Laboratory for Information and Decision Systems

The Laboratory for Information and Decision Systems (LIDS) is an interdepartmental laboratory for research and education in systems, control, optimization, communication, networks, and statistical signal processing. These disciplines, which span the domain of the analytical information and decision sciences and share a common approach to problems and a common mathematical base, play a critical and pervasive role in science, engineering, and society more broadly. LIDS provides this melting pot of disciplines with an energized environment that fosters the research needed for the future and instills in its students the disciplinary depth and interdisciplinary understanding required of research and engineering leaders of today and tomorrow.

LIDS faculty is principally drawn from the Department of Electrical Engineering and Computer Science (EECS) and the Department of Aeronautics and Astronautics. However, because the disciplines in which LIDS is involved are also of great interest across the Institute, it has built and continues to build collaborations and interactions with many other units, including the Operations Research Center (ORC); the Computer Science and Artificial Intelligence Laboratory (CSAIL); the Research Laboratory of Electronics; the MIT Energy Initiative (MITEI); the Transportation@MIT initiative; the Department of Civil and Environmental Engineering; the Department of Mechanical Engineering; the Department of Earth, Atmospheric, and Planetary Sciences; the Department of Brain and Cognitive Sciences (BCS); the Department of Economics; the MIT Sloan School of Management; the Harvard–MIT Division of Health Sciences and Technology; and the Singapore–MIT Alliance for Research and Technology (SMART). LIDS also plays an increasing role in MITEI, collaborating with various members of the MIT community on defining the future of research in energy as it pertains to systems issues. In addition, LIDS has a strong and growing set of interactions with industrial organizations, national laboratories, and international institutions that provide funding, collaborators, and challenging problems to drive its research. Among the organizations with which it has or is developing relations are Charles S. Stark Draper Laboratory, Lincoln Laboratory, Los Alamos National Laboratory, Siemens, Shell Oil Company, Honeywell International, Ford Motor Company, Société Nationale des Chemins de fer français, and Aurora Flight Sciences. Also, thanks to a rich history of research excellence and leadership, LIDS remains a magnet for the very best, attracting not only outstanding students and faculty but also a continuing stream of world-class researchers as visitors and collaborators.

Recent activities and events continue to demonstrate LIDS's position as a world leader among research organizations. Of particular note was the Interdisciplinary Workshop on Information and Decision in Social Networks (WIDS), held May 31–June 1, 2011, on the MIT campus and attended by over 250 participants. More than 40 talks and posters were presented at the workshop with contributions coming from a broad range of researchers, including social scientists, computer scientists, and economists. WIDS was also part of the MIT150 sesquicentennial celebration, which LIDS contributed to in various ways.

In addition, LIDS faculty and students continue to receive numerous national and international awards for their contributions. The LIDS website contains details on LIDS activities, people, awards, and research accomplishments and directions, including those mentioned in this report.

LIDS Intellectual Vision and Research Areas

The domain of research in LIDS can be described along several different dimensions:

- A common set of mathematical disciplines, including probability and statistics, dynamical systems, and optimization and decision theory
- A set of core engineering disciplines—namely, inference and statistical data processing, transmission of information, networks, and systems and control
- A set of broad challenges, emerging applications and critical national or international needs, and intellectual opportunities.

Research at LIDS involves activities within and across all these dimensions. The convergence of issues that arise from the challenges of the present and future has led LIDS to research that cuts across mathematical and engineering disciplines in new, exciting, and important ways. Research flows in both directions across these dimensions: work in each of the mathematical disciplines leads to new methodologies that enable advances in core disciplines and in interdisciplinary investigations; work in attacking those emerging interdisciplinary challenges provides direction and drivers for fundamental disciplinary activities and has led to the charting out of emerging new disciplines.

In particular, the availability of increasingly capable sensing, communication, and computation systems enables the collection and transfer of large amounts of data pertaining to complex and heterogeneous interconnected systems. The need for an intellectual platform to simultaneously address questions of data fusion, distributed learning, information transfer, and distributed decision making is stronger than ever as existing techniques fall short in addressing issues of scalability, robustness, and performance limits. Examples of areas in which LIDS research has and will continue to contribute include the following:

- Intelligence, surveillance, and reconnaissance systems
- Coordination of unmanned autonomous systems
- Energy information systems
- Biological systems and biomedical data analysis
- Large-scale data assimilation for the geosciences
- Network scheduling and routing
- Sensor networks
- Social network analysis and characterization
- Ultra-wideband and other emerging communications technologies.

