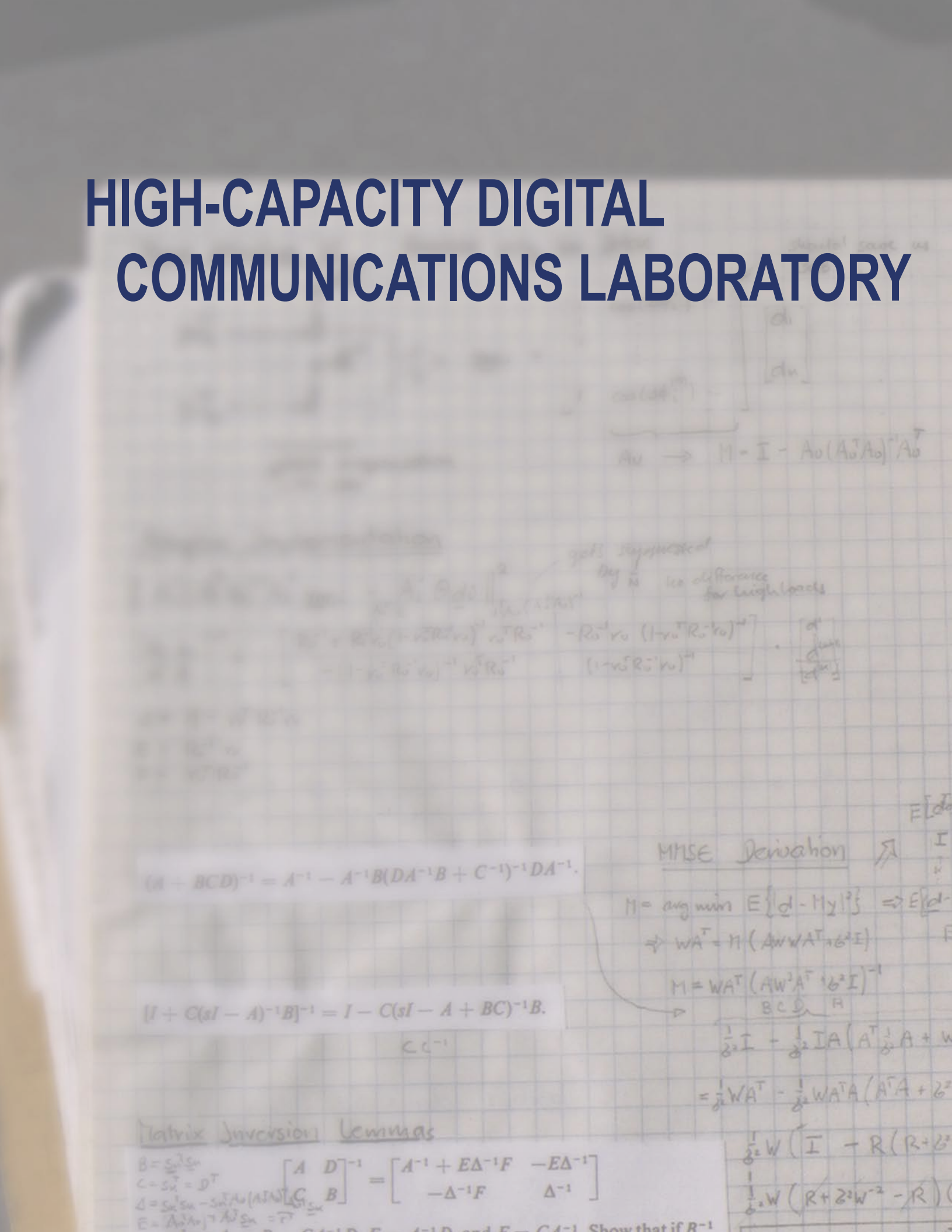
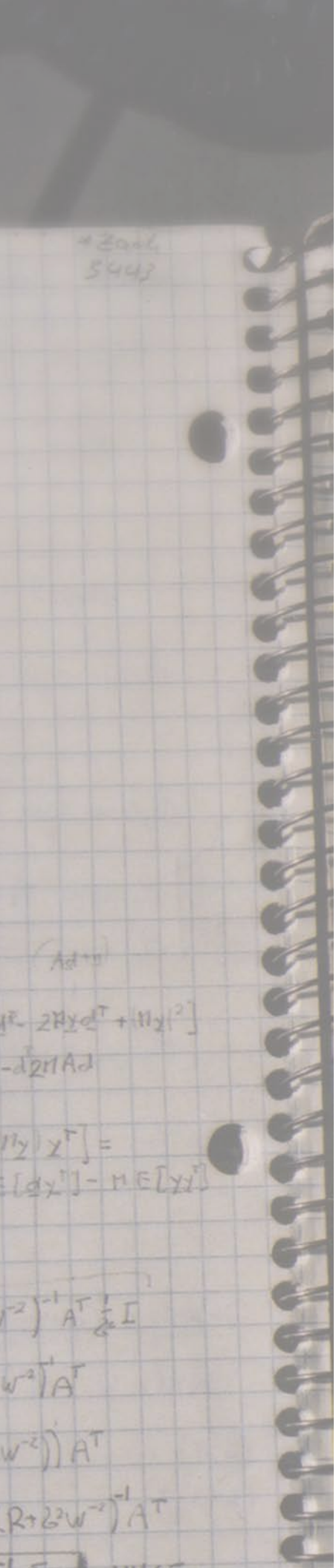
HIGH-CAPACITY DIGITAL COMMUNICATIONS LABORATORY





