Dr. Hussein Al-Zubaidy

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Work experience

Since 2011 ECE, University of Toronto Toronto, Canada

NSERC Post-Doctoral Fellow

- Developing a novel (min, x) calculus for multi-hop wireless networks.
- Information-theoretic approach to wireless networks analysis using (min, x) calculus.
- Stochastic network calculus theory and applications.
- Optimal stochastic control of queuing systems.

2010-2011 SCE, Carleton University Ottawa, Canada

Post-Doctoral Fellow

- Cooperative communications and Wireless Relay Networks (WRN).
- Security in wireless Ad-Hoc networks.

Summer 2009 HSNG, National Chung Cheng University (CCU) Chiya-Yi, Taiwan

Research Associate

- Security in wireless mobile Ad-Hoc networks.
- Optimal node selection in distributed public key generation in wireless Ad-Hoc networks.
- Giving talks in several universities and research labs in Taiwan, e.g., National Taiwan University (NTU), Institute of Information Science, Academia Sinica, National Cheng Kung University (NCKU), and National Sun Yat-Sen University (NSYSU).

2004–2010 Broadband Networks Lab., Carleton University Ottawa, Canada

Research Assistant

1) Conducting research in these areas:
   - Applied stochastic processes and probability.
   - Stochastic optimization of queuing systems: coupling method and stochastic dominance.
   - Modeling, analysis and optimization of packet scheduling in wireless systems using Dynamic Programming/Markov Decision Process.
   - Cross-layer design; scheduling algorithm design in emerging wireless networks.
   - Mesh networks planning, analysis and optimization.
   - Third and fourth Generation (3G/4G) mobile networks LTE, HSPA, WCDMA, UMTS.
   - Scheduling, QoS, and optimal resource allocation in wireless networks.
   - Building a system level simulator for the HSDPA system using OPNET modeler.
2) Supervising and mentoring graduate students. This resulted in a number of joint publications.
3) Preparing and publishing papers and technical reports to disseminate research results.
4) Presenting research findings in scholarly meetings and gatherings (e.g., conferences).
5) Chairing technical sessions in international conferences and contributing in the reviewing and selection process of the accepted papers.
6) Writing proposals for the sake of securing research funding, e.g., NSERC, Nortel and Defence Research and Development Canada (DRDC).

2004–2010 System and Computer Eng., Carleton University Ottawa, Canada

Teaching Assistant

- Supervised labs and presented tutorial sessions in OPNET, NS-2, assembly programming and distributed systems programming.
- Assisted in many courses including: Computer Networks, Distributed Systems, Networks Programming, Microprocessor Systems, Digital Communications, Communication systems lab, and Communication Systems Analysis and Design.
- Mentoring, Counseling and supervising undergraduate students.

2006–2007 Carleton University Foundry Program Ottawa, Canada

Consultant (Innovation management)

- Provide consultation to faculty members and students of Carleton University regarding the commercialization of their innovative ideas and inventions.
- Evaluate the potential of these projects and recommend funding options if deemed promising (The foundry grants funds to innovative ideas and spin-off companies).
- Provide the required professional advice and exposure by utilizing the Foundry resources and network of professionals from the surrounding community.

1997–2001 Faculty of Engineering at Hoon/ Tahaddi university Hoon, Libya

Faculty Member (Electrical and Computer Engineering Department)

- Instructed the following courses: Digital Systems Design, Microprocessor Systems, Computer Networks, Computer Architecture, and Assembly Programming.
- Conducted research in the area of Wireless Communication and Networks.
- Supervised the computer systems, the Electronic Engineering, and the Communication Engineering laboratories.
- Supervised several graduation projects.
- Chaired several thesis defense committees and took part in many others.

1995–1997 Almansour College University Baghdad, Iraq

Faculty Member (Computer Science Department)

- Instructed the following courses: Microprocessor Systems, Computer Programming (C/C++, Pascal, and BASIC), Computer Architecture, and Computer Networks.
- Supervised the Electronics lab and the Microprocessor systems lab.
- Supervised several graduation projects and was a member of many defense committees.

Interests

Research fields of interest:

- Stochastic network calculus: theory and application to multi-hop wireless network.
- Scheduling and resource allocation in multi-hop wireless networks over fading channels.
- Networks performance analysis and optimization using stochastic network calculus, queuing theory, stochastic modeling, coupling arguments and stochastic dominance.
- 3G/4G mobile systems; LTE, HSDPA, HSPA, CDMA2000/EVDO/EVDV, WIMAX.
- Fundamental research in networking and information theory.
- Mesh networks analysis, planning and optimization.

