broadcasting. OFDM has undergone three generations, each generation representing major advances in technology, performance and cost over previous generations. The benefits of third generation OFDM make it popular in today's broadband wireless communications industry, and new OFDM technologies are expected to be leading candidates for fourth generation wireless (4G) systems. A shortcoming of OFDM is the intercarrier interference (ICI) that results from frequency offsets. A novel pulse-shape discovered by our team has been shown to improve the performance of typical OFDM systems. Further new insights and results about pulse-shaping recently published by our team will be applied to the OFDM pulse-shaping problem in ICI environments.

Further proposed work on equalization for OFDM will have two aspects. The first is designing better equalizers for OFDM systems using particular modulation formats. The second is designing equalizers for zero-padding DCT OFDM systems.

3) Multi-user Detection and Interference Rejection

The development of multi-user detection techniques is one of the most important recent advances in communications technology. Frequency spectrum is a limited resource and multiple users must share spectrum. Multi-user detection techniques have the potential to increase system capacity by joint processing of multiple interfering user signals. Optimal multi-user detection receivers are prohibitively complex. In consequence, much research has been

done on sub-optimal multi-user detection techniques and on the related topic of interference rejection. Most multi-user detection and interference rejection research has focused on multi-user detection for code division multiple access (CDMA) spread spectrum (SS) systems. Meanwhile, greater user capacities can be achieved in all wireless systems: frequency division multiple access (FDMA), time division multiple access (TDMA) and UWB systems, by employing multi-user detection and interference rejection techniques, and letting several users share one communication channel. Building on recent research done at the iCORE Wireless Communications Laboratory our team will investigate individually optimal and jointly optimal receiver designs for co-channel interference (CCI) environments and simplified, implementation-friendly sub-optimal versions of the optimal designs. On separate tracks, we will also investigate whitening CCI receivers and other interference rejection approaches to increasing user capacities for FDMA, TDMA, UWB and CDMA systems.

4) Multiple-Input Multiple-Output (MIMO) Systems

MIMO systems provide real-time multimedia applications at high data rate and low latency, and also provide robustness to interference and significantly improve the error rate performance. Our team will perform detailed investigations into the fundamental limits of MIMO systems and into application strategies for approaching them. Our research will include:

- Non-coherent space time systems

- Smart antennas and adaptive modulation
- Low-complexity space-time coding systems and applications to wireless sensor networks

Furthering earlier work on low-complexity space-time coding (this code design methodology and some codes designed using it are the subject of a University of Alberta patent application), the team will develop systematic methodologies for designing codes that are robust against channel variations.

An additional focus for results and techniques obtained in our research into non-coherent space-time systems and low complexity space-time coding systems will be to design coding schemes for wireless sensor networks.

5) Computer Simulation and Semi-Analytical Techniques

Computer simulation is widely used in industry and academia to predict how well new systems and components will function and to optimize system performance. Our team has contributed some widely used computer simulation tools, including the most efficient method known for generating correlated Rayleigh samples for simulating urban fading channels. Advances in simulation methods are always needed because as the technology advances, the systems and components to be simulated become more complex. Building on our past and continuing work, we will investigate rejection sampling for efficient simulation of coding schemes. Some preliminary investigations carried out at iWCL indicate that by appropriately matching the rejection regions to the code structure

iCORE Chair Norman Beaulieu and some members of his associated research team at the 2004 Banff Informatics Summit



and to the quantization of the processed received signals, the dimensionality problem can be relieved for codes as long as hundreds and, in some cases, thousands of symbols.

We also propose to find more efficient simulation techniques for UWB systems by combining some semi-analytical models with the IEEE UWB channel model. Recent work we have published reports simple and highly accurate analytical approximations to sums of lognormal, Rayleigh and Ricean random variables. We will use these results to construct more efficient semi-analytical simulation models for UWB systems.

6) Wireless Networking

Two key research directions for future generation wireless networks are support of multimedia applications with different Quality of Service (QoS) requirements and inter-networking between heterogeneous wireless network architectures. Firstly, we will explore the use of a cross-layer design approach for QoS support in Mobile Ad-hoc Networks (MANETs), to develop and evaluate appropriate QoS provisioning mechanisms for MANETs, to investigate the QoS robustness of multimedia applications in MANET environments in the presence of hostile wireless channel and dynamic MANET topology, and to propose a cross-layer interactions framework for QoS support in MANETs and evaluate its performance. Secondly, we will focus on mechanisms for achieving efficient and effective Wireless Local Area Network (WLAN)-Cellular Inter-networking.

WLANs provide data rates much higher than those of 2G and 3G cellular networks, but operate within a local area. WLAN and cellular network technologies are mutually complementary and their integration will present an enhanced user experience and a strong market opportunity, especially in the enterprise environment. The main objectives of the proposed research on WLAN-Cellular Inter-networking are to design and evaluate protocols and mechanisms to achieve seamless inter-network roaming between 802.11 WLANs and cellular networks, to propose and evaluate mechanisms for provisioning, preserving and assuring the QoS of multimedia applications in an integrated network, and to design and evaluate protocols and mechanisms to achieve low-latency handoff of multimedia calls in an integrated network.