Furthermore, traditional paradigms of sensing, communication, and control are not adequate to address many emerging challenges. As a result, LIDS has initiated a set of fundamental research themes that cut across disciplinary boundaries and involve considerable interaction and collaboration with colleagues in other units at MIT and in other disciplines:

- Foundations of network science, including network algorithms, approximation, and information
- Foundations of decision theory for teams involving cooperation and competition, including dynamic mechanism design in game theory, learning in stochastic games, and the study of rational decisions for large interacting networks of agents
- Foundations and a theoretical framework of systemic risk
- Foundations of cyber-physical systems, including architectural design, cross-layer algorithms, and tools for analysis, verification, and performance guarantees
- Foundational theory for multiscale/granularity modeling, including methods for describing complex phenomena at multiple granularities, learning of such models from complex and heterogeneous data, and reduction/simplification of models to levels appropriate for particular questions of analysis or design.

Faculty Activities

Much of the major research activities of LIDS faculty not only cuts across disciplines, applications, and emerging areas mentioned previously but also is collaborative with others within LIDS and elsewhere at MIT.

Dimitri Bertsekas

Professor Bertsekas is interested in deterministic optimization problems and the role of convexity in solving them, possibly through the use of duality. He has recently written a textbook on the subject, which involves new research on the fundamental structures that guarantee the existence of optimal solutions while eliminating duality gaps. He is writing a companion textbook on convex optimization algorithms, which includes some of his recent research on problems whose cost function involves a sum of a large number of component functions: (1) separable large-scale convex optimization problems, known as extended monotropic programming problems, for which special duality results and algorithms are possible; (2) new polyhedral approximation algorithms for extended monotropic programming problems; (3) incremental subgradient and proximal methods; and (4) application of these methods to large-scale machine learning and energy production and distribution systems.

Professor Bertsekas also performs research on problems of sequential decision making under uncertainty, which are pervasive in communication networks, manufacturing systems, and logistics, and in the control of nonlinear dynamical systems. In theory, such problems can be addressed with dynamic programming techniques. In practice, only problems with a moderately sized state space can be handled. This research effort deals with the application of neural networks and other approximation and interpolation methodologies to overcome the curse of dimensionality of real-world stochastic control problems. Recent effort has focused on the use and analysis of popular temporal difference methods and Q-learning algorithms in the context of fully and partially observable Markov decision problems, on the simulation-based solution of large-scale least-squares problems, and on a number of issues relating to the central method of approximate policy iteration: convergence, rate of convergence, singularity and susceptibility to simulation noise of policy evaluation, exploration-enhanced methods, error bounds, policy oscillation, and issues of decision making in an asynchronous multi-agent environment.

Robert Berwick

Professor Berwick's research has spanned the broad areas of learning, evolution, and complex systems and dynamical systems theory in human cognition and biology, designing algorithms that can mimic human competence in language acquisition, evolution, and dynamical language change over time, as well as exploring the limits of current statistical techniques in light of human abilities. In particular, during AY2011, he investigated whether one can match the learning achieved via hierarchical Bayesian models advanced as a model of child language acquisition, but by far simpler, less computationally intensive means. This was confirmed during the past year both computationally and experimentally: both k-means and "one shot" algorithms work, both for computers and apparently for children. He has also continued to develop algorithms that apply new developments in linguistic theory to computer applications of natural language processing, specifically, the so-called "minimalist" framework of Institute Professor of linguistics (emeritus) Noam Chomsky and colleagues that attempts to reduce as much as possible the "human specific" component of language. During AY2011, he developed a probabilistic model to place on top of a "minimalist" parser, for use in analyzing large-scale corpora. This is the first probabilistic model of its kind.

Professor Berwick continued a new line of research in the area of the core biological foundations of language. As part of the MIT intelligence initiative, and in collaboration with Institute Professor of linguistics (emeritus) Morris Halle and Professor Chomsky, along with colleagues at the University of Utrecht and the University of Tokyo, this research connects human language to birdsong in a new way, by probing the commonalities in the rhythmic structure of both as a "window" into the common neurological basis of speech and birdsong. During the past year, Professor Berwick developed a novel computer program that can learn the rhythmic structure of both birdsong and human language from acoustic input. This research has already led to publications in the leading technical journals *Nature Neuroscience* and *Trends in the Cognitive Sciences*.