Personal interests:

Sport, music and reading. I was the captain of the soccer team of the Electrical Eng. dept.-Tahaddi University in 2001. I also play volleyball. My team and I won first place in Tahaddi University volleyball competition at Hoon, summer 2000.

Skills

Research skills:

I have developed many research skills from my past research experience such as:

- The ability for critical thinking and analysis
- The ability to identify research problems, provide intuition for the expected outcome of tackling such problems and communicate the findings effectively
- Knowledge of basic and advanced research protocols and procedures
- Drafting and completing research papers and technical reports and meeting deadlines
- Presenting research findings at scholarly and professional society meetings
- Teamwork and collaboration with research team members both in academia and industry.

I also acquired many interesting analytic techniques such as:

- Dynamic programming: Markov decision process (MDP) and POMDP.
- Stochastic modeling, stochastic dominance, dynamic coupling and sample path arguments.
- Fluid based analysis (FBA) approximations for queuing systems
- Queuing theory
- Stochastic network calculus, MGF calculus; *I developed (min, x) wireless network calculus*.

Simulation tools and programming languages:

I mastered several simulations and modeling software and programming languages such as: OPNET, NS-2, MathCAD, MATLAB, C/C++, VB, MPI and OpenMP parallel programming, Assembly programming (SDK86, Motorola 68020).

Education

2005-2010 Carleton University Ottawa, Canada

Ph.D. 18. **GPA: 11.5 / 12**

- Thesis: "Optimal Packet Scheduling in Emerging Wireless Networks."
- Supervisor: Prof. Ioannis Lambadaris.

2004-2005 Carleton University Ottawa, Canada

M.A.Sc. Systems and Computer Engineering. ***(****Upgraded to the PhD program in the summer of 2005***)**

- Thesis: "Quality of Service Provision in Third Generation HSDPA system."
- Supervisor: Prof. Ioannis Lambadaris.

1992-1994 University of Technology Baghdad, Iraq

M.Sc. Communication Engineering. **GPA: 85 / 100**

- Thesis: "Search Strategies for Serial Search DS-Spread Spectrum Acquisition Schemes."
- Supervisor: Prof. Waseem W. Jibrail.

1987-1991 University of Technology Baghdad, Iraq

B.Sc. Electronic and Communication Engineering. **Rank: 2 out of 73**

- Graduation project entitled: "Micro-computer Based Micro-processor Tester Design."

Honors and awards

- **NSERC Post-Doctoral Fellowship (PDF) for 2 years**, Canada, 2010.
- **NSERC Visiting Fellowship in Canadian Government Laboratories**, Canada, 2009.
- **NSERC Summer program in Taiwan,** held at CCU, Chiya Yi, Taiwan, 2009
- **Ontario Graduate Scholarship** (OGS), held at Carleton University, 2008-2009.
- **Ontario Graduate Scholarship for Science and Technology** (OGSST) *twice*, held at Carleton University, Ottawa, Canada, 2004-2006.
- **Dr. Roger Kaye Memorial Award for Ontario Students**, 2007 and 2008, Carleton University, Ottawa, Canada.
- **The Minister of Higher Education prize**, for ranking the 2nd of 73 graduates in a 4 years B.Sc. program, University of Technology, Baghdad, 1991.
- **Graduate scholarship** – SCE, Carleton University, for 5 years (2005 -2009).
- **Dean of Graduate Studies Academic Excellence Scholarship,**Carleton University, for 4 years (2006 -2009).
- **Best industry oriented project award,** Almansour College University, Baghdad, 1996.