7) Hardware Fading Channel Simulation

Our team will build an emulator to model Rayleigh, Ricean, Nakagami and lognormal fading conditions, and be suitable for MIMO and UWB design tests. Fast simulation of communications algorithms in base-band hardware is often required in order to optimize architectural parameters, and to verify functionality at low bit error rates. Channel emulators, implemented on field-programmable gate arrays (FPGAs), have recently been used to generate high-speed additive white Gaussian noise, and can be used to test novel error control decoding schemes at lower bit error rates than would be feasible in software simulation. In this project a ubiquitous channel emulator capable of emulating diverse fading channel conditions will be implemented on an FPGA device.

The channel emulator will then be expanded into a 4x4 MIMO channel emulator. Since throughput of this emulator might be limited by the size and speed of the available FPGA devices, an application-specific integrated circuit (ASIC) version of this emulator will be designed and fabricated.

OBJECTIVES FOR NEXT YEAR

The iCORE Wireless Communications Laboratory has established itself as an internationally leading wireless research centre, creating recognition and awareness of iCORE, the University of Alberta, and Alberta in the engineering science and industrial communities. Having achieved the immediate preliminary goals, the planning for the future evolution of the research program and the development of the laboratory aims at three objectives.

The first objective is to maintain or increase the present levels of scholarly research and training of highly skilled personnel to preserve the world-class



Norman C. Beaulieu

standing of the wireless research centre in Edmonton. The primary thrust of the research is investigation into fundamental properties, limitations, and improvements in broadband wireless communication systems. A secondary thrust is the application of the research results to present and future systems. This two-pronged approach is consistent with the Chair's belief that strong fundamental research is vital to the understanding and improvement of technically challenging systems, while application of the fundamental research results is an important step in creating economic benefits for the supporting community.

The second objective is the expansion of the team by the recruitment of two Junior Chairs. The Department of Electrical and Computer Engineering has been led by a new Department Head since July 1, 2004. We are working closely with the new Department Head to build Wireless as a key strategic area in research and teaching for the department. Moreover, the success and achievements of the first 56 months of operation of the iCORE Research Chair in Wireless Communications justify consideration of expansion of the group. Proposals for the establishment of two junior chairs are in preparation. These two positions would be adjunct to the iCORE Chair. The strategy is to seek industrial partners who would co-sponsor the junior chairs with a funding agency such as iCORE or with the university. In particular, it is desirable to add strength in the areas of space-time coding and of signal processing for wireless communications.

The third objective is the development of an intellectual property portfolio on the basic premise of creating benefit for the University of Alberta, and the province of Alberta. While maintaining or increasing the stature of the group as an international centre of excellence in wireless through research, publication and the training of highly skilled personnel, all research results will be carefully reviewed with a view to potential value in intellectual property. This process will be selective and will involve consultation with industrial collaborators. Results which are assessed as having true potential for wealth creation will be submitted to TEC Edmonton Ltd. (the Technology, Entrepreneur & Company Development agency of The University of Alberta) for patent prosecution and commercialization. All inventions will be assigned to the University of Alberta; there will be no commercialization independent of the University. In cases where inventions arise in collaborative research with researchers based outside the University of Alberta, fair interest in intellectual property will be retained for the University of Alberta. Consistent with this new objective of building an intellectual property portfolio, the Chair has filed two patents and one Report of Invention in the reporting year.

KRYZMIEŃ: RESEARCH PROJECTS

Professor Krzymień's current research work is the creation of key technologies essential for the future design of advanced broadband wireless packet data systems enabling bandwidth and power efficient high bit rate access to the Internet for nomadic and mobile users of data and multimedia services. The main application target of his work is 4G cellular radio systems and networks, although the technologies expected to emerge from it will also be very applicable to the design of high throughput broadband WLANs. The main research activity corresponds to the three major, and rapidly developing areas in digital wireless communications: radio link adaptation techniques and related optimized radio resource management, MIMO antenna systems and related space-time processing and coding, and effective and robust multi-carrier transmission techniques.

The team's work is currently focused on broadband high throughput packet data access to the Internet for mobile and nomadic users, employing OFDM and spread spectrum signalling, and MIMO antenna techniques. The work includes physical link layer issues such as adaptive modulation and coding, space-time coding, multiple access interference cancellation and long range channel state prediction, as well as MAC and radio resource management questions, such as hybrid ARQ and packet transmission scheduling algorithms

FAIR: RESEARCH PROJECTS

Dr Fair and his graduate students are investigating efficient channel coding techniques for digital communication systems. During the past year, this research has resulted in two journal letter items and eleven conference papers. The goal of Dr Fair's research is to develop efficient, easily implemented coding algorithms that result in improved performance in digital communication systems.