CHRISTIAN SCHLEGEL

iCORE Professor
Electrical and Computer Engineering, University of Alberta
http://ece.ualberta.ca/~hcdc/

The focus of the High-Capacity Digital Communications (HCDC) Laboratory is the efficient transmission of digital data through practically important communications channels, for example, wireless radio links. The objective is to research, study, propose, and demonstrate methods and techniques that can harness each channels theoretical maximal transfer capability, called the channel capacity.

EXECUTIVE SUMMARY

The 2003/2004 academic year was marked by a rapid expansion of our fundamental work in error control coding and an increase in the laboratory's reach within the department, as well as outside. The laboratory now has five participating ECE faculty members. The recently launched research and development group on low-density parity-check (LDPC) coding research is the largest, with four active faculty involved with their graduate students. The project on multiple antenna channel measurements has reached maturity. The laboratory has forged links with four industrial entities: SiWorks Inc. in Calgary, and L3 Communications, Sirius Radio, and Aquantia in the US. We have finalized our first two service contracts with L3 Communications and talks are under way to use HCDC's IP in future funded research projects with both SiWorks and L3 Communications. The laboratory hosted two research professors this past year, in addition to two postdoctoral visitors. One of these visitors is returning to the HCDC under a two-year grant from Alberta Ingenuity. A number of academicshave visited our laboratory during the past year, attesting to the increased visibility of our laboratory. A large number of publications have been generated and can be found on our laboratory website at www.ece.ualberta.ca/hcdc.

During this phase, the HCDC laboratory has expanded its team by hiring five new students, hosting two visiting professors, and hiring a postdoctoral researcher in the area of error control coding design, Dr Dimiti Troukhatchev from Lund University, Sweden. Dr Bruce Cockburn from the department of Electrical and Computer Engineering at the Unversity of Alberta has joined forces with the LDPC group on a project to generate an LDPC prototype ASIC decoder using HCDC patented IP. Dr Cockburn is a specialist in ASIC design techniques.

Professor Schlegel has been appointed General Chair for the IEEE Communication Theory Workshop 2005, and Technical Program Chair for the 2005 International Symposium on Information Theory in Adelaide, Australia.

The HCDC was host of the 3rd Analog Decoding Workshop in Banff in June 2004, held in conjunction with the iCORE Summit. This position arose from HCDC's leading activities in the area of analog decoding. We have recently completed the design and fabrication of the world's largest analog CMOS decoder, which is currently undergoing testing in our laboratory.

RESEARCH PROGRAM OVERVIEW

The focus of activities at the High-Capacity Digital Communications (HCDC) Laboratory, created by iCORE Professor Schlegel under iCORE funding, is the efficient transmission of digital data through a variety of popular transmission channels, most notably wireless channels. The goal is to transmit digital data with the least amount of resources, in terms of energy and bandwidth, and with the maximum amount of reliability. The laboratory's name, high capacity, pertains to the capacity limits which were theoretically established by Claude Shannon in 1948, and which give each channel a maximum rate at which reliable communication is theoretically possible. Achieving this rate has been the research and development focus of many scientists and engineers over the past half century. Among a large number of modern signal processing methods, error control coding is the single most important technique, which allows communications engineers to approach this elusive limit. The main focus of our projects is consequently the efficient and judicious application of error control coding and supporting signal processing techniques to achieve a channel's inherent data carrying potential that is, to approach or achieve the capacity limit.

Christian Schlegel

With the help of visiting Professor Marat Burnashev, the HCDC team has thoroughly analyzed the behavior of iterative receiver systems for random CDMA using parallel cancellation approaches. These findings are fundamental and have been submitted for publication in two separate papers. It has been shown that judicious choices of rates and powers can achieve a channel's capacity, even if only simple, low-complexity cancellation processing is used with simple error control decoders. Extensions of these findings to MIMO communications are underway, and are likely to identify capacity-achieving receiver structures.

