

The background of the image is a blurred, high-angle photograph of a document. The document contains a network diagram with various nodes (represented by rectangles and circles) and connecting lines. The text is overlaid on this background in a bold, dark blue font.

**BROADBAND  
WIRELESS NETWORKS,  
PROTOCOLS, APPLICATIONS,  
AND PERFORMANCE**

**WIRELESS  
INTERNET TRAFFIC MODELLING**

## CAREY WILLIAMSON

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*Dr Carey Williamson is completing the third year of an initial five-year appointment in this position. As of January 1, 2004, he also holds an NSERC/TELUS/iCORE Industrial Research Chair (IRC) in Wireless Internet Traffic Modeling. The combined research team of 18 members (faculty, research staff, and graduate students), works on interests in wireless networks, Internet technologies, and network performance. Much of the research is experimental in flavour, with an applied focus on industrially-relevant network and protocol performance issues.*

- 3 graduate students successfully complete their MSc programs;
- authoring or co-authoring over 20 research papers (3 journal, 10 conference, 3 book chapters, 1 internal report, 4 submitted, 6 in preparation);
- receiving the balance of funding required for the ELISA laboratory.

## RESEARCH PROJECTS

This section describes selected projects underway by the research group in 2003-2004. The number of projects discussed is small, for space reasons. The chosen projects reflect the variety of network performance research carried out in the group, and complement the larger set of projects discussed in reports from previous years.

### **I) Portable Networks**

We have continued our research on wireless Web servers and the “portable networks” paradigm. The portable network concept refers to the deployment and use of Web servers, media servers, or computing resources in a wireless ad hoc networking environment, without requiring any pre-existing network infrastructure.

## EXECUTIVE SUMMARY

**T**his document summarizes research activities for the reporting year of April 1, 2003 to March 31, 2004. The highlights of this reporting year include:

- the awarding of an NSERC/TELUS/iCORE IRC in Wireless Internet Traffic Modelling;
- expanding the team to 10 graduate students, 7 research staff, and 1 new faculty member;

In this project last year, we explored the feasibility of wireless Web server deployment in classroom area networks. This work was carried out primarily by Research Associate Guangwei Bai and MSc student Kenny Oladosu, with technical assistance provided by Martin Arlitt, Nayden Markatchev, and Tianbo Kuang.

A new emphasis in this past year has been on wireless media streaming in a portable network scenario. PhD student Jean Cao did a live field trial of a wireless media server with a French film class in March 2004. Her experiment successfully delivered up to 8 concurrent stored video streams to students using laptops in the wireless ad hoc classroom network. The student reviews of the technology in support of learning were very favourable. Research staff member Nayden Markatchev has done additional experiments with both live and stored video, using multicast. These experiments were part of his CPSC 502 course project work. A further field trial is planned for the Olympic Oval in 2004 in collaboration with Professor Jeff Boyd (Computer Science). His objective is to use computer vision and motion analysis to support the coaching and training of high-performance athletes.

We believe that portable networks offer a flexible and cost-effective solution for multimedia content delivery for education, training, or entertainment purposes. The University of Calgary has our Intellectual Property disclosure from last year regarding this work, but to the best of our knowledge no arrangements for patenting or licensing have been pursued. Three conference publications have resulted from the work so far,

with one journal paper in preparation for submission in summer 2004.

This project unifies many of the topics on which the team's graduate students and research staff are currently working. The challenges include not just Web content delivery, but also request scheduling, wireless media streaming, quality of service, TCP protocol performance, caching, security, and ad hoc routing. This project also provides a natural linkage to new faculty member Anirban Mahanti, whose specialty is multimedia content delivery systems on the wired Internet. Wireless access networks change many of the assumptions on which his multicast streaming systems are based.