Research projects with which Dr Fair is involved include the development of:

- Efficient turbo decoding techniques
- Error control codes for MIMO wireless systems
- Techniques to limit the peak-to-average power ratio in OFDM systems
- Techniques which integrate error control codes with codes for other system constraints such as limited PAPR and specific spectral characteristics



TELLAMBURA: RESEARCH PROJECTS

Dr Tellambura's research interests are focused on multicarrier techniques and wireless fading channel communications.

The research challenge is to design economical, efficient and high-data-rate wireless systems, overcoming fading and other inherent wireless distortions in standardization of 4G or "beyond third generation" (B3G) systems. The primary goals and objectives of the research program are therefore to develop and analyze physical layer protocols for emerging wireless standards and applications. Research projects include:

- Space-time coded multi-carrier modulation for high-data-rate wireless systems
- Efficient detection of differential space-time modulation
- Efficient space-time detection
- Estimation techniques for OFDM to develop efficient detection algorithms for space-time coded multiple antenna systems
- To develop efficient algorithms for parameter estimation for multiple antenna OFDM systems

FAPOJUWO: RESEARCH PROJECTS

Dr Fapojuwo and his graduate students are investigating efficient protocols and algorithms for high performance wireless communication networks. During the past year, this research has resulted in six journal papers, and seventeen conference papers. The research has also resulted in the successful completion of four MSc theses and one MEng project.

The goal of Dr Fapojuwo's research is to propose, develop and analyze the performance of new and efficient protocols at the data link, transport and network layers of the open system interconnection (OSI) reference model to achieve enhanced capacity and performance in future generation wireless WWANs, wireless local area networks, wireless personal area networks, MANETs and wireless sensor networks.

Research projects with which Dr Fapojuwo is involved during 2004 include:

- Radio resource management schemes for wireless Internet protocol (IP) networks

- Adaptive QoS techniques for CDMA2000 wireless networks
- QoS support in IEEE802.11 wireless local area networks
- Traffic measurements, modeling and characterization in wireless networks
- Impact of hidden nodes on wireless local area network performance;
- Security mechanisms in wireless local area networks
- QoS routing protocol for mobile ad hoc networks;
- Analysis of secure routing protocols for MANETs
- Medium access protocol for UWB WPAN Systems
- Interference Cancellation techniques in OFDM-WPAN Systems
- Sub-carrier Management in OFDM-based Cellular Systems
- Service discovery protocols for MANETs
- Hidden Markov Model based Speech Activation System for Wireless Home Networks
- Application of software agents to resource management in wireless networks

Objectives for the next year (2005) include:

- Design and deployment of CFI-funded wireless network testbed for testing and evaluation of the proposed protocols
- Propose and evaluate QoS routing protocols for Wireless Sensor Networks
- Design of a wireless data center
- Explore the gains and costs of cross-layer interaction as applied to wireless networks performance
- Study the implications of inter-working and inter-operability between WWAN, WLAN and MANET networks in an integrated/hybrid wireless network architecture
- Propose networking and capacity solutions for tactical MANETs

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

Team Leader

PROFESSOR NORMAN C. BEAULIEU
iCORE Chair in Broadband Wireless Communications
Canada Research Chair in Broadband Wireless Communications
Médaille K.Y. Lo Medal (2004)
Fellow of the Royal Society of Canada
NSERC E.W.R. Steacie Memorial Fellow
Fellow of the Institute of Electrical and Electronics Engineers (IEEE)
Fellow of the Engineering Institute of Canada (EIC)
Editor-in-Chief of the IEEE Transactions on Communications (2000-2003)
President of the Canadian Society for Information Theory

Beaulieu: Faculty Team Members

	ROLE	
Dr Witold A. Krzymień, Professor	Faculty Team Member	Rohit Sharma Professorship in Communications and Signal Processing (2003) Fellow of the Engineering Institute of Canada (EIC)
Dr Ivan Fair, Associate Professor	Faculty Team Member	
Dr Chintha Tellambura, Associate Professor	Faculty Team Member	
Dr Xiaodai Dong, Associate Professor	Faculty Team Member	
Dr Abraham Fapojuwo, Assistant Professor	Faculty Team Member	

Beaulieu: Postdoctoral Fellows

	TOPIC	AWARDS
Dr Julian Cheng	Advanced Wireless Technologies for 3G and 4G	
Dr M. Oussama Damen	Space-Time Coding and MIMO Systems	Nortel Networks Associate Research Chair in Communications
Dr Zheng Du	OFDM and Space-Time Coding	