List of Publications:

a) Articles published or accepted in refereed journals

1. **Al-Zubaidy, H.**, Huang C.C., Yan J., Dynamic Packet Scheduler Optimization in Wireless Relay Networks. *IEEE Journal on Selected Areas in Communications (JSAC*). Vol. 30, Issue. 9, Pages 1746 – 1753, October 2012.
2. **Al-Zubaidy, H.**, Lambadaris, I., Viniotis, I., Optimal Scheduling in A Multi-Server Queues With Random Connectivity and Retransmissions. *Elsevier Computer Communications*, Vol. 35, Issue 13, Pages 1626–1638, July 2012.
3. **Al-Zubaidy, H.**, Lambadaris, I., and Talim, J., Optimal Scheduling in High Speed Downlink Packet Access Networks. *ACM Transaction on Modeling and Computer Simulation* (*TOMACS*), Vol. 21 Issue 1, Pages 3:1 – 3:27 (+ 12 pages online appendix), December 2010.
4. Jibrail, W., **Al-Zubaidy, H.,** Search Strategies for Acquisition of DS Spread Spectrum Signals. *International Journal of Electronics*, Vol. 84, No. 2, Pages 83-104, 1998.

b) Journal articles submitted/under preparation:

1. **Al-Zubaidy, H**., Liebeherr, J., Burchard, A., Performance Analysis of Multi-Hop Fading Channels Using (min, x) Network Calculus.
2. **Al-Zubaidy, H.**, Lambadaris, I., Viniotis, I., Optimal Scheduling Policies in a Multi-server Homogeneous Queuing System with Random Connectivity.
3. **Al-Zubaidy, H.**, Lambadaris, I., Viniotis, I., Optimal Key Generation Policies for Threshold Security Scheme in Mobile Ad-Hoc Networks.

c) Other refereed contributions (conferences)

1. **Al-Zubaidy, H**., Liebeherr, J., (2013) Service Characterizations for Multi–Hop Multiaccess Wireless Networks. Submitted to IEEE INFOCOM'14, Toronto, Canada.
2. **Al-Zubaidy, H**., Liebeherr, J., Burchard, A., (2013) A (min, x) Network Calculus for Multi-Hop Fading Channels. IEEE INFOCOM'13, Turin, Italy.
3. **Al-Zubaidy, H.**, Huang C.C., Yan J., (2011) Most Balancing Algorithms for Optimal Packet Scheduling in Multi-Server Wireless Systems. IEEE WCNC'2011, Mexico.
4. **Al-Zubaidy, H**., I. Lambadaris, I. Viniotis, C. C. Huang, R. H. Hwang, (2010) Optimal Key Generation Policies for MANET Security. Globecom'10, Miami, USA.
5. **Al-Zubaidy, H.**, Lambadaris, I., Viniotis, I., Yu, R. (2010) Optimal Multi-server Allocation to parallel queues with random connectivity and retransmissions. ICC'10, South Africa.
6. **Al-Zubaidy, H.**, Lambadaris, I., Viniotis, I. (2009) Optimal Resource Scheduling in Wireless Multi-service Systems with Random Channel Connectivity. IEEE Globecom'09, USA.
7. **Al-Zubaidy, H.**, Lambadaris, I., and Talim, J. (2008) Code Allocation Policy Optimization in HSDPA Networks Using FSMC Channel Model. IEEE WCNC'08, USA.
8. **Al-Zubaidy, H.**, Lambadaris, I., and Talim, J. (2008) Analytic Evaluation of Achievable Downlink Service Rate and Server Sharing in 3G Wireless Networks. ICTTA'08, Syria.
9. Abou El Saoud, M., **Al-Zubaidy, H.**, and Mahmoud, S. (2008) Connectivity Model for Wireless Mesh Networks. ICC'08, Beijing, China.

10. Abou El Saoud, M., Mahmoud, S., **Al-Zubaidy, H.** (2008) Effect of Inter-Link Dependencies on the Connectivity of Wireless Mesh Networks. IEEE WCNC'08, USA.
11. **Al-Zubaidy, H.**, Talim, J., and Lambadaris, I. (2007) Dynamic Scheduling in High Speed Downlink Packet Access Networks: Heuristic Approach. MILCOM07, USA.
12. **Al-Zubaidy, H.**, Lambadaris, I., Talim, J. (2007) Determination of Optimal Policy for Code Allocation in High Speed Downlink Packet Access with Multi-State Channel Model. ACM/IEEE MSWiM'07, Greece.
13. **Al-Zubaidy, H.** (2007) Downlink Scheduler Optimization in HSDPA Networks. Communication, 2nd Canadian Summer School on Comm. and Info. Theory, Banff, Canada.
14. **Al-Zubaidy, H.**, Lambadaris, I., Talim, J. (2007) Service Rate Determination for Group of Users with Random Connectivity Sharing a Single Wireless Link. IASTED WOC 2007 Montreal.
15. **Al-Zubaidy, H.**, Talim, J., Lambadaris, I. (2007) Optimal Scheduling Policy Determination for High Speed Downlink Packet Access. IEEE ICC'07, Scotland.
16. **Al-Zubaidy, H.**, Lambadaris, I., Talim, J. (2007) Downlink Scheduler Optimization in High-Speed Downlink Packet Access Networks. 26th IEEE INFOCOM'07, USA.
17. **Al-Zubaidy, H.**, Talim, J., Lambadaris, I. (2007) Heuristic Approach of Optimal Code Allocation in High Speed Downlink Packet Access Networks. ICN'07, French Caribbean.
18. **Al-Zubaidy, H.**, and Omari, T. (2006) RED Performance Evaluation Using Stochastic Modeling and Fluid-Based Analysis. CCECE06, Canada.
19. Omari, T., and **Al-Zubaidy, H.** (2005) Call Center Performance Evaluation. CCECE05, Canada.