## 2) Multi-Channel MAC Protocols

The TCP protocol often suffers from throughput and fairness problems in multihop wireless ad hoc networks. The problems arise from hidden node and exposed node problems, which can lead to channel contention in the forward direction between TCP DATA packets that are part of the same TCP flow control window, as well as contention between TCP DATA and TCP ACK packets flowing in opposite directions. This contention problem arises because of the single channel shared by the wireless devices in the network. The adverse impact on TCP throughput is drastic, particularly as the number of hops in a network communication path increases.

Our research is studying the performance of multi-channel Medium Access Control (MAC) protocols. Multi-channel protocols have been proposed in the literature. A multi-channel configuration offers  $N$  channels, with 1 control channel and  $N - 1$  data channels. Channel access is coordinated using the control channel, with frame transmissions carefully scheduled on the data channels to reduce interference problems and increase spatial reuse of frequencies, improving overall system throughput. Our work is carried out using ns-2 network simulation.

In our work, we propose and evaluate a novel bidirectional multi-channel MAC protocol designed to improve TCP performance over a multihop wireless network. The protocol uses multiple transmission channels at the physical layer to reduce TCP DATA-DATA contention, and bidirectional RTS/CTS channel reservations to reduce TCP DATA-ACK collisions. Simulation results on a static multihop chain network show up to 65 percent improvement in TCP throughput compared to a conventional IEEE 802.11 MAC protocol. Part of this benefit comes from the multi-channel feature, but the bidirectional channel reservations play an equally important role. Fairness is also improved, since contention is confined to a short handshake period on the control channel.



Carey Williamson

This work has been carried out primarily by Research Associate Tianbo Kuang, with some assistance from Research Associate Qian Wu. One paper has been written describing this work, and is ready for submission at this time.

### 3) Anonymous Network Communication

The goal of an anonymous communication scheme is to keep the identities of communicating parties secret from eavesdroppers and adversaries. Two types of anonymity are required to anonymize an application fully: data anonymity hides identities on an application-specific basis (for example, remailers that remove identifying information from email headers), and connection anonymity hides identities at the network layer by obscuring communication patterns.

Anonymous communication is important for certain network applications. For example, sender anonymity is required for applications such as e-voting and e-counseling for victims of abuse, while receiver anonymity may be needed to protect freedom of speech when publishing certain documents on the Web. Other applications may require both sender anonymity and receiver anonymity, as well as unlinkability, so that sender-receiver relationships cannot be discerned. Military communication between allied groups is an example where unlinkability is desirable, since an enemy may gain tactical advantages from a structural understanding of communication patterns.

There have been several systems proposed for providing anonymous network communication. For example, Mixes provide anonymity by re-routing a

message through a series of intermediate nodes, using layered encryption to hide the contents of a message from hop to hop. Broadcasting approaches send each encrypted message to everyone, though only the intended receiver has the key required to decrypt the message.

MSc student Andreas Hirt has spent the past year designing, implementing, and evaluating an anonymous communication scheme. Andreas is co-supervised by Michael Jacobson (with expertise in cryptography, security, and computational number theory) and myself (with expertise in networks, protocols, and performance evaluation).

The design of our anonymous communication scheme is based on the Buses protocol from the literature. Buses provide strong mutual anonymity without the overhead incurred by mixes and broadcasting. The Buses protocol uses the metaphor of a city bus with a scheduled route through the network. The bus hides a message's route through the network just like a public transit bus hides a passenger's route through a city.

Andreas has implemented and evaluated his modified Buses protocol in a Linux cluster environment. Several modifications to the original Buses protocol were necessary to protect against replay attacks, to make the protocol scalable, and to make it practical for implementation. To the best of our knowledge, Andreas has created the first practical implementation of any Buses protocol in the literature. The experiments show that his protocol is indeed scalable: the



Carey Williamson and some research team members at the 2004 Banff Informatics Summit



overhead of the protocol grows linearly with the number of nodes in the network.

This work is exciting and significant. Our measurement results show that our protocol is a promising alternative for providing strong anonymity with manageable overhead. The potential impact of this work on Internet-based communication is huge.