Beaulieu: PhD Students

	TOPIC	AWARDS
Kareem Baddour	Autoregressive Simulation Methods for MIMO systems	
Yunfei Chen	Wireless Channel State and Model Parameter Estimation	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
Ethan Davis	Signal Classification and Modulation Identification	
Payam Dehghani Rahimzadeh	Synchronization for OFDM Wireless Systems	
Golnaz Farhadi	Space Time Processing in MANETs	iCORE International Graduate Student Award (2004-2005) Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
Sasan Haghani	Capacity of Fading Wireless Channels	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship J. Gordin Kaplan Graduate Student Award
Bo Hu	Performance Analysis and Design of UWBs	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
Pavel Loskot	Efficient Semi-Analytical and Simulation Methods for Wireless System Performance Assessment	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship Mary Louise Imrie Graduate Student Award
Reza Nikjah	Novel MC-FH-CDMA Technology for Multimedia Wireless Systems	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
Somasundaram Niranjan	Modeling and analysis of channel impairments in UWB Systems	
Amir Masoud Rabiei	Multiuser Detection and Power Control	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship Mary Louise Imrie Graduate Student Award
Kathiravetpillai Sivanesan	Receiver Designs for Multiuser Detection	Conference Travel Award (IEEE Military Communication Conference 2004, Monterey, CA, USA)
Peng Tan	Novel Receivers for OFDM Communications Systems	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
David Young	A Novel Increased Data Rate Multiuser Transmission Scheme	
Xiaodi Zhang	Performance analysis of H-S/MRC systems	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship

Beaulieu: MSc Students

	TOPIC	AWARDS
Robert Carruthers	An Improved Markov Model for Signal Amplitude Fading over Wireless Channels	
Jeremiah Hu	Simple Analytic Models for Equal Gain Combining Diversity Systems	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship iCORE Science to Society Conference Scholarship J Gordon Kaplan Graduate Student Awards Walter H. Johns Graduate Studies Scholarship Alberta Learning Graduate Student Scholarship NSERC PGS
Wenyu Li	Novel Diversity Combining Schemes for Space-Time Systems	
Tim Poon	Optimal Multiuser Receiver Designs for Co-Channel Interference Environments	
Faruq Rajwani	Novel Closed-Form Approximations to Lognormal Sum Distributions	iCORE Graduate Student Scholarship NSERC PGS

Beaulieu: Undergraduate Student

	TOPIC	AWARDS
Steven Soneff	Bounds on the Number of Vectors Having a Maximum Cross-Correlation Magnitude	Dean's Research Award, Faculty of Engineering, University of Alberta NSERC Summer Undergraduate Research Scholarship President's Citation, University of Alberta Transalta Memorial Scholarship Luscar Engineering Scholarship

Beaulieu: Other Team Members

	POSITION	ROLE
Lingzhi Cao	Research Engineer	Conduct preliminary research on high-risk ideas and prepare audio-visual and outreach material
Chris Jones	System Administrator	Provide computer support to Dr Beaulieu and all team members associated with the iWCL.
Adil Kodian	System Administrator	Provide computer support to Dr Beaulieu and all team members associated with the iWCL.
Sharon Walker	Administrative Assistant	Provide administrative and secretarial assistance to Dr Beaulieu and all team members associated with the iWCL.
Sandra Abello	Administrative Assistant	Provide administrative and secretarial assistance to Dr Beaulieu and all team members associated with the iWCL.



Kryzmięń: Postdoctoral Fellows

	ROLE/TOPIC	AWARDS
Dr Bartosz Mielczarek	Alberta Ingenuity Fellow/ Techniques for High Throughput Wireless Packet Data Access	
Dr Erik Haas	Visiting Scientist from the German Aerospace Centre (funded by the German side)/Advanced Algorithms for OFDM Signal Detection	

Kryzmięń: PhD Students

	ROLE/TOPIC	AWARDS
Robert Elliott	TRLabs PhD Student, NSERC Canada Graduate Scholar, Alberta Ingenuity Scholar/Scheduling Algorithms for High Throughput Multiple Antenna Wireless Packet Data Systems	TRLabs Fellowship NSERC Canada Graduate Scholarship Alberta Ingenuity Studentship
Kevin Jacobson	TRLabs PhD Student, NSERC Scholar/Relay Networks for 4 th Generation Cellular Systems	TRLabs Fellowship NSERC PGS B Scholarship
Chunlong Bai	TRLabs PhD Student and Alberta Ingenuity Scholar (co-supervised with Dr I.J. Fair)/Hybrid ARQ Protocols Optimized for Adaptive Multi-Carrier MIMO Wireless Packet Data Systems	Alberta Ingenuity Fund Studentship TRLabs Fellowship
Jia Liu	TRLabs PhD Student/Non-Linear Transmitter Pre-Processing Algorithms for Layered MIMO Multi-User Wireless Systems	TRLabs Scholarship
Shreeram Sigdel	TRLabs PhD Student/Efficient Receiver Algorithms for MIMO Wireless Systems Employing Adaptive Multi-Carrier Transmission	TRLabs Scholarship
Geoffrey Messier	TRLabs PhD Student/Techniques for Improved CDMA Forward Link Performance (project completed, Mr Messier graduated in summer 2004)	TRLabs Scholarship
Ge Li	TRLabs PhD Student (co-supervised with Dr I.J. Fair)/Low Density Parity Check (LDPC) Codes for MIMO Wireless Systems	TRLabs Scholarship
David Mazzaresse	TRLabs PhD Student and Rohit Sharma Scholar/High Throughput Downlink Cellular Packet Data Access with Multiple Antennas and Multi-User Diversity	TRLabs Scholarship
Robert Novak	TRLabs PhD Student/Adaptive Spread Spectrum OFDM High Throughput Cellular Packet Data Systems	TRLabs Scholarship
James Z. Yang	PhD Student (co-supervised with Dr C. Schlegel)	
Kay Wee Ang	Part-time PhD student; employed by the Institute for Infocomm Research, Singapore/Improved Hybrid Subtractive Interference Cancellation Schemes (project completed, Mr Ang graduated in December 2004)	