During AY2011, Professor Berwick published a book on the acquisition of language, *Rich Grammars from Poor Inputs* (Oxford University Press), an edited collection resulting from the conference he organized at MIT the previous year that reviewed current state-of-the-art research in the early biological stages in human language acquisition. He also organized and taught the first-ever course on evolutionary biology at MIT, joint with the biology department, as part of the new computer science and molecular biology major.

Munther Dahleh

Professor Dahleh has led a research effort focused on control of networked systems, with emphasis on the problem of distributed decision making and control under limited observations and communications. This work includes problems of control in the presence of communication constraints, distributed computation over networked computational units, and the detection and mitigation of systemic risk in interconnected and networked systems. Recently he has been interested in social networks as well as the future power grid.

Robust Route Choice Decisions for Urban Transportation Networks

In collaboration with postdoctoral associate Giacomo Como, research scientist Ketan Savla, and professors Daron Acemoglu and Emilio Frazzoli, Professor Dahleh led a project on characterization of route choice decisions of drivers under limited information that render maximum resilience to a transportation network towards unexpected disruptions. In particular, it was shown that decisions that exhibit appropriate combination of inertia towards regular path preference and myopia towards real-time local information are the most resilient route choice decisions. Exact characterization of the resilience of the network in terms of the topology and nominal operating condition were derived under different real-time information patterns for the drivers. These results rely on novel distributed control strategies for dynamical flow networks and as such are also applicable to other application domains, such as data networks and production networks.

Side Information in Decision-Making Problems

In collaboration with student Giancarlo Baldan, Professor Dahleh led an effort in understanding how to exploit side information in decision-making problems. Their work focused mainly on how to optimally design a channel so that the decision based on the collected data minimizes a suitable cost function. This technique has been applied both to binary hypothesis testing problems and to shortest path problems, leading to an explicit solution valid for small capacities in the first case and to more general analytical bounds in the second. All the results show how the capacity of the channel can affect the performances of the decision-making process.

Low-Dimensional Neural Spiking Model

In collaboration with professor Emery Brown and Dr. Savla, Professor Dahleh and student Rose Taj Faghih proposed a low-dimensional neural spiking model that has the ability to exhibit most of the neural spiking activities that can only be generated by more complex dynamical models (such as the Hodgkin-Huxley model). This model is an extension to the FitzHugh-Nagumo (FHN) model and overcomes the limitations of the FHN model by allowing time variation in the parameters of the FHN model, where the hypothesis is that the time variations of these parameters are physiologically programmed within a neuron. This extension has various applications, such as modeling neural spiking activities in the thalamus and respiratory center. They also developed a computationally fast algorithm for estimating the spiking threshold in their proposed extension to the FHN model.

Study of Rare Events

With student Mesrob Ohannessian and professor Sanjoy Mitter, Professor Dahleh led a study of rare events. They focused on the question of when meaningful statistical inference about events that have very little data, or even none, can be made. In particular, they considered the problem of events determined by discrete outcomes that appear a fixed small number of times in the data, known as the Good-Turing estimation problem. Showing that regularity of the tail of the distribution is crucial for estimation to be non-trivial, they established a relationship with the tail estimation problem, which is traditionally studied in the area of extreme value theory. Consequently, they were able to borrow analytical and algorithmic tools from the latter, and to give new solutions to the Good-Turing estimation problem that, under tail regularity, achieve stronger performance than the classical approaches.

Volatility of Price, Supply, and Demand in Future Power Grids

In collaboration with research scientist Mardavij Roozbehani and Professor Mitter, Professor Dahleh investigated fundamental aspects of volatility of price, supply, and demand in future power grids. A distinguishing feature of future power grids is that due to the presence of demand response, which can be in the form of real-time pricing or similar dynamic pricing mechanisms, the power markets and the consumers interact in closed loop. This is in contrast to today's systems, in which there is little real-time interaction between consumers and markets. This research finds that in the absence of a carefully designed control law, such direct feedback between could increase volatility and lower the system's robustness to uncertainty in demand and generation, allowing for small disturbances to induce large fluctuations in market prices and, subsequently, supply and demand. More precisely, volatility can be characterized in terms of the market's relative price elasticity, defined as the ratio of the price elasticity of consumers to that of the producers. As this ratio increases, the system may become more volatile, eventually becoming unstable when the ratio exceeds one. As the penetration of new demand response technologies and distributed storage within the power grid increases, so does the price elasticity of demand, and this is likely to increase volatility and possibly destabilize the system under current market and system operation practices. While the system can be stabilized and volatility can be reduced in many different ways, different pricing mechanisms pose different limitations on competing factors of interest. Consequently, systematic analysis of the implications of different pricing mechanisms and quantifying the value of information and characterization of the fundamental trade-offs between price volatility and economic efficiency, as well as system reliability and environmental efficiency, are important directions of future research.

