

1 BIOGRAPHY

Moe Z. Win (S'85-M'87-SM'97-F'04) received both the Ph.D. in Electrical Engineering and M.S. in Applied Mathematics as a Presidential Fellow at the University of Southern California (USC) in 1998. He received an M.S. in Electrical Engineering from USC in 1989, and a B.S. (*magna cum laude*) in Electrical Engineering from Texas A&M University in 1987.

Dr. Win is an Associate Professor at the Massachusetts Institute of Technology (MIT). Prior to joining MIT, he was at AT&T Research Laboratories for five years and at the Jet Propulsion Laboratory for seven years. His research encompasses developing fundamental theories, designing algorithms, and conducting experimentation for a broad range of real-world problems. His current research topics include location-aware networks, intrinsically secure wireless networks, aggregate interference in heterogeneous networks, ultra-wide bandwidth systems, multiple antenna systems, time-varying channels, optical transmission systems, and space communications systems.

Professor Win is an IEEE Distinguished Lecturer and elected Fellow of the IEEE, cited for “contributions to wideband wireless transmission.” He was honored with the IEEE Eric E. Sumner Award (2006), an IEEE Technical Field Award for “pioneering contributions to ultra-wide band communications science and technology.” Together with students and colleagues, his papers have received several awards including the IEEE Communications Society’s Guglielmo Marconi Best Paper Award (2008) and the IEEE Antennas and Propagation Society’s Sergei A. Schelkunoff Transactions Prize Paper Award (2003). His other recognitions include the Laurea Honoris Causa from the University of Ferrara, Italy (2008), the Technical Recognition Award of the IEEE ComSoc Radio Communications Committee (2008), Wireless Educator of the Year Award (2007), the Fulbright Foundation Senior Scholar Lecturing and Research Fellowship (2004), the U.S. Presidential Early Career Award for Scientists and Engineers (2004), the AIAA Young Aerospace Engineer of the Year (2004), and the Office of Naval Research Young Investigator Award (2003).

Professor Win has been actively involved in organizing and chairing a number of international conferences. He served as the Technical Program Chair for the IEEE Wireless Communications and Networking Conference in 2009, the IEEE Conference on Ultra Wideband in 2006, the IEEE Communication Theory Symposia of ICC-2004 and Globecom-2000, and the IEEE Conference on Ultra Wideband Systems and Technologies in 2002; Technical Program Vice-Chair for the IEEE International Conference on Communications in 2002; and the Tutorial Chair for ICC-2009 and the IEEE Semiannual International Vehicular Technology Conference in Fall 2001. He was the chair (2004-2006) and secretary (2002-2004) for the Radio Communications Committee of the IEEE Communications Society. Dr. Win is currently an Editor for IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS. He served as Area Editor for *Modulation and Signal Design* (2003-2006), Editor for *Wideband Wireless and Diversity* (2003-2006), and Editor for *Equalization and Diversity* (1998-2003), all for the IEEE TRANSACTIONS ON COMMUNICATIONS. He was Guest-Editor for the PROCEEDINGS OF THE IEEE (Special Issue on UWB Technology & Emerging Applications) in 2009 and IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS (Special Issue on Ultra-Wideband Radio in Multiaccess Wireless Communications) in 2002.

2 CORE INFORMATION

Moe Win

(United States Citizen)

Associate Professor
Laboratory for Information & Decision Systems (LIDS)
Massachusetts Institute of Technology

Details can be found at <http://wgroup.lids.mit.edu/>

Business

Massachusetts Institute of Technology
77 Massachusetts Avenue, Room 32-D658
Cambridge, MA 02139
Tel: (617) 253-9341
e-mail: moewin@mit.edu