Kryzmięń: MSc Students

	ROLE/TOPIC	AWARDS
Yu Fu	MSc student, (co-supervised with Dr C. Tellambura)/Intercarrier Interference Reduction in MIMO OFDM Systems	

Kryzmięń: Other Team Members

	ROLE/TOPIC	AWARDS
Robert Hang	Research Associate/ Algorithms for Layered MIMO Systems	

Fair: Postdoctoral Fellows

	ROLE/TOPIC	AWARDS
Dr Yan Xin	Postdoctoral Fellow/PAPR reduction in OFDM systems	Alberta Ingenuity Associateship

Fair: PhD Students

	ROLE/TOPIC	AWARDS
Fengqin Zhai	PhD Student/Integration of error control and constrained sequence codes	
Ge Li	PhD Student (Co-supervised with Dr Krzymięń)/Low density parity check (LDPC) codes for MIMO wireless systems	
Chunlong Bai	PhD Student (Co-supervised with Dr Krzymięń)/Hybrid ARQ coding schemes for adaptive high throughput wireless data links employing MIMO antenna systems	Alberta Ingenuity Fund Full-time Studentship TRLabs Fellowship
Yongguang Zhu	PhD Student/Constrained sequences	
Emma Frontana	PhD Student/PAPR and ICI reduction in OFDM systems	CONACYT Scholarship

Fair: MSc Students

	ROLE/TOPIC	AWARDS
Aaron Hughes	MSc Student/Integration of error control and constrained sequence codes	TRLabs Scholarship
Ali Alavi	MSc Student (co-supervised with Dr Tellambura)/Techniques for peak-to-average power ratio reduction in OFDM systems (defended his MSc thesis in December 2004)	
Marco Castellon	MSc Student (co-supervised with Dr Elliot)/Development of power efficient turbo decoder	



Tellambura: Postdoctoral Fellows

	ROLE/TOPIC	AWARDS
Dr Wen Chen	PDF/Coding for OFDM	

Tellambura: PhD Students

	ROLE/TOPIC	AWARDS
Dung Ngoc Dao	PhD Student/Space division multiple access methods	
Saeed Fouladi Fard	PhD Student/Nonlinear decoding methods for CDMA	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
Alireza Ghaderipoor	PhD Student/Space-time Coding and Decoding Techniques	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
Yue Wu	PhD Student/Space-time coding techniques	
Luqing Wang	PhD Student/Reduction of High Peaks of OFDM Signals	

Tellambura: MSc Students

	ROLE/TOPIC	AWARDS
Tao Cui	MSc Student/Efficient decoding methods for high data rate systems	Alberta Ingenuity Studentship iCORE Graduate Student Scholarship
Yu Fu	MSc Student/Interference Cancellation for OFDM	
Saeed Kaviani	MSc Student/Closed-loop Transmit Diversity for Multiple Antenna Systems	
Yunxia Chen		Successfully defended her MSc thesis in August 2004
Ali Alavi		Successfully defended his MSc thesis in December 2004

Fapojuwu: Postdoctoral Fellows

	ROLE/TOPIC	AWARDS
Dr Jiang Zhu	Medium Access Protocols for WPANs and WLANs	

Fapojuwu: PhD Students

	ROLE/TOPIC	AWARDS
Abdul Hasib	PhD Student Joint Radio Resource Management in WLAN-Cellular Network	
Xiao Liu	PhD Student/SIM-based WLAN Authentication	TRLabs Scholarship NSERC Graduate Scholarship

	ROLE/TOPIC	AWARDS
Ian Lee	PhD Student/Wireless Multimedia Traffic Modeling, Characterization, Performance and Control	
Changqin Huo	PhD Student (co-supervised w/Dr Sesay)/OFDM-based Downlink Multi-cell Multi-access	
Helen Lampow-Maundy	PhD Student (part-time)/WLAN and Cellular Inter-networking	
Mohamed Shehata	PhD Student (Co-supervised with Dr Eberlein)/A Semi-formal framework for requirements engineering	