d) Technical reports (TR):

1. **Al-Zubaidy, H.**, Liebeherr, J., Burchard, A., A Network Calculus Approach for the Analysis of Multi-Hop Fading Channels, http://arxiv.org/abs/1207.6630, July 2012.
2. **Al-Zubaidy, H**., Huang, C.C., Yan, J. Dynamic Packet Scheduler Optimization in Wireless Relay Networks, http://arxiv.org/abs/1104.3165, April 2011.
3. **Al-Zubaidy, H**., Lambadaris I., Viniotis I. Optimal Multi-Server Allocation to Parallel Queues With Independent Random Queue-Server Connectivity, http://arxiv.org/abs/1103.1448, March 2011.
4. **Al-Zubaidy, H.** (2009) Optimal Node Selection for Distributed Security Management in Wireless Systems. TR # SCE-09-12, SCE, Carleton University.
5. **Al-Zubaidy, H.** (2009) Optimal Control of Parallel Queues Served by Two Homogeneous Randomly Connected Servers with Retransmission. TR # SCE-09-11, SCE, Carleton University.
6. **Al-Zubaidy, H.** (2009) Optimal Channel Resource Allocation in Emerging Wireless Networks. TR# SCE-09-02, SCE, Carleton University.
7. **Al-Zubaidy, H.**, Talim, J., and Lambadaris, I. (2006) Optimal Scheduling in High Speed Downlink Packet Access Systems. TR # SCE-06-16, SCE, Carleton University.
8. **Al-Zubaidy, H.** (2006) Dynamic Frequency Hopping (DFH) in Mobile Communication. TR # SCE-06-17, SCE, Carleton University.
9. **Al-Zubaidy, H.** (1994) Search Strategies for Serial Search Direct-Sequence Spread Spectrum Acquisition Schemes. M.Sc. Thesis, University of Technology.

e) Conference presentations:

1. IEEE INFOCOM'13, Torino, Italy. Apr. 2013.
2. IEEE Globecom'10, Miami, Fl, USA. Dec. 2010.
3. IEEE Globecom'09, Honolulu, HI, USA. Dec. 2009.
4. IEEE International Wireless Comm. and Networking Conference WCNC, USA. Mar. 2008.
5. IEEE International Conference on Information & Comm. Technologies ICTTA, Syria 2008.
6. Two presentations. International Military Comm. Conference MILCOM, Orlando, USA. Oct 2007.
7. Three presentations. IEEE International Conference on Communications ICC, Scotland. June 2007.
8. International IASTED Wireless and Optical Communications. Montreal, Canada, May 2007.
9. Canadian CCECE'06, Ottawa, May 2006, Canada.
10. CCECE'05, Saskatchewan, May 2005, Canada.

f) Invited talks:

1. Invited talk at EPFL, Lausanne, Switzerland, May 2013.
2. BCWS Seminar Series, Systems and Computer Engineering, Carleton University, April 2013.
3. IEEE Computer Communication Workshop (CCW), Sedona, AZ, USA. Nov. 2012.
4. MITACS research workshop on estimation, fusion and detection in networked systems, Bellairs Research Institute, Barbados, Mar. 2011.
5. Fields-MITACS Workshop on Probabilistic Methods in Wireless Nets, Ottawa, Canada, Aug. 2011.
6. Toronto Networking Seminar Series, University of Toronto, Dec. 2010.
7. BCWS Seminar Series, Systems and Computer Engineering, Carleton University, July 2009.
8. Invited talks at National Taiwan Univ. and at Institute of Information Science, Taipei, Taiwan 2009.
9. Invited talk at National Cheng Kung University (NCKU) in Kaohsung, Taiwan. July 2009.
10. Invited talk at National Sun Yat-Sen University (NSYSU) in Tainan, Taiwan. July 2009.
11. Canadian Summer School on Communications and Information Theory, Banff, August 2007.