Demand Response and the Values of Load Shifting and Storage

In collaboration with Dr. Roozbehani and students Ali Faghih and Ohannessian, Professor Dahleh conducted research on mathematical modeling of consumer behavior in response to real-time electricity prices and characterization of the intertemporal utility of consumption in the presence of storage and/or load shifting. The models quantify the dependencies of an individual consumer's demand on price, time, and the internal state of the consumer, and are thus valuable for designing demand response and real-time pricing mechanisms for matching supply and demand.

While the expected monetary value of storage is an increasing function of price volatility, it is shown that due to finite ramp constraints the value of storage saturates quickly as the capacity increases, regardless of price volatility. The implications of this result are manifold: first, since volatility is favored by storage, strategic behavior to induce volatility is likely and properly designed market mechanisms to prevent such behavior are needed; and second, the monetary value of storage might not justify the investment costs, particularly in the presence of ramp rate constraints, resulting in underinvestment in storage. Consequently, the design of market mechanisms to price externalities such as the reliability value and the environmental value of storage are important directions of the next steps for this research.

Games of Crises in Social Networks

In collaboration with postdoctoral associate Alireza Tahbaz-Salehi and student Spyros Zoumpoulis, Professors Dahleh and professor John Tsitsiklis have been studying how the topology of the social network affects the outcomes of self-fulfilling crisis phenomena, such as currency attacks, debt crises, bank runs, and political revolutions. The work relies on quantifying the connection between the social network and the predictability of individual behavior, as well as the connection between the social network and societal attitude towards risk. The focus is on establishing necessary and sufficient conditions for the sharing of information between social agents (i.e., for the topology of the social network) to result in uniqueness versus multiplicity of game-theoretic equilibria.

Emilio Frazzoli

Professor Frazzoli's main research interests are in the area of control of planning and control for mobile cyber-physical systems, with an emphasis on autonomous vehicles, mobile robotics, and transportation networks.

Real-time Planning and Control for Autonomous Vehicles

Building on the efforts leading to MIT's successful participation in the 2007 Defense Advanced Research Projects Agency (DARPA) Urban Challenge, Professor Frazzoli and his group continue to work on developing real-time planning and control algorithms for autonomous vehicles. In particular, in the past year, Professor Frazzoli's group developed planning and control algorithms for autonomous forklifts, in the context of the Agile Robotics for Logistics (ARL) program (led by professor Seth Teller in CSAIL, in collaboration with professor Jonathan How's group in LIDS). This program is aimed at automating logistics for the United States Army in forward deployment areas. In addition to several challenges already faced in design of the DARPA Urban Challenge vehicle, the ARL program required new advances due to the ability of the forklift to interact directly with its environment—for example, manipulating pallets. LIDS students Sertac Karaman, Jeong hwan Jeon, and Brandon Luders (advised by Professor How) have extended the DARPA Urban Challenge planning and control software to the forklift and developed novel algorithms for pallet detection and manipulation. The effectiveness of the autonomous forklift in realistic Army logistics scenarios was successfully demonstrated in June 2009 at Fort Belvoir, VA, in the presence of Army leadership.

These technologies are being further developed in the context of a new project on the future of urban mobility with SMART. In particular, Professor Frazzoli and his group—in collaboration with Professor Dahleh and professor Patrick Jaillet in LIDS, and research affiliate Sushmita Roy, professor Daniela Rus, and Professor Teller in CSAIL—are working on:

- Autonomy in mobility-on-demand systems: The goal is to demonstrate how autonomy, and in general automatic control/optimization (on-board cars and/or in the traffic infrastructure), can drastically enhance the safety and throughput of urban mobility, e.g., through mobility-on-demand services.
- Green driving: The goal is to demonstrate how autonomy and in general automatic control/optimization (on-board cars and/or in the traffic infrastructure) can drastically reduce fuel consumption and noxious emissions, both at the car level and at a city-wide level.
- Scalable situation awareness: The goal is to reduce the cost of the sensor package used on autonomous vehicles from approximately $500K down to approximately $50K. The idea is to leverage wireless communications, e.g., for localization and situational awareness (where the car is relative to the world, and relative to other cars).