Fapojowo: MSc Students

	ROLE/TOPIC	AWARDS
Liqi Shi	MSc Student/QoS routing in MANETs	
Thaya Kumarasamy	MSc Student/Intelligent Resource Management Protocols for DS-CDMA Wireless networks	
Mudit Seth	MSc Student/Adaptive QoS Techniques for CDMA2000 networks	iCORE Graduate Student Scholarship MSc Thesis, September 2004
Xiaohua Zeng	MSc Student / Voice Activation System for Wireless Home Networks	NSERC Industrial Scholarship TRLabs Scholarship
Rob Sizeland	MSc Student (Co-supervised with Dr Davies)/Quality of Service in IEEE802.11 wireless LANs	NSERC Industrial Scholarship TRLabs Scholarship MSc Thesis, September 2004
Travis Stevens	MSc Student /QoS in MANETs	NSERC Industrial Scholarship TRLabs Scholarship
Yagi Uhuegbulem	MSc Student (Co-supervised with Dr Sesay)/Performance analysis of IEEE802.11 WLANs with exposed nodes	TRLabs Scholarship MSc Thesis, April 2004
Rajeev Babbar	MSc Student (Co-supervised with Dr Far)/Application of software agents to resource management in wireless networks	MSc Thesis, March 2005
Kevin Luo	MSc Student/Packet Scheduling mechanisms in wireless IP networks	
Kejin Huang	MSc Student/Dynamic Software Upgrading	
Chaoji Liu	MSc Student/Service Discovery protocols for MANETs	
Hemang Shah		Graduated M Eng, March 2005



COLLABORATIONS

BEAULIEU: COLLABORATIONS

PROVINCIAL
<p>The iCORE Wireless Communications Laboratory provided funding to the iCORE High Capacity Digital Communications (HCDC) lab to August 31, 2004. The money contributed was used to fund a graduate student co-supervised by Professor Schlegel and Professor Krzymieñ.</p>
<p>The Masters of Internetworking Program is an initiative under the iCORE Chair in Broadband Wireless Communications to establish a program for advanced graduate level training in the strategic area of Internetworking. Increased capacity in this field is expected to greatly enhance Alberta's ICT sector in the short, medium and long terms. This program combines networking projects and specialized courses which are jointly offered between the Departments of Electrical and Computer Engineering and Computing Science. There is a strong industrial focus to the program and Cisco and Telus are major sponsors of this program, having donated close to \$1M in equipment to support its training and research activities. The first intake of 15 students started the Master's degree program in September with course and lab delivery occurring on-site in Edmonton and with a distance lecture component through SAIT in Calgary. A major equipment donation has been received through Telus to supplement the existing Cisco-supplied lab. An agreement with SAIT has been signed to cover the remote delivery components in Calgary. Efforts are underway to secure additional industrial funding of the program.</p>
<p>Department of Mathematical and Statistical Sciences, University of Alberta (Douglas R. Wiens): Research on fading channel amplitude distribution order statistics. This collaboration has resulted in one submitted journal paper.</p>
INTERNATIONAL
<p>Samsung Electronics, Korea. August 23-24, 2004, Samsung Electronics sponsored a think tank, Samsung 4G Forum 2004: Migration Paths Towards 4G Networks. This in-house event was by invitation only and the attendance of all delegates was funded by Samsung Electronics. The event brought together around 150 leaders of wireless communications from around the world. Manufacturers, service providers, industry researchers and university researchers were all well represented at this important meeting to discuss global strategy and the path towards 4G technology.</p> <p>The President of Telecommunications Network Business Samsung Electronics, Ki-Tae Lee comments, "Together, we have opened a path towards 4G technology. Moreover, we have built relationships and consensus that will allow our collective vision to become reality."</p>
<p>Laboratory for Information and Decision Systems – Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, U.S.A. (Moe Win): Research on hybrid selection/maximal ratio diversity combining digital receivers. This collaboration has resulted in one published journal paper and one submitted journal paper in the reporting period.</p>
<p>Electronics and Telecommunications Research Institute (ETRI), Daejeon, South Korea (S.J. Lee): Research on multicode DS-CDMA systems. This collaboration has resulted in one accepted journal paper and one submitted conference paper in the reporting period.</p>
<p>Department of Engineering Science, University of Modena, Modena, Italy (Maria Luisa Merani): Research on efficient generation of cross-correlated fading amplitude sequences for simulation of correlated branch diversity systems. This collaboration has resulted in one journal paper published in the reporting period.</p>
<p>Department of Electrical Engineering, University of Missouri, Columbia, Missouri, U.S.A. (Chengshan Xiao): Research on novel channel models and simulation techniques for line-of-sight fading channels and on novel diversity combining methods. This collaboration has resulted in two submitted journal papers and one published conference paper in the reporting period.</p>
INDUSTRIAL
<p>The iCORE Chair continued as Director of the Corporation of Eleven Engineering Incorporated, Edmonton, Alberta in the reporting period. He has been actively involved in technology and product planning as well as in the recruitment of highly qualified personnel.</p>

TELLAMBURA: COLLABORATIONS

INSTITUTION	NATURE OF COLLABORATION
INTERNATIONAL	
A. Annamalai Electrical Engineering Department, Virginia Tech, USA	Research on diversity systems and their performance in wireless environments.
M. Parker Electrical Engineering Department, University of Bergen, Norway	Research on peak power reduction for OFDM systems