References:

1) Ioannis Lambadaris, Ph.D (Professor)

(My PhD Thesis supervisor)

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Research Statement:

Introduction: I am currently a post-doctoral fellow at the ECE department, University of Toronto. My research interests lie in the broad field of computer networks with emphasis on performance analysis and optimization of wireless networks. I approach complex problems in an innovative manner and ask critical questions with major implications. Examples that showcase my approach to research include: (i) providing a solution to an open optimal scheduling problem that was initially formulated by Tassiulas and Ephremedis [1] in 1993; (ii) challenging and disapproving the conventional wisdom, where I debunked two incorrect, commonly used assumptions, that existed since the 1970s, in the computation of the connectivity models for wireless mesh networks; and more recently, (iii) addressing the open question regarding the relationship between information theory and communication networks that was elegantly posed by Ephremedis and Hajek in [5] and providing a novel approach to analyze the performance of multi-hop wireless networks in terms of fading channel parameters.

Previous research work: In my PhD thesis, I investigated the problem of optimal packet scheduling policy in a homogenous system of parallel queues and multiple servers with random queue-to-server connectivity. Optimality is defined as minimization, in a stochastic ordering sense, of a range of cost functions of the queue lengths. This model is an important tool in studying scheduling in emerging wireless networks. It is highly theoretical and involves important research in the area of *stochastic optimization*.

This problem can be traced back to the seminal work of Tassiulas and Ephremedis [1]. They presented a proof for a simple version of this problem, where a group of parallel queues (L queues), with symmetrical arrival processes, are competing for the service of a single server. They proved that the Longest Connected Queue (LCQ), a policy that allocates the single server to the longest connected queue in the system at every time slot, is optimal. Even with the limitation to a single server, this work spurred a wide interest in the research community and was heavily cited in the literature. In 2007, Ganti, Modiano and Tsitsiklis at MIT [2] extended the model in [1]. They considered multiple queues and servers system, where during each time slot a set of K homogenous (symmetrical) servers may be allocated to K out of the L queues (where $K \leq L$) in the system. In their model a queue is assumed to be "either connected (at a given time slot) to all servers or not connected at all." Another simplifying assumption that they made is that "a queue can only be served by one server during each time slot." This assumption results in a reduction of the system state space and the space of scheduling policies. However, this assumption limits the applicability of such model in emerging wireless systems. In such systems, a user (queue) may be assigned ***one or more*** of the available resources (servers) in the system at any given time slot, a situation that is excluded in [2]. Under the aforementioned assumptions, it was shown that LCQ policy, a policy that allocates the K servers to the K longest connected queues in the system at every time slot, is optimal.

For my PhD thesis, I studied and solved the general problem of homogenous multi-server system ***without*** the simplifying assumptions of [2]. In this model, each queue has *independent connectivity* to each server in the system and can be served by *one or more* of the connected servers (contrary to [2]) during the same time slot. I introduced a new class of scheduling policies, namely the ***Most Balancing*** (MB) policies, and provided a mathematical characterization for these policies. Any such policy will allocate servers to queues (in a work conserving manner) in such a way that minimizes the differences in the lengths of all queues in the system. I proved, using *stochastic dynamic coupling* [3] and *stochastic dominance techniques* [4] that any optimal scheduling policy must belong to the class of MB policies. I also introduced several viable implementations of MB policies. In order to validate my theoretical proofs, I also conducted comparative simulations. The proof is of considerable complexity and requires strong theoretical background and deep knowledge of stochastic optimization and optimal control theory. Several extensions of this work, including the proof that "the optimality of MB policies holds for lossy channels with retransmissions," were also investigated in my PhD thesis.

Another important research project that I worked on was to address the lack of tractable and accurate connectivity models for wireless mesh networks. Most of the previous work done in this context was under two simplifying assumptions, (i) independence between links connecting geometrically co-located nodes and (ii) vanishing boundary effect in node connectivity for larger mesh networks. My intuition suggested that the first assumption is unrealistic and the second one is incorrect. I derived a closed form expression to find the upper bound for the network connectivity of a triangular lattice topology when both assumptions are relaxed and compared it to our earlier analysis. The results showed that the widely used assumption of link independence almost always underestimate the network connectivity. The results also showed that neglecting the boundary effect overestimates the network connectivity by a factor that is increasing in the size of the network.