Two research papers have been prepared related to this work. One paper is a comprehensive survey of anonymous communication schemes from the literature, complete with careful analyses of the strengths and weaknesses of each scheme. One main conclusion from this survey paper is that Buses are one of the most promising approaches to anonymous communication. The second paper is a description of the design, implementation, and experimental evaluation of our modified Buses protocol. Both papers have been submitted for possible publication, and are currently in the review process.

Extension of the protocol to wireless ad hoc networks remains as the primary challenge for Andreas when he starts the PhD program in September 2004.

## OBJECTIVES FOR THE NEXT YEAR

Two exciting Internet technologies are the World Wide Web and wireless networks. The Web has made the Internet available to the masses, through its TCP/IP protocol stack and the information-hiding principle

of layering. Wireless technologies have revolutionized the way people think about networks, by offering users freedom from the constraints of physical wires. These technologies are available today, in laptop or handheld form, at relatively modest cost. Mobile users want to exploit the functionality of the technology at their fingertips, as wireless networks bring closer the “anything, anytime, anywhere” promise of mobile networking.

My research program focuses on combining wireless technologies and the Web, maximizing the value of each. This applied research program has a strong focus on experimental computer systems performance research.

The general goals of the research program are:

- Identify protocol performance problems in wireless Web communication systems;
- Propose and evaluate creative solutions to these performance problems; and
- Promote deployment of wireless Web infrastructure at the University of Calgary

Progress was made on each of these objectives this year. Similar objectives related to the NSERC IRC were also pursued.

## RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

The research team currently consists of two faculty members, seven full-time research staff, and nine graduate students (one of whom is co-supervised).

The main additions to my research team during this year were:

*Anirban Mahanti.* Anirban joined the Department of Computer Science as an Assistant Professor on January 1, 2004. His hiring fulfills the University of Calgary’s commitment for a junior faculty position supporting this iCORE Professorship. While it took two recruiting years to fill this position, we definitely found the right candidate for the job.

Anirban’s research expertise is Multimedia Streaming/Internet Content Delivery Systems. He does experimental computer systems research, using implementation, simulation, and analytical modeling. He successfully defended his PhD dissertation (supervised by Derek Eager) on March 2, 2004 at the U. of Saskatchewan. I have known Anirban for over 5 years, and have had many successful research interactions



Carey Williamson and Lane Mearns at an iCORE event

with him in that time. He is a perfect fit for my research group, and I am delighted to have him join us.

Anirban has no teaching duties during his first semester at the University of Calgary. His main efforts have been finishing 1 or 2 papers related to his thesis, setting up his research lab using his startup grant, applying for an Alberta Ingenuity Grant, preparing his NSERC Discovery Grant application, and preparing lecture materials for his upcoming teaching duties in Fall 2004. Anirban expects to have 2 new graduate students for September 2004. I am serving as a mentor to Anirban as he starts his academic career.

*Hongxia Sun.* Hongxia joined my research team in September 2004. She has a 1999 PhD in Computer and Communication Engineering from Southwest University in China, and several years of post-doctoral wireless networking research experience in North America, first with Dr. Joseph Hui in the Telecommunications Research Center at Arizona State University, and most recently with Dr. Herman Hughes in the Wireless and High Speed Networks Lab at Michigan State University. Her background and publication record fit very well with the needs of my TELUS

Mobility project. I am pleased to welcome her to my research team and to the Province of Alberta.

*Yujing Wu.* Following the NSERC IRC award, I short-listed several candidates for a Post-Doctoral Fellowship (PDF) position within my IRC research team. I interviewed two of these candidates in Calgary in December and January, and then selected Yujing Wu for the position. She has a PhD in Electrical and Computer Engineering from the University of Massachusetts at Amherst in 2003. This is a well-regarded school, particularly in Computer Science and Computer Engineering. Yujing's work on performance modeling of network queues was supervised by Professor Weibo Gong. Yujing has a solid publication record, including collaborations with Lixin Gao in ECE at UMass, and a paper co-authored with Professor Don Towsley, a distinguished researcher from the Department of Computer Science at UMass, who I know quite well. Yujing Wu has first-rate credentials, and I look forward to working with her. She joined my team on February 1, 2004.