FAPOJUWO: COLLABORATIONS

INSTITUTION	NATURE OF COLLABORATION
INDUSTRIAL	
General Dynamics Canada	Networking and capacity solutions for tactical mobile ad hoc networks.
Telus Mobility	Development of a network-level simulator for CDMA200 (1xRTT) performance simulation

INTELLECTUAL PROPERTY

PATENTS	TITLE/NAME	STATUS
N. C. Beaulieu and Y.Chen	"Receiver for Pilot Symbol Assisted (Aided) Modulation"	US and Canadian Patent Application, filed October 12, 2004
N. C. Beaulieu and P. Tan	"A Novel and Improved DCT-OFDM System"	US and Canadian Patent Application, filed October 13, 2004
REPORT OF INVENTION	TITLE/NAME	STATUS
N. C. Beaulieu and P. Tan	"An Improved MMSE Equalizer for One-Dimensional Modulation OFDM Systems"	Submitted December 6, 2004

FUNDING

For this year, Norman Beaulieu and his team have attracted funding from NSERC (\$334K), CFI (~\$169K) and ASRA (~\$185K). Other sources of funding are from the University of Alberta (\$97K) and industry (~\$75K). Dr Beaulieu is a Tier 1 Canada Research Chair which contributes \$200K each year to his research program.



PUBLICATIONS

BEAULIEU

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K. Sivanesan and N. C. Beaulieu, "Exact BER Analysis of Bandlimited BPSK with EGC and SC Diversity in Cochannel Interference and Nakagami Fading," *IEEE Communications Letters*, vol. 8, pp. 623-625, October 2004.

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Y. Chen and N. C. Beaulieu, "Estimators Using Noisy Channel Samples for Fading Distribution Parameters," accepted for publication in *IEEE Transactions on Communications*.

K. E. Baddour and N. C. Beaulieu, "Robust Doppler Spread Estimation in Nonisotropic Fading Channels," accepted for publication in *IEEE Transactions on Wireless Communications*.

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X. Zhang and N. C. Beaulieu, "SER of Threshold-Based Hybrid Selection/Maximal-Ratio Combining in Correlated Nakagami Fading," accepted pending revisions for publication in *IEEE Transactions on Communications*.

P. Loskot and N. C. Beaulieu, "The Input-Output Weight Enumerator of Binary Hamming Codes," accepted pending revisions for publication in *European Transactions on Telecommunications*.

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B. Hu and N. C. Beaulieu, "Accurate BER of Time-Hopping and Direct-Sequence UWB Systems in Multi-User Interference," *IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM'05)*, Victoria, Canada, Aug. 24-26, 2005.

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N. C. Beaulieu and L. Cao, "Robust and Accurate SER Computation for M-ary Orthogonal Signalling on a Discrete Memoryless Channel," *IEEE Canadian Conference on Electrical and Computer Engineering CCECE 2005, Saskatoon, Canada, May 1-4, 2005*.

Z. Du and N. C. Beaulieu, "A Closed-Form Result for the Average Pairwise Error Probability of $t=2, r=1$ Differential Cyclic Unitary Space-Time Modulation," *IEEE Wireless Communications and Networking Conference WCNC2005, New Orleans, Louisiana, Mar. 13-17, 2005*.

Z. Du and N. C. Beaulieu, "A New Two Level Differential Unitary Space-Time Modulation," *IEEE Wireless Communications and Networking Conference WCNC2005, New Orleans, Louisiana, Mar. 13-17, 2005*.

Z. Du and N. C. Beaulieu, "A New Differential Monomial Space-Time Code," *IEEE Wireless Communications and Networking Conference WCNC2005, New Orleans, Louisiana, Mar. 13-17, 2005*.

K. Sivanesan and N. C. Beaulieu, "Accurate BER Analysis of Bandlimited DS-CDMA System with EGC and SC Diversity over Nakagami Fading Channels," *IEEE Wireless Communications and Networking Conference WCNC2005, New Orleans, Louisiana, Mar. 13-17, 2005*.