Wireless packet networking research has reached a strong level of activity within the group with several directions. Firstly, a novel uncoordinated packet format has been analyzed in its capability to utilize a large fraction (up to 90 percent) of the radio channels inherent information theoretic capacity. Further work on the integration of higher order protocols to enable such channel utilization is in progress. Furthermore, HCDC researchers have been tackling the question of network capacity and devised a linear algebraic characterization of the connectivity of a random network. This characterization has been used to modify packet transmission protocols, in particular 802.11, to achieve higher levels of fairness and total network throughput. These preliminary results have been submitted totwo different conferences for publication.

In the area of error control coding, the team has become very active in the study and design of low-density parity-check (LDPC) codes, as well as LDPC convolutional (LDPCC) codes. Several implementations and decoder architectures have been studied and readied for implementation. In cooperation with L3, a novel method of rate compatibility has been invented and is currently undergoing patenting. The method may also serve as a standard proposal, pending L3's direction.

The analog and stochastic processing group within the HCDC team has produced the worlds largest analog decoder, a 256-bit turbo product decoder which is currently undergoing detailed testing and verification. Progress has been made in the design of a completely analog receiver for ultra-low power applications. The ultimate research goal in this direction is a receiver

that can operate at high speeds with scavenged energy only, suitable for implantable devices, for example. A working model of a stochastic decoder has been programmed and is being readied for implementation in an FPGA.

Stochastic decoding may replace conventional algorithmic decoding if our hypothesis that it can be implemented with less complexity is verified. This is a target for the next phase of the project. Two key invention disclosures have been made and are currently being patented by the university. These will be used to leverage our industrial component of the research projects.

ACHIEVEMENTS OVER PAST YEAR

The following is a list of achievements over the past 12 months.

- Our multiple antenna (MIMO) testbed has been expanded into a real-time version capable of capturing channel data fast enough to conduct high-speed measurements. This activity has been supervised by Robert Hang. Several demonstrations to local and US industry have been given. To the best of our knowledge, our real-time MIMO measurement equipment is currently not available at any other academic institution, where measurements are usually performed with off-line equipment after data collection. The key innovation in this project is a novel low signal to-noise ratio timing acquisition and tracking algorithm, which forms a vital function for future high-capacity communications systems
- Simulation, theoretical analysis, and implementation of a novel frequency compensation algorithm developed by HCDC members. This is a critical component for robust packet transmission systems. Frequency and timing acquisition were studied for code-division multiple access (CDMA) based transmission systems. The results will form the basis for our next step towards implementable low-SNR receivers for mobile packet transmission systems.
- Adaptation of the MIMO test-platform to make it ready for the implementation of novel communications systems and testing with real data communications in circuit and packet switched mode. The exact formulation of next year's goals will be debated at a brainstorming session with the participation of outside team members. The current hardware testbed effort will be channeled into two parallel research efforts: i) dealing with the issue of multiple joint access using concurrent but completely asynchronous transmissions of data packets, and, ii) the expansion of the MIMO channel measurement testbed into a MIMO communications prototype testbed using layering techniques for channel separation. A unique iterative inversion filter has been built in VHDL by one of Dr Schlegel's former student. This filter can and will be used as a key component in the layering of subchannels.
- On the analog decoding front a complete characterization of the analog product decoder,

iCORE Professor Christian Schlegel and some of the associated researchers at the 2004 Banff Information Summit

construction of an adequate measurement setup, and dissemination of results has been accomplished. If the processing core behaves as expected, the design focus will shift towards the efficient interface design. Industry contacts will be pursued and Christopher Winstead, the senior PhD student on this project, has recently graduated with these results. New PhD students are being hired and will pursue the question of efficient interface technologies, possibly in conjunction with the iCORE group of Professor Haslett in Calgary, which specializes in analog RF technology. The long-term goal will be a complete analog receiver capable of operating at extremely low power levels.

- The HCDC web site has been completely redesigned and is currently undergoing testing for completeness and ease of use. It now contains useful features such as mail buttons and a complete conference list with links and deadlines of major conferences that are targeted by HCDC as forums dissemination of results and on-line MIMO measurement results. The website is located at the University of Alberta web address www.ualberta.ca/hcdc.