Residence

36 Nipmuc Road
Framingham, MA 01702
Tel: (617) 459-6610

URL: <http://wgroup.lids.mit.edu>

2.1 EDUCATION

- **Doctor of Philosophy** in Electrical Engineering, *Presidential Fellow*, May 1998
University of Southern California, Los Angeles, CA
Topic: Wireless Multiple Access Communications using Ultra -Wide Bandwidth
Impulse Radio in Dense Multipath Channels
Advisor: Professor Robert A. Scholtz
- **Master of Science** in Applied Mathematics, *Presidential Fellow*, May 1998
University of Southern California, Los Angeles, CA
Topic: Polyphase Sequences
Advisor: Professor Solomon W. Golomb
- **Master of Science** in Electrical Engineering, May 1989
University of Southern California, Los Angeles, CA
Topic: Coherent Optical Communications using Frequency Stabilized Solid State Lasers
Advisor: Professor Robert A. Scholtz
- **Bachelor of Science** in Electrical Engineering, *Magna Cum Laude*, May 1987
Texas A&M University, College Station, TX
Topic: PPM Sequences with Desirable Correlation (Honors Undergraduate Thesis)
Advisor: Professor Costas N. Georghiadis

2.2 RESEARCH SUMMARY

Twenty years of experience in leading research institutions working on a broad range of communications problems including ultra-wide bandwidth communications systems, ranging and localization systems, intrinsically secure large-scale wireless networks, aggregate interference in heterogeneous networks, design and analysis of multiple antenna systems, measurement and modeling of time-varying channels, and optical communications systems. Widely published in leading journals, with worldwide contacts in communication theory and wireless systems.

2.3 HONORS AND AWARDS

- **The Royal Academy of Engineering Distinguished Visiting Fellowship** for "sharing first-hand insight into world-class cutting-edge knowledge, recognising excellence, and inspiring the next generation," United Kingdom, 2009.
- **IEEE Globecom '09 Best Paper Award**, IEEE Global Communications Conference, 2009.
- **L3 Communications Prize** for the "first practical demonstration of cooperative UWB-IR location-aware networks," Soldier Design Competition, MIT Institute for Soldier Nanotechnologies, 2009.
- **Technical Recognition Award** of the IEEE ComSoc Radio Communications Committee for "exceptional technical contributions to radio communications," 2008.
- **Guglielmo Marconi Best Paper Award** of the IEEE Communications Society for "an original paper in the field of Wireless Communications published in the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS," 2008.
- **Laurea Honoris Causa**, Dottore "Ad Honorem" in Ingegneria e Tecnologie per le Telecomunicazioni e l'Elettronica. Awarded by the Università degli Studi di Ferrara, with the approval of the Ministro dell'Università e della Ricerca, Italy, 2008.
- **IEEE Distinguished Lecturer**, selected by the IEEE Communications Society, 2008-2009.
- **IEEE ICC '08 Best Paper Award**, IEEE International Conference on Communications, 2008.
- **IEEE VTC '08 Best Paper Award**, IEEE 67th Vehicular Technology Conference, 2008.
- **Wireless Educator of the Year Award** for "pivotal role in educating and preparing tomorrow's wireless technology leaders" and "ability to inspire students to high levels of accomplishment." Selected by the governing Board of Directors of the Global Wireless Education Consortium (GWEC), 2007.
- **IEEE WCNC '07 Best Paper Award**, IEEE Wireless Communications and Networking Conference, 2007.
- **IEEE Eric E. Sumner Award**, the IEEE Technical Field Award for "pioneering contributions to ultra-wide band communications science and technology," 2006.
- **IEEE ICUWB '06 Best Paper Award**, IEEE International Conference on Ultra-Wideband, 2006.
- **IEEE ICUWB '06 Best Student Paper Award**, IEEE International Conference on Ultra-Wideband, 2006.
- **ACM IWCMC '06 Best Paper Award**, International Wireless Communications and Mobile Computing Conference, 2006.
- **Lifetime Achievement Award** from the People of Bangladesh for "fundamental contributions to communication theory," 2006.
- **IEEE ICNEWS '06 Best Paper Award**, IEEE 1st International Conference on Next-Generation Wireless Systems (co-sponsored by IEEE Communications Society), 2006.
- **Global Wireless Education Consortium Certificate of Recognition** for "[...] outstanding contributions and accomplishments in wireless education," 2006.
- **IEEE Distinguished Lecturer**, selected by the IEEE Communications Society, 2006-2007.
- **Elected Fellow of the IEEE** for "contributions to wideband wireless transmission." Following a rigorous evaluation procedure, the IEEE Board of Directors annually elects "recipients for one of the Institute's most prestigious honors [...] IEEE Fellow," the highest grade of membership, 2004.