In addition, two new graduate students (Alok Madhukar and Ian Wormsbecker) were admitted in September 2003.

## Research Team Members

FACULTY TEAM NAME	ROLE	TOPIC
Carey Williamson	Team Leader	Wireless Internet Performance
Anirban Mahanti	Assistant Professor	Multimedia

OTHER RESEARCH TEAM MEMBERS	EXPERTISE
Martin Arlitt	Web Performance, Network Traffic Measurement, Workload Characterization, P2P Networking, Grid
Guangwei Bai	Internet Traffic Modeling, Wireless Web Measurement
Tianbo Kuang	Wireless Traffic Measurement, Media Streaming
Qian Wu	Network Simulation, TCP/IP, ns-2
Hongxia Sun	Simulation/Analytic Modeling, CDMA, Cellular

POSTDOCTORAL FELLOWS	TOPIC
Yujing Wu	Simulation/Analytic Modeling, Wireless, CDMA



PHD STUDENTS	TOPIC
Xiaozhen (Jean) Cao	Wireless Multimedia, Middleware, QOS
Mingwei Gong	Queue Scheduling, Wireless Performance

MSC STUDENTS	TOPIC
Abhinav Gupta	Location-Aware Ad Hoc Routing
Andreas Hirt	Network Security and Anonymity
Gwen Houtzager	Optimizing Web Proxy Cache Placement
Alok Madhukar	P2P Support in Wireless Ad Hoc Networks
Dan Munteanu	General-Purpose Network Processors
Ian Wormsbecker	Minimizing Wireless Network Contentions
Fang (Shelly) Xiao	Fairness Issues for Wireless TCP
Kehinde (Kenny) Oladosu	Performance and Robustness Testing of Wireless Web Servers
Yujian (Peter) Li	Modeling Web/TCP Transfer Latency

SUPPORT AND TECHNICAL STAFF	TOPIC
Nayden Markatchev	Network/System Administration, Lab Manager ,Network Simulation, Mobile Computing

## AWARDS

In this reporting year, the Chair was awarded an NSERC/TELUS/iCORE Industrial Research Chair (IRC) in Wireless Internet Traffic Modeling. This is a major award that increases the size of the research team and research program budget by about 50 percent. It also adds a national level of recognition to the stature of the iCORE research program.

Three of my students received scholarship awards this year. Andreas Hirt received a prestigious NSERC CGS scholarship for his PhD program starting in September 2004. PhD student Jean Cao received an NSERC Industrial Postgraduate Scholarship plus a TRILabs Fellowship. MSc student Alok Madhukar received a TRILabs Scholarship.