- S. Haghani and N. C. Beaulieu, "Postdetection Switch-and-Stay Diversity in Rician Fading," *IEEE Wireless Communications and Networking Conference WCNC2005*, New Orleans, Louisiana, Mar. 13-17, 2005.
- P. Loskot and N. C. Beaulieu, "Sample Rejection for Efficient Simulation of Intersymbol Interference Channels with MLS," *IEEE Wireless Communications and Networking Conference WCNC2005*, New Orleans, Louisiana, Mar. 13-17, 2005.
- K. Sivanesan and N. C. Beaulieu, "Interference Whitening Receivers for Bandlimited DS-CDMA Systems in Nakagami Fading," *IEEE Wireless Communications and Networking Conference WCNC2005*, New Orleans, Louisiana, Mar. 13-17, 2005.
- Y. Chen and N. C. Beaulieu, "Optimum Diversity Receiver Structures for Combining with Estimation Errors," *IEEE GLOBECOM*, Dallas, Texas, Nov. 29-Dec. 3, 2004.
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- Z. Du, J. Cheng and N. C. Beaulieu, "Error Rate of OFDM Signals in Frequency Selective Nakagami-m Fading Channels," *IEEE GLOBECOM*, Dallas, Texas, Nov. 29-Dec. 3, 2004.
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- J. Hu and N. C. Beaulieu, "Accurate Simple Closed-Form Approximations to the Distributions and Densities of a Sum of Independent Rayleigh Random Variables," *38th Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, California, Nov. 7-10, 2004.
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- K. E. Baddour and N. C. Beaulieu, "Improved Pilot Symbol Aided Estimation of Rayleigh Fading Channels with Unknown Autocorrelation Statistics," *IEEE Vehicular Technology Conference - Fall*, Los Angeles, Sept. 26-29, 2004.
- B. Hu and N. C. Beaulieu, "Pulse-Shaping in UWB Communication Systems," *IEEE Vehicular Technology Conference - Fall*, Los Angeles, Sept. 26-29, 2004.
- L. Cao and N. C. Beaulieu, "BER of PSAM 16-QAM with Channel Estimation Error and MRC Diversity," *International Symposium on Wireless Communication Systems ISWCS 2004*, Port-Louis, Mauritius, pp. 90-94, Sept. 20-22, 2004.
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- L. Cao and N. C. Beaulieu, "Closed-Form Results for the BER of Maximal Ratio Combining with Channel Estimation Errors in Ricean Fading Channels," *The Ninth IEEE Symposium on Computers and Communications ISCC 2004*, Alexandria, Egypt, pp. 645-650, June 28 - July 1, 2004.
- P. Loskot and N. C. Beaulieu, "Efficient Simulation of Multidimensional Communication Systems by Sample Rejection," *IEEE International Conference on Communications ICC 2004*, Paris, France, pp. 2240-2245, June 20-24, 2004.
- P. Loskot and N. C. Beaulieu, "Average Error Rate Evaluation of Digital Modulations in Slow Fading by Prony Approximation," *IEEE International Conference on Communications ICC 2004*, Paris, France, pp. 3353-3357, June 20-24, 2004.

Y. Chen and N. C. Beaulieu, "Estimation of Ricean and Nakagami distribution parameters using noisy samples," *IEEE International Conference on Communications ICC 2004*, Paris, France, pp. 562-566, June 20-24, 2004.

K. Sivanesan and N. C. Beaulieu, "Performance Analysis of Bandlimited DS-CDMA Systems in Nakagami Fading," *IEEE International Conference on Communications ICC 2004*, Paris, France, pp. 400-404, June 20-24, 2004.

B. Hu and N. C. Beaulieu, "Accurate Evaluation of Multiple Access Performance in Time-Hopping UWB Systems," *IEEE International Conference on Communications ICC 2004*, Paris, France, pp. 300-305, June 20-24, 2004.

J. Wu, C. Xiao and N. C. Beaulieu, "Optimal Diversity Combining based on Noisy Channel Estimation," *IEEE International Conference on Communications ICC 2004*, Paris, France, pp. 214-218, June 20-24, 2004.

SPECIAL/INVITED PRESENTATIONS

N.C. Beaulieu, "Wireless Research in the iCORE Wireless Communications Laboratory," Mini-Workshop, SAMSUNG ELECTRONICS, IT Center, Suwon, Korea, August 25, 2004, Invited Talk.

N.C. Beaulieu, "Wireless Research in the iCORE Wireless Communications Laboratory," SAIT, Samsung Advanced Institute of Technology, Suwon, Korea, August 20, 2004, Invited Talk.

N.C. Beaulieu, "Wireless Research in the iCORE Wireless Communications Laboratory," NORTEL NETWORKS Tech Expo 2004, Westwinds Innovation Centre, Calgary, Alberta, June 10, 2004, Invited Talk.

N.C. Beaulieu, "Wireless Research in the iCORE Wireless Communications Laboratory," iCORE Banff Informatics Summit 2004, Banff, Alberta, June 8, 2004.

N.C. Beaulieu, "Multiple Access Interference in Time Hopping Ultra-Wideband Radio," The International Society for Optical Engineering (SPIE) Second International Symposium on Fluctuations and Noise 2004, Noise in Communication Conference, Masapalomas, Gran Canaria, Spain, May 25-28, 2004, Invited Keynote Paper.

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P. Goud Jr., C. Schlegel, W. A. Krzymieñ, R. Hang, "Multiple antenna communication systems - an emerging technology", *Canadian Journal of Electrical & Computer Engineering, Special Issue on Advances in Wireless Communications and Networking*, vol. 29, no. 1/2, January/April 2004, pp. 51-59.

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E. Haas, W. A. Krzymieñ, "Coherent OFDM Receiver with Two-Dimensional Decision-Feedback Pilot and Data Symbol Correction", in *Proc. 9th Intl. OFDM Workshop*, Dresden, Germany, Sept. 2004, 5 IEEE format pages.

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