- **Outstanding International Collaboration Award** for “innovative analytical and experimental work that has led to the creation of ultra -wideband industry.” Awarded by the Industrial Technology Research Institute (ITRI), founded by the Ministry of Economic Affairs (MOEA) of Republic of China, Taipei, Taiwan 2004.
- **Institute of Advanced Study Natural Sciences and Technology Fellowship**, to devote time and creative energy to theoretical and applied research, to explore fundamental issues of Wideband Wireless Transmission Systems in a cross-disciplinary context, and to deliver Institute Lectures at the University of Bologna, Italy, 2004.
- **Fulbright Foundation Senior Scholar Fellowship Award**, to pursue research and lecturing at the Centre for Wireless Communications (CWC) in Oulu, Finland, 2004.
- **AIAA Young Aerospace Engineer of the Year**, 2004.
- **Presidential Early Career Award for Scientists and Engineers (PECASE)** from the United States White House for “pioneering work on novel Ultra -Wide Band radio communication systems including fundamental propagation studies, channel modeling, and signal acquisition protocols; providing the foundation for utilizing this new form of radio communication in the design of secure, fade resistant, high data rate wireless networks.” The PECASE Award is the highest honor bestowed by the U.S. Government on outstanding Scientists and Engineers as they embarked upon their independent careers, 2004.
- **MIT School of Engineering Educational Innovation Award** for AY 2003-04.
- **Office of Naval Research Young Investigator Award** for “academic achievements, ability to contribute to the strength of the Nation’s research and development, and exceptional promise for outstanding research and teaching careers.” Recipients of this award are considered to be the best and brightest young academic researchers across nationwide, 2003.
- **Sergei A. Schelkunoff Transactions Prize Paper Award** of the IEEE Antennas and Propagation Society for “the best Transactions paper judged on the basis of technical contributions, style and presentation,” 2003.
- **Charles Stark Draper Assistant Professor**, Massachusetts Institute of Technology, 2002-2004.
- **International Telecommunications Innovation Award** for “fundamental contributions to communication theory, pioneering analytical and experimental advances, and outstanding leadership that created the ultra -wide bandwidth industry.” Presented annually, when merited, by the Korea Electronics Technology Institute (KETI) under the Ministry of Commerce, Industry, and Energy (MOCIE) to international scholars who have revolutionized communications technology with entirely new and innovative ideas that have significant impact on global industry, 2002.
- **Distinguished Alumni Award** (First Recipient), Mountain View College, 2002.
- Honorable Mention as the runner-up, **Stephen O. Rice Prize Paper Award** of the IEEE Communications Society for “the best paper in the field of Communications Theory published in the IEEE TRANSACTIONS ON COMMUNICATIONS,” 2001.
- **Presidential Fellow**, “the highest honor the university bestows upon its graduate students.” Presidential Fellows Program provides formal training in leadership to its most promising future leaders in the professional and graduate schools, University of Southern California, 1996-1997.
- NetWorld+Interop ‘97 **Best Student Paper Award** of the IEEE Communications Society, Fourth Annual NetWorld+Interop Engineer Conference, 1997.
- **Phi Kappa Phi Student Recognition Award** at the Sixteenth Annual Academic Honors Convocation for “outstanding scientific and scholarly works,” University of Southern California, 1997.

- **Best Poster Presentation Award** for “outstanding poster presentation,” at the Communication Sciences Institute Annual Technical Review, University of Southern California, 1997.
- **IEEE ISSSTA '96 Best Student Paper Award**, IEEE Fourth International Symposium on Spread Spectrum Techniques and Applications, Mainz, Germany, 1996.
- **Outstanding Research Paper Award (First Award)** for “best research paper written by a student,” University of Southern California, 1996.
- **Best Poster Presentation Award (First Award)** for “outstanding poster presentation,” at the Communication Sciences Institute Annual Technical Review, University of Southern California, 1996.
- **NASA Monetary Award** for “creative development, technical innovation, and contribution to the National Space Program, and to the mission of the Jet Propulsion Laboratory,” 1993.
- **NASA Monetary Award** for “creative development, technical innovation, and contribution to the National Space Program, and to the mission of the Jet Propulsion Laboratory,” 1991.
- **University Undergraduate Fellow** for “superior academic and research contributions in the community of undergraduate and faculty scholars,” Texas A&M University, 1986-1987.
- **Academic Excellence Award**, 1985-1986, Texas A&M University.
- **Distinguished Student Award** for “outstanding academic achievement,” Texas A&M University, Spring 1986.
- **Undergraduate Summer Research Award**, Texas A&M University, Summer 1986.
- **Herman F. Heep Scholarship** for “superior scholastic performance, outstanding leadership qualities, and participation in student activities and organizations,” Texas A&M University, 1985.
- **Dean’s List** for “highest rank of scholastic success,” Mountain View College, Fall 1983, and Spring 1984.
- **Honorable Mention** for “excellent achievement in Mathematics,” Mountain View College, 1984.
- **All Star Student of the Year** for “exceptional achievement in Science, Math and Technology,” Mountain View College, 1984.