On the applied research and development side, the group can list the following accomplishments:

- We have reached a significant milestone in developing a solid and reliable VHDL/Matlab implementation capability. This capability allows us to implement novel receiver algorithms, test them in the real world with the hardware we acquired (MIMO Testbed, Spectrum Analyzer, Arbitrary Waveform Generator, and Vector Signal Analyzer), and compare their performance with theoretical analysis. This acquired implementation capability led to completion of the Channel Estimator Design and the start of our work on packet transmission (both points are described below) and will enable us to pursue ambitious goals in the coming year.
- We completed the Multiple-Input Multiple-Output (MIMO) Channel Estimator Design. This is a significant milestone for the HCDC Laboratory, as well as for the University of Alberta. To our knowledge, there is no university (at least in North America) that has a similar testbed. This Channel Estimator design is capable of taking real-time channel measurements of a MIMO channel in the 905 to 925MHz frequency band. The design interfaces to Matlab for efficient display and processing of real-world wireless channel measurements. The Channel Estimator design has been demonstrated at various locations: at the Wireless 03 Conference in Calgary, at TRLabs Calgary, and to our industry partner, L-3 Communications, in Salt Lake City, Utah, USA. Two German exchange students who are writing their thesis projects at the HCDC Laboratory have completed a regimented measurement campaign with the goal of generating a comprehensive measurement database which we are going to publish on the internet for free access by researchers on MIMO technology worldwide.

Dr Kamil Zigangirov, iCORE Visiting Professor

The team members that took part in the VHDL development were Michael Mah (co-op student), Billie Kwan (part-time researcher), and Nikolaj Larionov (summer student), managed by Robert Hang (research associate) and Dr Christian Schlegel.

- The completion of a Timing Recovery block (fundamental block of Channel Estimator Design) allowed HCDC to move on to research on wireless packet data transmission/reception. We are currently working on the performance analysis and VHDL implementation of a novel packet receiver scheme that will run on the HCDC hardware testbed. As of December 31, 2003, the VHDL design for the packet receiver is undergoing testing. The design is being tested in the lab under real conditions. So far, the testing reveals that in a low frequency offset situation, the packet detection algorithm works well. However, to make the design more robust, we decided to go back to the drawing board and make it more resistant to frequency offset. We will implement a differential detection algorithm to that end. With fewer resources available (the funding for the students involved in the design has stopped at the

end of December) the target date for completion of this differential packet detection algorithm is May/June 2004.

The research team for the packet transmitter/receiver scheme is made up of Michael Mah (co-op student), Micheal Nham (volunteer student), and Billie Kwan (part-time researcher) managed by Robert Hang (research associate) and Dr Christian Schlegel.

OBJECTIVES FOR NEXT YEAR

The objectives for next year are highlighted by the following points:

On the MIMO channel side it is planned to study various acquisition and channel tracking methods, primarily using iterative decoding methods, for their suitability to achieve the channel capacity and their implementability in hardware. A particular focus will be given to mobile channels with rapidly time-varying characteristics in an effort to prove viability of MIMO technology for mobile applications. A primary direction of thrust will be the spread pilot embedding method pioneered by our extended team member Dr Behrouz Farhang. After theoretical studies concerning channel estimation and tracking in conjunction with our colleagues have come to a completion, the implementation of a pilot embedded channel estimation system will be considered. Embedded pilot channel estimation essentially forms a direct and logical extension of our current MIMO channel measurement signaling.

Completion of our theoretical studies on near-capacity communications over multiple access channels using CDMA and the effective use of error control codes in such systems is expected to continue in the next phase. During this period, a complete characterization of iterative cancellation schemes using random code-division multiple access (CDMA) channels has been completed. This know-how is planned to be applied to MIMO communications systems, possibly resulting in capacity achieving, low-complexity receiver structures for such channels. This will then open the possibility to implement such receiver structures in future testbed implementations.

Our recently initiated studies in the area of efficient packet transmission systems using advanced joint receivers is expected to generate guidelines and results for highly efficient packet structures, as well as communications protocols. Future implementation of high-density packet test networks is currently being discussed among the different team members. During this period, the team has further analyzed a

novel uncoordinated random packet communications format and system, and shown that it is capable of harnessing a large percentage of the capacity of the radio channel, far outperforming current mobile radio packet systems.

With the arrival of Dr Stephen Bates as new member of the HCDC we have one more FPGA hardware expert on board, and potential new directions that are being contemplated are the extension of high-capacity transmission systems to wireline channels, such as Ethernet. Dr Bates and his students have initiated an implementation program for extremely high-speed error control decoding systems for wirebound channels using low-density parity-check convolutional coding (LDPCC), first proposed by iCORE Visiting Professor Kamil Zigangirov.