## COLLABORATIONS

PROVINCIAL
<p>At the University of Calgary, the research team interacts closely with the TeleSim research group coordinated by Rob Simmonds and Brian Unger. We attend weekly joint meetings with the TeleSim group, who have broader interests in parallel/distributed simulation, high performance computing, and grid computing. Several jointly authored publications have resulted in the past few years. The chairholder has attended two strategic planning meetings of the so-called "Wireless Pillar" group at the University of Calgary. This group is fostering multidisciplinary collaboration on wireless research initiatives at the U of C. Several other iCORE researchers (for example, Graham Jullien, Gerard Lachapelle, Jim Haslett) are part of this group, along with CRC Chairholder Michal Okoniewski.</p> <p>The chairholder is an affiliated researcher with CISAC (Centre for Information Security and Cryptography), organized by iCORE Chair Hugh Williams.</p>
MULTIDISCIPLINE OR MULTI-INSTITUTIONAL PARTNERSHIPS
<p>The main multi-institutional partnership involves the CFI-funded Experimental Laboratory for Internet Systems and Applications (ELISA), being constructed jointly between the University of Calgary and the University of Saskatchewan. CFI-matching funds totaling \$626,482 were awarded to the University of Saskatchewan by the Province of Saskatchewan in Spring 2003.</p> <p>Research Services at the University of Calgary is drafting an inter-institutional agreement with the University of Saskatchewan regarding the ELISA project. This process has been underway for about 18 months. A one-year extension to the ELISA project has been sought and received from CFI so that the equipment acquisition process can proceed. The project end date is now March 31, 2005. The RFP process for equipment was completed in late January 2004. All equipment decisions have been made, and purchase orders are ready to send at the University of Saskatchewan. However, orders are on hold until the University of Calgary completes the inter-institutional agreement.</p> <p>A second collaborative initiative is hosting the 2005 ACM SIGMETRICS Conference. Derek Eager (University of Saskatchewan) and the chair are sharing duties as General Chairs for this conference, which is the premiere annual international conference on computer systems performance evaluation. Approximately 150 conference attendees are expected for the conference on June 6-10, 2005. We have selected Banff as the location, with the Banff Park Lodge as the conference hotel.</p>
INDUSTRY
TELUS MOBILITY
<p>My primary industrial interaction has been with TELUS Mobility in Toronto, as part of my NSERC/TELUS/iCORE Industrial Research Chair in Wireless Internet Traffic Modeling.</p> <p>One trip was made to TELUS Mobility in September 2003 to discuss progress and plans on the Wireless Internet Traffic Modeling project. We met with Michael Wu, Dave Keegstra, Christina Czernuszka, and others at TELUS Mobility to update them on research results, to obtain further information about their wireless/cellular CDMA networks, to tour their facilities, and to discuss plans for the NSERC IRC.</p> <p>A significant portion of the Chair's research time this past year was spent on network capacity planning work suggested by TELUS Mobility. Research team member Hongxia Sun and the Chair did most of this work, spending many CPU hours on call-level simulations of network performance for widely-varying network traffic models. Regular teleconference call meetings were held with TELUS Mobility during this work, with a 20-page internal technical report provided to TELUS Mobility in December 2003 as a deliverable. The report was received by TELUS in December, and finalized and approved in January 2004. The contents of this report are confidential to TELUS Mobility and cannot be described here.</p> <p>We have established reasonable research momentum on this project, including the development of a user interface and a call-level simulation tool for network capacity planning, and simulation results illustrating the sensitivity of call blocking performance to different assumptions about the network workload. Most of the interface design and tool development work was done by research team member Qian Wu. Most of the simulation validation testing was done by Jean Cao. Most of the simulation studies were done by Hongxia Sun. TELUS Mobility seems pleased with our progress to date.</p> <p>Two telephone meetings with TELUS Mobility took place in the past quarter. Collection of measurement data from the TELUS Mobility network is the primary focus for the next year (Year 2) of the project. A non-disclosure agreement (NDA) has been signed with Telus Mobility, which will allow us to have access to more detailed configurational and operational information about their network.</p> <p>My research activity on this project has been limited this semester due to teaching commitments. Research activity will resume in earnest in Summer 2004.</p>
TRLABS
<p>The chair joined TRILabs as an Adjunct Scientist in Spring 2003, to be part of a new initiative on Home Networking Technologies. Two graduate students are funded in part by TRILabs. PhD student Jean Cao has an NSERC Industrial Postgraduate Scholarship (IPS) with TRILabs as the industrial partner. They supplement her IPS award with a TRILabs Fellowship. MSc student Alok Madhukar holds a TRILabs Scholarship. Several possible areas for research collaboration have emerged.</p>





## INTELLECTUAL PROPERTY

As mentioned earlier, a primary research theme this year has been on wireless Web servers, to evaluate their feasibility and performance. The University of Calgary has our Intellectual Property disclosure from last year regarding this work, but to the best of my knowledge no arrangements for patenting or licensing have been pursued. We continue to stay in touch with Richard May from InnoCentres and Geoff Moon from UTI regarding other aspects of our ongoing research activities. The commercial potential for wireless Web servers and portable networks is high. However, we are still seeking the “killer app” or market niche for the use of this technology. Our work on anonymous network communication also has significant potential impact.