3 EXPERIENCE

Detailed description of specific research projects can be found at <http://www.moewin.com>
Hard copies will be provided by request.

3.1 WORK EXPERIENCE

- **Laboratory for Information & Decision Systems (LIDS)**
Massachusetts Institute of Technology
Charles Stark Draper Assistant Professor
Associate Professor
Cambridge, MA
Sept. 2002 - Aug. 2004
Sept. 2004 - Present
- **AT&T Labs - Research, Wireless Systems Research Department**
Promoted to Principal Technical Staff Member
Senior Technical Staff Member
Middletown, NJ
Apr. 2000 - Mar. 2002
Jan. 1998 - Mar. 2000
- **Jet Propulsion Laboratory, California Institute of Technology**
Member of Technical Staff
Digital Signal Processing Research Group
Guidance and Control Section
Communications Systems Research Section
Pasadena, CA
July 1996 - Dec. 1996
Jan. 1991 - June 1995
May 1987 - Jan. 1991
- **University of Southern California**
Research Assistant
Integrated Media Systems Center
Communication Sciences Institute
Los Angeles, CA
Sept. 1996 - Dec. 1997
June 1994 - Aug. 1996
- **Texas A&M University**
Student Researcher
Telecommunication and Control Systems Laboratory
College Station, TX
June 1986 - May 1987
- **Texas Engineering Experiment Station**
Laboratory Technician
VLSI CAD laboratory & Microelectronics Research Center
College Station, TX
Mar. 1985 - May 1986

3.2 CONSULTING EXPERIENCE

- **DoCoMo Communications Laboratories USA, Inc.**
Consultant
Palo Alto, CA
Sept. 2006 - Present
- **Mitsubishi Electric Research Laboratories**
Consultant
Cambridge, MA
Jan. 2005 - Mar. 2005
- **RadioLabs, Consortium at University of Rome "Tor Vergata"**
Technology Consultant
Rome, Italy
Mar. 2000 - Present
- **Graham & James LLP**
Consultant
Los Angeles, CA
Oct. 1996 - Feb. 1997
- **Pulson Communications & Time Domain Systems, Inc.**
Consultant
Huntsville, AL
June 1994 - Sept. 1995

3.3 TEACHING EXPERIENCE

- **Massachusetts Institute of Technology**
Departments of Electrical Engineering & Computer Science, and Aeronautics & Astronautics,
Sept. 2002 – Present
 - **EECS 6.976/AA 16.399**: Space Communications and Networks
Fall 2002
 - **AA 16.900**: Computational Tools for Engineering
IAP 2003
 - **EECS 6.976/AA 16.399/ME 2.996/ESD.930**: Statistics with Engineering Applications
Fall 2003, New course development and preparation for the SoE
 - **MATH 18.996/AA 16.399**: Random matrix theory and its applications
Spring 2004
 - **MATH 18.338J/AA 16.394J**: Random matrix theory and its applications
Fall 2004
 - **EECS 6.041**: Probabilistic Systems Analysis and Applied Probability (2 Recitation Sections)
Spring 2005
 - **EECS 6.434J/AA 16.391J**: Statistics for Engineers and Scientists
Fall 2005, New course development and preparation for the SoE
 - **EECS 6.434J/AA 16.391J**: Statistics for Engineers and Scientists
Spring 2006
 - **EECS 6.986**: Principles of Wide Bandwidth Communication
Fall 2006, New course development and preparation
 - **AA 16.395**: Principles of Wide Bandwidth Communication
Fall 2007
 - **AA 16.36**: Communication Systems Engineering
Spring 2008
 - **AA 16.001/002**: Unified Engineering (Signals & Systems)
Fall 2008
 - **AA 16.003/004**: Unified Engineering (Signals & Systems)
Spring 2009
 - **EECS 6.434J/AA 16.391J**: Statistics for Engineers and Scientists
Fall 2009
 - **AA 16.62x** : Experimental Projects
Spring 2010
- **Mountain View College, Mathematics Laboratory**
Teaching Assistant, May 1984 – Aug. 1984
 - Assisted students with Differential and Integral Calculus, Elementary Probability and Statistics, Analytic Geometry, Trigonometry, Algebra, etc.
- **University of Texas (Arlington), Summer Institute of Linguistics**
Teaching Assistant, Sept. 1983 – Dec. 1983
 - Assisted students with Burmese language.