Furthermore, the analysis showed that the error due to either assumption depends on the link connectivity as well as the network size, and can be very significant.

Current research work: Recently, I made an important contribution to the field of wireless networks where I devised a novel methodology to analyze and provide end-to-end performance bounds for a multi-hop wireless network over a cascade of point-to-point fading channels in terms of the information theoretic capacity of the underlying channels. Such analysis was not feasible before this work due to the fundamental incompatibility of information theory and communication networks (since information theory does not consider delay and traffic burstiness [5]) and the existing results in this regard is mainly asymptotic scaling factors for delay and network throughput, e.g., [6]. I used a unique approach to address the incompatibility of the two worlds by performing the analysis in a devised transfer domain that I refer to as *"SNR domain."* In this domain, the service process is given in terms of instantaneous SNR at the receiver instead of channel capacity and the cumulative traffic is given in terms of the required SNR to transmit that amount of traffic when transmitting at the channel capacity limit. A key discovery of this work is that the analysis in the SNR domain is governed by ***(min, x)*** *dioid algebra*. This motivated me to develop a ***wireless network calculus*** based on (min, x) algebra.

I continued to advance the new approach and develop its theoretical part. I had several questions pertained to this new approach that deserved answers. One such question is: "How does (min, x) calculus models and deals with interference in the wireless channel?" To answer that question, I formulated a service description, using the concept of *leftover service*, for fading channels that are prone to interference from other sources transmitting on the same channel. Another important question that I addressed is related to the *tightness* of the obtained bounds. I computed *asymptotic lower performance bounds* using Gartner-Ellis large deviation theorem and showed that the asymptotic rate of decay of the upper and lower bounds are the same. The importance of this work is that it reconciles information theory and communication networks and in the process, opens the door for a new line of research that utilizes the advancements in information theory to derive innovation in wireless networks and perhaps revolutionize wireless networks as it did to wireless communications.

Directions for future research: The approach that I developed for wireless network performance analysis can be used to answer many existing questions regarding multi-hop wireless networks. On the other hand, it poses many new ones. The ability to obtain explicit, end-to-end performance bounds of wireless networks in terms of the underlying channel distribution enables the formulation of new questions that were inconceivable before. One such question is: "Can we combine the physical layer resource allocation algorithms with the dynamic packet schedulers, e.g., EDF, FIFO, etc.; how does that affect the network performance and can they be jointly optimized?"

For my future research, I am interested in the application of this calculus to *wireless sensor networks, wireless ad-hoc networks* as well as *heterogeneous networks*. The goal is to gain a useful insight to the operation and performance of these networks and to study specific issues pertaining to their unique nature. These networks are mostly chaotic and unpredictable due to their random and intermittent nature, which makes the application of other existing analytic methods, e.g., queuing theory, effective bandwidth, etc., impractical unless heavy assumptions on traffic and configuration of these networks are enforced. They also represent true, multi-hop, store-and-forward wireless networks, which make them excellent candidates for analysis using the (min, x) network calculus. Network calculus approach can be used for performance analysis of *heterogeneous networks* since network calculus admits a variety of traffic models and can be used for analysis of wired as well as wireless networks.

References:

[1] L. Tassiulas and A. Ephremides, "Dynamic server allocation to parallel queues with randomly varying connectivity," *IEEE Transactions on Information Theory*, vol. 39, issue 2, page(s):466 - 478, March 1993.

[2] A. Ganti, E. Modiano, J.N. Tsitsiklis, "Optimal transmission scheduling in symmetric communication models with intermittent connectivity," *IEEE Trans. on Information Theory*, vol. 53, issue 3, March 2007.

[3] T. Lindvall, *Lectures on the coupling method*, New York: Wiley (1992).

[4] D. Stoyan, *Comparison Methods for Queues and other Stochastic Models*, Wiley and Sons, 1983.

[5] A. Ephremides and B. Hajek, "Information theory and communication networks: An unconsummated union," *IEEE Trans. on Information Theory*, vol. 44, pp. 2416–2434, Oct. 1998.

[6] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. on Inform. Theory*, vol. 42, pp. 388-404, Mar. 2000.