Complete characterization of the analog product decoder, construction of an adequate measurement setup, and dissemination of results will be continued. If the processing core behaves as expected, the design focus will shift towards the efficient interface design. Golam Mostafa is expected to continue the effort in the direction of efficient interface technologies, possibly in conjunction with the iCORE group of Professor Jim Haslett in Calgary, since Christopher Winstead is graduating this fall and will take up a faculty position in the US in 2005.

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

As of May 2003, the following are the team members of the HCDC Laboratory broken down into two groups: The Core Team which comprises the permanent members of the research team and the Extended Team, which comprises members with limited-time association such as graduate students and academic visitors.

Team Leader

PROFESSOR CHRISTIAN SCHLEGEL
iCORE Professor, Canada Research Chair
Dr Schlegel recently completed his research monograph *Trellis and Turbo Coding* published by IEEE/Wiley, 2004. He has been appointed General Chair of the 2005 Communication Theory Workshop to be held in June 2005 in Park City, Utah, and as Technical Program Director of the International Symposium on Information Theory (ISIT 05), to be held in the fall of 2005 in Adelaide, Australia. He taught the on-line short course "Turbo Coding and Applications" through Stevens Institute of Technology's (SIT) on-line short course system. SIT has recently been ranked the number one on-line university.

Faculty Team Members

	ROLE
Dr Witold Krzymieñ, Professor	Associate Member
	Professor Krzymieñ acts as an Associate Member and helps the HCDC in a supervisory role of the laboratory engineers and in an advisory role to the Chair. Professors Krzymieñ and Schlegel jointly supervise two PhD students and hold an NSERC strategic grant in the area of wireless and MIMO communications jointly with Drs. Tellambura, Dong, and Beaulieu.
Dr Vincent Gaudet, Professor	Associate Member
	Professor Gaudet is a recent hire by the University of Alberta with a specialty in analog VLSI and signal processing. He works with Professor Schlegel in building the analog portion of the HCDC laboratory, and supervising Christopher Winstead as well as the newly hired graduate students in the area of analog processing. Professor Gaudet has taken leadership in the group's recently formed task force on the implementation of LDPC codes. This program has received $US 25,000 of initial support from US industry and is poised to acquire a much larger grant next year.
Dr Stephen Bates, Professor	Associate Member
	Professor Bates was hired by the University of Alberta last year and has joined efforts with HCDC. Dr Bates is an expert in traffic modeling for wireless networks. He also has industrial experience in design and production of ASICs. He supports HCDC in its networks research and is a member of the LDPC task force. He is currently working on the implementation of LDPC convolutional code, a novel idea that was examined with Visiting Professor Zigangirov late last year.
Dr Bruce Cockburn, Professor	Associate Member
	Professor Cockburn is a University of Alberta faculty member with expertise in ASIC development. He and his graduate student have joined forces with HCDC in the LDPC task force. The plan is to implement a state-of-the art digital LDPC decoder to verify novel HCDC intellectual property recently developed.

	ROLE
Dr Warren Gross, Professor	Associate Member
	Dr Gross is an Assistant Professor with the Department of Electrical and Computer Engineering, McGill University, Montreal, Quebec, Canada. His research interests are in the design and applications of signal processing microsystems, VLSI design,coding theory, and computer architecture.
Dr Glen Gulak, Professor	Associate Member
	Dr Gulak is a professor in the Department of Electrical and Computer Engineering at the University of Toronto. His research interests are in the areas of circuits, algorithms and VLSI architectures for digital communications and signal processing applications. He has received five teaching awards for undergraduate courses taught in both the Department of Computer Science and the Department of Electrical and Computer Engineering at the University of Toronto.

Research Team Staff

	ROLE
Paul Goud	General Lab Director
	Mr Goud was hired by the Chair in December 2001 to head the hardware development of the laboratory. He is in charge of the evolving testbed and will also execute a supervisory role starting this fall as the hardware activities expand to include coop students and a new VHDL design engineer. To date he has been operating and documenting the multiple antenna testbed. He has interfaced and directed our subcontractors providing RF designs, interfaced with the L3 Communications VHDL design team (see Partners), and with SiWorks Inc., with whom we are exploring error-control coding know-how transfer. Mr Goud has conducted and supervised channel measurements and written four research papers on these measurement campaigns and related findings. Chair of the Communications, Computers and Solid State Circuits (CCSSC) Chapter of the Northern Canada Section of the IEEE
Robert Hang	VHDL Design Director
	Mr Hang was hired by the Chair and Dr Krzymieñ in December 2002 to lead the VHDL design efforts and FPGA implementations of our test and prototype equipment. He is in charge of the design details and interfaces with the Chair and graduate students on the transfer of theoretical results to FPGA implementation. During the past year, Mr Hang has mainly concentrated on implementing the timing recovery algorithm required by the real-time measurement equipment. Recently, he has been involved in the design of fast LDPC code core components for FPGA implementation. He is part of the LDPC taskforce. Mr Hang is paid 50 percent by an NSERC strategic grant held jointly by Professors Krzymieñ, Schlegel, and others.
Charmaine Ramdass	Research Coordinator
	Ms Ramdass acts as the Research Coordinator facilitating the flow of information and administrative responsibilities of the team.