3.4 RESEARCH HIGHLIGHTS

- **Ultra-Wide Bandwidth (UWB) Communications:** Performed pioneering work on UWB radio and provided a foundation for the design of UWB wireless networks. UWB has the desirable characteristic of high resistance to fading. The Federal Communications Commission (FCC) approved unlicensed UWB operation and commercial deployment of UWB technology under Part 15 rules in February 2002 for a vast array of new applications including broadband internet access, medical imaging, and ground penetrating radar. Specific contributions include:
 - **Propagation Measurement and Statistical Modeling:** Conducted the first UWB signal propagation experiments, devised a statistical propagation channel model, and demonstrated the robustness of a UWB signal in a multipath environment.
 - **Receiver Design, Analysis, and Simulations:** Proposed theoretical analysis and experimental techniques, all of which enabled the efficient design and accurate performance prediction of UWB transmission. Proposed reduced-complexity Rake receivers based on partial combining (PRake) and selective combining (SRake), and evaluated their link performance in a *realistic* UWB channel.
 - **Transmitted-Reference (TR) Signaling for UWB Communications:** Developed an analytical framework, based on a sampling expansion approach, to evaluate the performance of TR and differential TR signaling for UWB systems with autocorrelation receivers. The analysis includes the effect of narrowband interference and is valid for a broad class of fading channels. Obtained a rule of thumb for the asymptotic SNR penalty which is useful for comparing a simple TR system to an ideal Rake receiver.
 - **Unified Spectral Analysis:** Derived general expressions for the power spectral density (PSD) of a variety of time-hopping spread-spectrum signaling schemes in the presence of timing jitter using *stochastic theory*.
- **Cooperative Localization for UWB Networks:** UWB technology is well-suited for localization due to its potential for highly accurate ranging and robust communication. These attributes allow UWB nodes to cooperatively propagate and refine position information throughout the network. Cooperative localization can achieve network-wide location-awareness, particularly in GPS-denied environments. Contributions include:
 - **Fundamental Performance Bounds:** Proposed the notion of equivalent Fisher information (EFI) to characterize the localization accuracy. This decomposes the contributions from line-of-sight (LOS), non line-of-sight (NLOS), and a priori knowledge to position error bounds, resulting in new insights in node placement strategies. Extended the concept of EFI to cooperative localization and quantified the benefit of agents' cooperation. Proposed a distributed iterative algorithm that unifies anchors and agents for calculating position error bounds.
 - **Scalable and Distributed Iterative Algorithms:** Developed a scalable, cooperative distributed localization algorithm for large UWB networks, based on factor graphs and belief propagation. Each node iteratively refines its location estimate using belief messages propagated from neighboring nodes, allowing efficient, distributed computation. Evaluated outage probability in a variety of settings. Performed wideband channel measurements using UWB as the underlying model for the localization algorithm.
 - **Channel Classification and Non-line-of-sight Mitigation Using Machine Learning:** Performed an extensive measurement campaign on the MIT campus using commercially available FCC-compliant UWB radios to collect numerous channel realizations in indoor office environments. Developed classification and regression algorithms, based on machine learning techniques, which are capable of 1) assessing whether a signal was transmitted in line-of-sight or non-line-of-sight (NLOS) conditions, and 2) reducing ranging error caused by NLOS conditions. Evaluated the performance of these algorithms using experimental data.
- **Optimal Search Strategies:** Established a framework and determined the fundamental limits of search strategies by bringing together ideas from the disciplines of engineering and mathematics,

involving communication, signal processing, convexity, and optimization theories. Specific contributions include:

- **η -optimal Search:** Developed methodologies for the design of deterministic search algorithms that approach the fundamental limits.
- **Randomized Search:** Proposed and analyzed randomized search strategies that are robust to variations in channel conditions.