## FUNDING

Carey Williamson holds both an iCORE Professorship and an iCORE Industrial Chair. The Industrial Chair is supported by iCORE (\$100K/year) and TELUS Mobility (\$100K/year), with matching funds from NSERC (\$100K/year) recently approved (December 2003) and expected in September 2004, completing the joint NSERC/iCORE/TELUS Mobility Industrial Research Chair in Wireless Internet Traffic Modeling.

## PUBLICATIONS

### REFEREED JOURNAL PUBLICATIONS

M. Arlitt and C. Williamson, “Understanding Web Server Configuration Issues”, *Software: Practice and Experience*, Vol. 34, No. 2, pp. 163-186, February 2004.

T. Kuang and C. Williamson, “Hierarchical Analysis of RealMedia Streaming Traffic on an IEEE 802.11b Wireless LAN”, *Computer Communications*, Vol. 27, pp. 538-548, 2004.

L. Titchkosky, M. Arlitt, and C. Williamson, “A Performance Comparison of Dynamic Web Technologies”, *ACM Performance Evaluation Review*, Vol. 31, No. 3, pp. 3-12, December 2003.

### TEN MOST IMPORTANT PUBLICATIONS OVER LIFETIME

M. Arlitt and C. Williamson, “Internet Web Servers: Workload Characterization and Performance Implications”, *IEEE/ACM Transactions on Networking*, Vol. 5, No. 5, pp. 631-645, Oct. 1997.

M. Arlitt and C. Williamson, “Web Server Workload Characterization: The Search for Invariants”, *Proc. ACM SIGMETRICS Conference*, Philadelphia, PA, pp. 126-137, May 1996.

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.

M. Busari and C. Williamson, “On the Sensitivity of Web Proxy Cache Performance to Workload Characteristics”, *Proc. IEEE INFOCOM Conference*, Anchorage, AL, pp. 1225-1234, April 2001.

C. Williamson, “On Filter Effects in Web Caching Hierarchies”, *ACM Transactions on Internet Technology*, Vol. 2, No. 1, pp. 47-77, Feb. 2002.

C. Williamson, R. Simmonds, and M. Arlitt, “A Case Study of Web Server Benchmarking Using Parallel WAN Emulation”, *Performance Evaluation*, Vol. 49, No. 1-4, pp. 111-127, Sept. 2002.

C. Williamson, T. Harrison, W. Mackrell, and R. Bunt, “Performance Evaluation of the MoM Mobile Multicast Protocol”, *ACM/Baltzer Journal on Mobile Networks and Applications (MONET)*, Vol. 3, No. 2, pp. 189-201, Aug. 1998.

M. Arlitt and C. Williamson, “Understanding Web Server Configuration Issues”, *Software: Practice and Experience*, Vol. 34, No. 2, pp. 163-186, Feb. 2004.

C. Williamson, “Dynamic Bandwidth Allocation Using Loss-Load Curves”, *IEEE/ACM Transactions on Networking*, Vol. 4, No. 6, pp. 829-839, Dec. 1996.

C. Williamson, “Optimizing File Transfer Response Time Using the Loss-Load Curve Congestion Control Mechanism”, *Proc. ACM SIGCOMM Conference*, San Francisco, CA, pp. 117-126, Sept. 1993.

## CONFERENCES

G. Bai and C. Williamson, "The Effects of Mobility on Wireless Media Streaming Performance", to appear, *Proceedings of Wireless Networks and Emerging Technologies (WNET)*, Banff, AB, July 2004. Accepted April 20, 2004.

C. Williamson and N. Kamaluddeen, "Network Traffic Measurement of a Wireless Classroom Network", to appear, *Proceedings of Wireless 2004*, Calgary, AB, July 2004. Accepted April 1, 2004.