Extended Team Members

	ROLE
Kamil Zigangirov	iCORE Visiting Professor
	Professor Zigangirov from Lund University in Sweden visited us last year in the capacity of iCORE visiting professor. Professor Zigangirov is an expert in error control coding research and pioneered low-density parity-check convolutional codes (LDPCC), whose feasibility for very high-throughput applications is currently being evaluated by Professor Bates and students in cooperation with Professor Zigangirov.
Marat Burnashev	NSERC Visiting Professor
	Professor Burnashev visited the HCDC laboratory for a period of five months from October 2003 to March 2004. He is a world-renowned mathematician from Moscow's famous Institute for Problems of Information Transmission. Professor Burnashev has assisted the mathematical direction of the academic research projects in the area of multiple access and joint detection. Professor Burnashev will visit us again later this year in the capacity of an iCORE Visiting Professor.
Lance Perez	Academic Visitor
	Professor Perez from the University of Nebraska is an associate member of Dr Schlegel's team. He is an expert in turbo coding techniques, and is the co-author to Dr Schlegel book *Trellis and Turbo Coding*. He is working with HCDC on a collision-based multiple access system using frequency-shift keyed modulation useful for robust wireless networks. NSF CAREER Awardee, Editor, *Information Theory Society Newsletter*
Alex Grant	Academic Visitor
	Professor Grant from the University of South Australia is active in the theory and practice of multiple user communications and is working with Dr Schlegel on a joint book project and a tutorial on the subject. He orchestrated the exchange of Dr David Haley, which targeted the implementation of an LDPC analog decoder, using the analog serial interface developed by PhD candidate Christopher Winstead.
Behrouz Farhang	Joint Project
	Professor Farhang at the University of Utah is working with the HCDC on the study of efficient channel estimation procedures to be incorporated into the efficient transmission systems researched for MIMO channels. Dr Farhang and Dr Schlegel currently co-supervise one graduate student and a postdoctoral research fellow at the University of Utah. Dr Farhang has a number of joint publications with HCDC members.
Zhenning Shi	Joint Project
	Dr Shi is a Research Associate at the Australian National University. He worked on joint detection for linear multiple access channels such as CDMA and MIMO channels. Dr Shi co-authored several papers with Dr Schlegel and Dr Burnashev on iterative joint detection of CDMA and MIMO capacity. Cooperation with Dr Shi is expected to continue after his transfer.
David Haley	Joint Project/Academic Visitor
	Dr Haley visited the HCDC last year for a period of three months to work with our analog design team on transferring know-how and to duplicate some of HCDC's analog designs in the implementation of an analog LDPC decoder. Further cooperation is being discussed.
Dmitry Trukhachev	Academic Visitor
	Dr Trukhachev, a former student of Professor Zigangirov's, visited the HCDC last year and gave a couple of lectures. Dr Troukhatchev won a two-year Alberta Ingenuity Fellowship to join HCDC as postdoctoral research fellow starting this fall.

	ROLE
Zachary Bagley	Partner
	Mr Bagley is a principal engineer at L3 Communications and a VHDL/ FPGA designer. He was involved in multiple antenna research conducted jointly with Dr Schlegel and Dr Farhang. He also acts as a liaison to L3 Communications, and assisted in HCDC's first US company grant this year.
Shayne Messerly	Joint Project
	Mr Messerly is a former MSc graduate from the University of Utah and currently works for L3 communications. He is supervised by Dr Schlegel and Mr Bagley. Mr Messerly is an experienced VHDL design engineer, and has just completed the VHDL design of an iterative Gauss-Seidel filter for implementation of layering filters for our research in MIMO and CDMA systeMs