This work is applicable to a broad class of search scenarios including minimal-time search algorithms that exploit multipath for acquisition of wide bandwidth wireless signals. In particular, it provides the fundamental basis for the design and analysis of UWB fast synchronization systems, which are essential for the rapid deployment and operation of future communication and sensor networks.

- **Intrinsically Secure Large Scale Wireless Networks:** Introduced an information-theoretic definition of the intrinsically secure communications graph (iS-graph), based on the notion of strong secrecy. The proposed framework considers spatially scattered users and eavesdroppers, subject to generic wireless propagation characteristics. Specific contributions include:
 - **Local Characterization of the iS-graph:** Provided a complete probabilistic characterization of node degrees, maximum secrecy rates, and isolation probabilities of a typical node in the Poisson iS-graph, using fundamental tools of stochastic geometry.
 - **Techniques for Communication with Enhanced Secrecy:** Proposed sectorized transmission and eavesdropper neutralization as two techniques for enhancing the secrecy of communication, and quantified their effectiveness in terms of the resulting average node degrees.
 - **The Case of Colluding Eavesdroppers:** Quantified exactly how eavesdropper collusion degrades the secrecy properties of the legitimate nodes, in comparison to a non-colluding scenario.
 - **Percolation in the iS-graph:** Proved the existence of a phase transition in the Poisson iS-graph defined on the infinite plane, whereby an unbounded component of connected nodes arises as the density of legitimate nodes increases. This shows that long-range communication is still possible even in a wireless network when a security constraint is present.
- **Interference Analysis in Heterogeneous Networks:** Developed a mathematical model for coexistence analysis in wireless networks composed of both narrowband (NB) and UWB nodes. The model accounts for the spatial distribution of interferers, and the propagation characteristics of the wireless environment. Specific contributions include:
 - **Probabilistic Invariance of Aggregate Interference with Application to FCC Rule Making:** Proved that cumulative interference from radiators located at points of a Poisson random set obeys stable laws and possesses a *surprising* invariance with respect to essentially *any* fading distribution. Hence, these results are valid for a large class of fading environments and are helpful in characterizing the effect of unlicensed transmitters in the context of rule making by the FCC in the US and equivalent regulatory agencies in Europe and Asia-Pacific.
 - **Spectral Outage:** Characterized the spectrum of the aggregate interference at any location in the Poisson plane, and put forth the new concept of spectral outage probability (SOP). The SOP can be used to quantify and limit the impact of network interference on a given frequency band, and serves as an insightful network design criterion.
 - **Error and Capacity Performance:** Derived the performance expressions (in terms of error probability and channel capacity) for a NB/UWB link subject to cumulative UWB/NB interference, fading, and additive white Gaussian noise (AWGN). The approach generalizes the conventional analysis of linear detection in the presence of AWGN and fast fading, allowing the traditional results to be extended to include the effect of aggregate interference.
- **Subset Diversity Techniques:** Subset diversity techniques are reduced-complexity diversity methods where only a subset of the available diversity branches are utilized. These techniques are applicable to the many different forms in which diversity arises. The contributions have focused on spatial diversity through multiple antennas or relays; and multipath diversity due to wideband transmission. Specific contributions include:

- **Multiple-Input Multiple-Output (MIMO) Systems:** Developed an analytical framework for the performance of MIMO systems operating in multipath-fading environments, where a subset of antennas is chosen at both the transmitter and receiver sides. Derived simple, yet tight, bounds on the performance of such systems.
- **Hybrid Selection/Maximal-ratio Combining (H-S/MRC) Diversity Systems:** Developed an analytical framework to study the performance of H-S/MRC in a multipath-fading environment. In H-S/MRC, the best L out of N diversity branches are selected and combined using MRC, yielding improved performance over L branch MRC.
- **Efficient Evaluation of Error Rate for Hybrid Diversity Systems:** Derived simple explicit bounds for assessing the error rate of hybrid diversity systems. The bounds are tight and valid for all values of signal-to-noise ratios; thus alleviating the need for complicated analysis and multiple numerical integrals. Contrary to a previous conjecture, the penalty of a hybrid diversity system relative to MRC diversity was shown not to be constant; it is not independent of the signal-to-noise ratio (SNR) and the target symbol error probability (SEP).
- **Reduced-Complexity Rake Receivers:** Quantified the effects of spreading bandwidth on spread spectrum systems in dense multipath environments in terms of performance, complexity, and channel parameters. Developed an analytical framework that provides fundamental insights on how wideband reduced-complexity Rake receivers can best take advantage of multipath, and a theoretical basis for deciding how many fingers should be included in the receiver architecture.
- **Subset Diversity with Practical Channel Estimation:** Developed an analytical framework for evaluating the performance of subset diversity schemes in the presence of channel estimation error. Showed that such a system preserves the full diversity order. The study revealed that the asymptotic performance loss due to estimation error has a surprising lack of dependence on the number of combined branches or the total number of available diversity branches.
- **SNR Penalty Characterization for Subset Diversity Systems:** Derived simple explicit bounds and approximations for assessing the error rate of subset diversity systems with practical channel estimation. These bounds and approximations are based on the performance loss, or SNR penalty, that occurs between subset diversity systems with: 1) different combining architectures, or 2) different amounts of energy devoted to channel estimation. Obtained remarkably simple expressions, in several important cases, for the exact SNR penalty.
- **Cooperative and Distributed Techniques:** Cooperative processing constitutes a new networking paradigm whereby nodes work together in order to achieve a common goal. Harnessing the collective power of the network enables increased coverage, longer network life, and massively parallel processing. Specific contributions include:
 - **Outage-Optimal Opportunistic Relaying:** Put forth simple opportunistic relaying strategies under an aggregate power constraint. Developed distributed relay-selection algorithms requiring only local channel knowledge. Proved that opportunistic decode-and-forward relaying is outage-optimal, that is, it is equivalent in outage behavior to the optimal strategy that employs all potential relays. The results revealed that cooperation offers diversity benefits even when the cooperative relays choose not to transmit, but rather choose to cooperatively listen.
 - **Cooperation in Bandwidth-Constrained Wireless Sensor Networks:** Evaluated two different fusion architectures in terms of system reliability and average energy consumption where the degree of cooperation among the sensor nodes varies. Proposed a consensus flooding protocol for cooperation. Obtained insights into the trade-offs between reliability and energy efficiency with regard to spatially varying sensor observations, network connectivity, and realistic link models.
 - **Optimal and Robust Power Allocation in Wireless Relay Channels:** Developed an analytical framework to obtain the optimal relay power allocation in multiple-relay amplify-and-forward channels in the presence of ideal global channel state information (CSI). Proposed an efficient algorithm for relay power allocation using second-order conic programming. Extended the results