G. Bai, K. Oladosu, and C. Williamson "Performance Issues for Wireless Web Servers", to appear, *Proceedings of the International Workshop on Mobile and Wireless Ad Hoc Networking (MWAN)*, Las Vegas, NV, June 2004. Accepted March 19, 2004.

G. Bai and C. Williamson, "Simulation Evaluation of Wireless Web Performance in an IEEE 802.11b Classroom Area Network", *Proceedings of the Third International Workshop on Wireless Local Networks (WLN)*, Bonn, Germany, pp. 663-672, October 2003.

M. Gong and C. Williamson, "Quantifying the Properties of SRPT Scheduling", *Proceedings of the 11th IEEE/ACM Symposium on the Modeling, Analysis, and Simulation of Computer and Telecommunication Systems (MASCOTS)*, Orlando, FL, pp. 126-135, October 2003.

G. Houtzager and C. Williamson, "A Packet-Level Simulation Study of Optimal Web Proxy Cache Placement", *Proceedings of the 11th IEEE/ACM Symposium on the Modeling, Analysis, and Simulation of Computer and Telecommunication Systems (MASCOTS)*, Orlando, FL, pp. 324-333, October 2003.

L. Titchkosky, M. Arlitt, and C. Williamson, "Performance Benchmarking of Dynamic Web Technologies", *Proceedings of the 11th IEEE/ACM Symposium on the Modeling, Analysis, and Simulation of Computer and Telecommunication Systems (MASCOTS)*, Orlando, FL, pp. 250-253, October 2003. Short paper only.

T. Kuang, F. Xiao, and C. Williamson, "Diagnosing Wireless TCP Performance Problems: A Case Study", *Proceedings of SCS SPECTS Conference*, Montreal, PQ, pp. 176-185, July 2003.

C. Williamson and N. Markatchev, "Network-Level Impacts on User-Level Web Performance", *Proceedings of SCS SPECTS Conference*, Montreal, PQ, pp. 637-646, July 2003.

C. Kiddle, R. Simmonds, C. Williamson, and B. Unger, "Hybrid Packet/Fluid Flow Network Simulation", *Proceedings of the 17th ACM International Workshop on Parallel and Distributed Simulation (PADS)*, San Diego, CA, pp. 143-152, June 2003.

## OTHER

C. Williamson, "Wireless Internet: Protocols and Performance", book chapter in *Performance Tools and Applications to Networked Systems*, Springer Lecture Notes in Computer Science, October 2003. 25 pages. Invited.

C. Williamson, "The Role of Awareness in Internet Protocol Performance", book chapter in *Performance Evaluation: Stories and Perspectives*, Austrian Computer Society, ISBN 3-85403-175-0, pp. 203-214, Vienna, Austria, December 2003. Invited.

R. Bunt and C. Williamson, "Temporal and Spatial Locality: A Time and Place for Everything", book chapter in *Performance Evaluation: Stories and Perspectives*, Austrian Computer Society, ISBN 3-85403-175-0, pp. 381-392, Vienna, Austria, December 2003. Invited.

C. Williamson and H. Sun, "Network Capacity Planning Simulation Report", proprietary internal report to TELUS Mobility, 22 pages, January 2004.

## SUBMITTED PAPERS

M. Arlitt and C. Williamson, "The Never-Ending Challenges of Network Traffic Measurement", submitted to *IEEE Internet Computing*, February 2004.

G. Bai and C. Williamson, "Time-Domain Analysis of Web Cache Filter Effects (Extended Version)", submitted to *Performance Evaluation journal*, March 2003. Revised based on reviewer comments and re-submitted for a second round of review, March 2, 2004.

A. Hirt, M. Jacobson, and C. Williamson, "Survey and Analysis of Anonymous Communication Schemes", submitted to *ACM Computing Surveys*, October 2003.

C. Williamson and N. Markatchev, "Network-Level Impacts on User-Level Web Performance (Extended Version)", submitted to *International Journal of Communication Systems*, September 2003. Invited paper.