PhD Students

	ROLE/TOPIC
Sheryl Howard	Mrs Howard is a PhD student who transferred from Utah with Dr Schlegel. She is working in the area of efficient coded modulation using iterative receiver principles. Recently, she added LDPCs to her experience and is now a leading member of the LDPC task force.
Christopher Winstead	Mr Winstead is a PhD student who transferred from Utah with Dr Schlegel. He is working on analog decoder implementations. Mr Winstead has designed and fabricated the world's first CMOS analog error control decoder, and now the world's largest analog decoder which is currently undergoing testing. Mr Winstead is graduating this fall and will take up a faculty position with Utah State University in January of 2005.
Sumeeth Nagaraj	Mr Nagaraj is a PhD student who was hired by Dr Schlegel in 2002. He is working on efficient wireless MAC protocols and wireless packet system throughput analysis. Mr Nagaraj has a Master's degree from Utah State University in Logan, Utah.
Roland Kempter	Mr Kempter is a PhD student from Germany who was hired by Dr Schlegel in 2002 under L3 funding in Utah. He is working on the capacity limits of random packet multiple access systems using joint detection at the receiver. He has recently developed a novel protocol to exploit the capacity of the random access channel.
Golam Mostafa	Mr Mostafa is a PhD student hired by Dr Schlegel in 2003. Mr Mostafa will concentrate on analog processing. He comes from his prior job as a design engineer with Texas Instruments.
Siavash Zeinoddin	Mr Zeinoddin received his masters degree in Germany, and joined the HCDC as a graduate student last year. His work is in the area of interleaver design for low error floor coding in turbo and LDPC codes. He is a member of the LDPC task force.
Jung Ko	Mr Ko joined HCDC as a graduate student last year working on the software defined radio project guided by Dr Gaudet.
Lukasz Krzymien	Mr Krzymien, a new graduate student at HCDC is working in the area of multiple antenna systems and simplified layered receiver architectures. He is directly supervised by Dr Schlegel.
Zhenning Shi	PhD completed 2003. Research topic - Iterative Joint Detection of CDMA, Australia National University

MSc Students

	ROLE/TOPIC
Dave Nguyen	Mr Nguyen, an MSc student hired in 2003, is part of the analog design group. He has successfully implemented test chips for our analog decoder interfaces.
Mimi Yiu	Ms Yiu started working with HCDC as a co-op student on an automated FPGA test setup to measure and characterize our analog Hamming decoder implementation. She has now been accepted as a graduate student and will continue her work on testing of analog decoders.
Soraya Kasnavi	Ms Kasnavi was admitted as graduate student last year and pursues her MSc degree in the area of circuits for CM-based IP routers.
David Li	Mr Li was admitted as an MSc student last year and pursues work in the area of CMOS imaging techniques.
Anthony Rapley	Mr Rapley, an NSERC scholar, joined the HCDC two years ago as a MSc student. His research led him to the study of stochastic decoding, a novel method that may prove more implementation efficient than conventional digital circuits. Mr Rapley is supervised by Dr Gaudet. He is also a member of the LDPC task force.
Tobias Kiefer	Mr Kiefer is a visiting Master student from the University of Applied Sciences in Offenburg, Germany. He is working on wireless MIMO channel measurement improving the MIMO testbed software and designing a web interface for public access to the MIMO channel measurements database. Mr Kiefer is supervised in Offenburg by Dr Tobias Felhauer and his final project at the High Capacity Digital Communications Laboratory is being co-supervised by Dr Schlegel.
Ivan Kocev	Mr Kocev is a visiting Master student from the University of Applied Sciences in Offenburg, Germany. He is working on wireless MIMO channel measurement improving the MIMO testbed software and designing a web interface for public access to the MIMO channel measurements database. Mr Kocev is supervised in Offenburg by Dr Tobias Felhauer and his final project at the High Capacity Digital Communications Laboratory is being co-supervised by Dr Schlegel.

Co-op Students

Michael Mah, ECE Co-op Student
Micheal Nham, ECE Co-op Student

COLLABORATIONS

The HCDC maintains strong academic partnerships as well as liaisons to industry. Currently the following partners are actively contributing to our program:

L3 Communications, Salt Lake City, Utah

This company has had a long-standing liaison with Dr Schlegel and is currently supporting hardware oriented research efforts by funding Zachary Bagley and Shayne Messerly. Both engineers have developed VLSI systems for the transmission and reception stages of our hardware testbed. This cooperation is expected to continue next year. Mr Bagley and Mr Messerly will continue with their work of implementing an iterative layering processor in FPGA to be used to separate the data streams in our MIMO systems testbed. L3 communications widened its relationship with HCDC by signing a research service agreement for US$25,000, which is expected to lead into a more substantial research contract next year.

North Carolina State University (NCSU)

Joint US NSF funding with NCSU is currently in place with the PIs, Dr Brian Hughes and Dr Gianlucca Lazzi. The topic of this joint research work is efficient space-time coding systems. The funding currently supports students at NCSU and Utah. Cooperation on the hardware testbed by duplicating the setup at NCSU continues to be on hold due to funding problems at NCSU.