- to the case of non-ideal global CSI, and designed robust relay power allocation protocols using the worst-case approach.
- **Detection in Censoring Sensor Networks:** Established a general framework for decentralized binary hypothesis testing in which sensors are allowed to be cooperatively censored (put to 'sleep') based on observed side-information. Studied the tradeoff between detection performance and resource consumption. Developed an asymptotically optimal strategy that is simple, distributed, and depends only on the local information, provided that the network has a large number of sensors and the false alarm probability is constrained to be small.
 - **Detection in Tree Networks with Bounded Height:** Studied the detection performance of bounded height tree architectures for energy efficiency and bounded delay. Showed the surprising fact that under some mild conditions, the asymptotically optimal Neyman-Pearson detection performance of such an architecture is the same as the standard parallel configuration. Quantified the performance loss as a function of tree height for the Bayesian framework.
 - **Markov-chain Monte Carlo (MCMC) Methods based Inference for Hidden-Markov Model (HMM):** Developed a class of MCMC methods to perform the widely used forward-backward algorithm on HMM at drastically reduced computational complexity and storage requirements. Incorporated these methods in iterative (turbo) detection schemes. Successfully applied to iterative equalization for non-linear Satellite channels.
 - **Optimum Combining:** Solved an open problem (considered intractable for 20+ years) of optimum combining (OC) in wireless systems using *random matrix theory*. Results obtained are general and valid for an arbitrary number of antennas as well as interferers, and were confirmed by Monte Carlo simulation. Obtained fundamental new insights that are useful in the design of MIMO systems with OC.
 - **Distribution-Invariant Monotonicity Theorems on Multi-Channel Diversity:** Established an analytical framework and proved monotonicity theorems with which one can compare the performance of a given diversity system in different wireless environments, characterized by their average properties. The strength of the proposed framework is that the results are invariant with respect to essentially *any* fading distribution, and therefore fading statistics are not required to compare the performance of a given diversity system in different environments.
 - **Diversity with Practical Channel Estimation:** Developed an analytical framework for evaluating the performance of practical diversity systems with non-ideal channel estimates. This framework is simple and applicable to channels with arbitrary distributions, including correlated fading. The analysis showed that the SNR penalty, due to estimation error, has a surprising lack of dependence on the number of diversity branches. It was proven that the practical estimator preserves the full diversity order, in contrast to results in the literature which state that, even with an arbitrarily good estimate, the diversity order is that of a single-branch system.
 - **Optimized Simple Bounds for Diversity Systems:** Proposed a simple class of bounds, whose parameters are optimized, on the symbol error probability (SEP) for detection of arbitrary two-dimensional signaling constellations with diversity in the presence of non-ideal channel estimation. Unlike known bounds, the optimized simple bounds are tight for all signal-to-noise ratios (SNRs) of interest. The new bounds enable the characterization of the symbol error outage (SEO), SEP-based outage probability, in a shadowing environment and are useful for the design of digital radio systems with diversity reception.
 - **Slow Adaptive Modulation:** Proposed a slow adaptive M -QAM scheme for multi channel reception in the presence of fading and non-ideal channel estimation, requiring the signaling constellation to follow only the slow variation of the channel such as shadowing. The proposed slow adaptive modulation (SAM) scheme provides substantial improvement over a non-adaptive scheme. Furthermore, the performance of SAM is close to that of fast adaptive modulation (FAM) in many scenarios, despite the fact that SAM is less complex and requires a lower feedback rate than FAM.

- **Inequalities Arising from Linear Programming:** Conjectured new inequalities that are not easily obtainable by the direct method of Hardy, Littlewood, and Pólya. These inequalities arise in a variety of communication engineering problems, and were proved using ideas of convexity and linear programming.
- **Canonical Forms for Performance of MRC in Correlated Nakagami Fading:** Derived closed-form expressions for three performance measures: 1) probability density function of the combiner output SNR; 2) error rate for coherent detection; and 3) outage probability. Obtained a canonical structure for these performance measures as a weighted sum of the corresponding expressions for a non-diversity (single-branch) system. This result is fundamental: the canonical structure depends only on the properties of the channel and diversity combiner, and not on the specific modulation technique.
- **Frame Synchronization:** Derived metrics that allow fair comparison of various frame synchronization techniques. Proposed metrics can be used for a design of fast synchronization systems.
- **Quantum Error Recovery:** Quantum error correction efforts to date have generally focused on generic noise models, and thus generic error recovery procedures. The contributions have examined the benefits of quantum error recovery (QER) tailored to a specific noise model. Specific contributions include:
 - **Optimum QER as a Semidefinite Program:** Demonstrated that using *entanglement fidelity* as the measure of performance, the optimum QER operation can be computed as the result of a semidefinite program (SDP). An SDP is a convex optimization routine, for which efficient algorithms are well understood. In this way, for any given noise model and encoding, the optimum recovery can be computed.
 - **Eigen Analysis for QER:** Demonstrated the utility of eigen-analysis in interpreting and deriving QER techniques. Developed an eigenvector based algorithm to approximate the optimum QER operation for high dimensional channels (for which computing the optimum via a SDP is computationally burdensome).
- **Frequency Noise Measurement and Model for an Optical Phased-Locked Loop (OPLL):** Modeled the frequency noise spectrum of diode-pumped Nd:YAG ring lasers. Verified the model with experimentally measured frequency noise. Demonstrated for the first time that this spectrum possesses strong $1/f$ and $1/f^2$ components, in addition to having the commonly accepted white frequency noise model. Designed and analyzed the OPLL for free-space coherent optical communications and experimentally demonstrated phase locking of both the CW and BPPM optical signal.