University of Utah

A cooperative link exists with the University of Utah where Dr Schlegel works with Dr Behrouz Farhang on the design of efficient and rapid equalization methods for multiple antenna systems. One remaining Utah PhD students and a Postdoctoral Research Fellow are jointly supervised by Drs Farhang and Schlegel in this project.

SiWorks Inc. Calgary

A number of talks and meetings have been held with this Calgary-based wireless company about expertise and IP transfer from HCDC, primarily the LDPC task force, to SiWorks.

We hope to be able to organize a research cooperation with them soon. They have also provided assistance in an HCDC Ideas-to-Innovation application to NSERC.

PARTICIPANTS	NATURE OF COLLABORATION
PROVINCIAL	
HCDC Laboratory; SiWorks Inc (Calgary)	Application submitted to NSERC for an NSERC I2I grant. NSERC will decide on this application on June 28th, 2004.
HCDC Laboratory; Ghaith Saab (University of Alberta)	Ghaith Saab (Co-op Engineering student) has been working on a faster USB interface to our MIMO testbed.
NATIONAL	
HCDC Laboratory; University of Toronto team	NSERC SRO application
INTERNATIONAL	
HCDC Laboratory; Claude Berrou (ENST-Bretagne, France); Dr Emmanuel Boutillon (Universite de Bretagne Sud, France); Texas A&M University, (USA)	Application submitted for an NSERC SRO grant. Collaboration active between participants.
HCDC Laboratory; Tobias Kiefer and Ivan Kocev (University of Applied Sciences, Offenburg, Germany).	Tobias Kiefer and Ivan Kocev (Masters students)have been taking measurements using the HCDC MIMO testbed. HCDC will use these measurements to build a database. The data will be available on the HCDC website.
HCDC Laboratory; Semi-Conductor Research Corporation; Agere	In January 2003 Stephen Bates secured funding from the Semi-Conductor Research Corporation to investigate the design and implementation of transceiver architectures for wireline systems. This project is also backed by Agere Inc. and looks at designing high-speed decoders andencoders for applications such as communications and hard-disk read heads. The funding is to run for 3 years.
INDUSTRIAL	
HCDC Laboratory; Dr Ayyoob Abbaszadeh, Senior Engineer, L3 Communications(USA)	HCDC Laboratory; Dr Ayyoob Abbaszadeh, Senior Engineer, L3 Communications(USA)
HCDC Laboratory; Zachary Bagley, Principal Research Engineer, L-3 Communications (USA)	HCDC Laboratory; Zachary Bagley, Principal Research Engineer, L-3 Communications (USA)
HCDC Laboratory; Dr Behrouz Farhang, Associate Professor, University of Utah (USA)	HCDC Laboratory; Dr Behrouz Farhang, Associate Professor, University of Utah (USA)

FUNDING

Christian Schlegel receives funding from NSERC ($70K/year), CFI ($170K) and the University of Alberta ($550K cash and in kind) to support building his research lab. He received industry funding worth $35K. Dr. Schlegel holds a Tier 2 Canada Research Chair which is worth $100K per year. He also hosted an iCORE Visiting Professor, Dr. Kamil Zigangirov.

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

C. Schlegel, Zhenning Shi, Marat Burnashev, Asymptotically Optimal Power Allocation and Code Selection for Iterative Joint Detection of Coded Random CDMA"", submitted to *IEEE Transactions on Information Theory*.

S. Howard, C. Schlegel, "Differential Turbo Coded Modulation with APP Channel Estimation", *IEEE Transactions on Communications* submitted, December 2003.

V. Gaudet and G. Gulak, "A 13.3Mbps 0.35um CMOS Analog Turbo Decoder IC with a Configurable Interleaver," *IEEE Journal of Solid-State Circuits*, Vol. 38, No. 11, pages 2010-2015, November 2003.

P. Goud Jr., C. Schlegel, W.A. Krzymien, R. Hang, "Multiple Antenna Communication Systems - An Emerging Technology", C*anadian Journal of Electrical and Computer Engineering*, accepted for publication.

C. Schlegel and A. Grant, "Differential space-time turbo codes," *IEEE Transactions Information Theory*, September, 2003.

Z. Shi, C. Schlegel, and B. Farhang-Boroujeny, "Efficient Approximations to the Capacity Outage of MIMO Channels", *IEEE Transactions on Communications*, submitted, June, 2003.

Haidong Zhu, Zhenning Shi, Behrouz Farhang-Boroujeny, Christian Schlegel, "An Efficient Statistical Approach for Calculation of Discrete Capacity of MIMO Channels", submitted to *IEEE Transactions on Communications*, May 2003.

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