Unmanned Aircraft Systems

As part of a multiyear collaborative effort on control science with the Air Force Research Laboratory and the University of Michigan, Professor Frazzoli is investigating mission planning and control systems for heterogeneous, mixed-initiative networks of unmanned aerial vehicles (UAVs), piloted aircraft, and human operators. During the past year, significant contributions were made in the context of incremental sampling-based algorithms for real-time motion planning. It was shown that state-of-the-art algorithms, such as the rapidly-exploring random trees (RRT), almost surely converge to non-optimal solutions; new algorithms were proposed, called rapidly-exploring random graph (RRG) and RRT* (an incremental sampling-based motion planning algorithm with the asymptotic optimality guarantee), which are provably asymptotically optimal, i.e., almost surely converge to an optimal solution. The computational complexity of these new algorithms is shown to be essentially the same as that of the baseline RRT. The analysis of the new algorithms hinges on novel connections between sampling-based motion planning algorithms and the theory of random geometric graphs. In addition, RRG is at the core of a new computational framework, enabling the efficient (i.e., polynomial time) incremental computation of mission plans subject to complex logic and temporal constraints. This can be accomplished by combining state-of-the-art motion-planning algorithms in robotics with a general class of formal language (e.g., mu-calculus), so far ignored in the context of mission specification languages. Also, Professor Frazzoli and his students continue to develop strategies for UAV mission planning that embed cognitive models of human operators, explicitly taking into account the effects of human operators, workload, and situational awareness. A theory of queuing systems with humans in the loop is being developed along with queue-control techniques based on the exploitation of human cognitive models. Dr. Savla and student Christine Siew are involved in this work.

Mobile Robotic Networks

Another main focus of Professor Frazzoli's research is the development of analysis and synthesis tools for control of mobile robotic networks. Within the context of several projects on the topic sponsored by the National Science Foundation (NSF), his research group is analyzing a broad class of multiple-vehicle motion coordination problems, from dynamic vehicle routing to path coverage and traffic deconfliction. Recent advances include the analysis of dynamic vehicle routing problems with priority demands (joint work with student Marco Pavone, and professor Francesco Bullo and student Stephen Smith at the University of California, Santa Barbara) and customer impatience, the analysis of decentralized algorithms for equitable partition of a planar region (also with Pavone), and the discovery of an endogenous phase transition in the optimal network "social" organization caused by the vehicles' dynamics (with University of California, Los Angeles, visiting researcher John Enright, and Dr. Savla). Such phase transitions have been observed in biological systems but the understanding of such phenomena remains limited.

Spacecraft Formation Flying

A special class of mobile robotic networks studied by Professor Frazzoli, in collaboration with professor David Miller and students Jaime Garza Ramirez and Pavone, is spacecraft clusters. Decentralized control laws were designed to provably ensure convergence of the spacecraft to an evenly spaced configuration on a zero-effort elliptical trajectory, with minimal requirements on the computation and communication capabilities of the spacecraft. The proposed control laws were tested in an experiment conducted on the synchronized position hold engage and reorient experimental satellites testbed aboard the international space station by astronaut (and MIT alumnus) Gregory Chamitoff—who reportedly stated that the orbiting spacecraft were "the most beautiful thing" he saw during his space mission.

Other projects address diverse topics such as high-speed driving (with professor Panagiotis Tsiotras at the Georgia Institute of Technology), vision-based navigation, and sampling-based algorithms for differential games (with Jim Paduano at Aurora Flight Sciences).

Jonathan How

Professor How has led a research effort focused on the control of multiple autonomous agents, with an emphasis on distributed decision making with uncertainty; path planning, activity and task assignment; mission planning for UAVs; sensor network design; and robust, adaptive, and nonlinear control. Recent research includes the following:

Robust Planning

With Professor How, students Luke Johnson and Sameera Ponda developed a distributed task-planning algorithm that provides provably good, conflict-free, approximate solutions for heterogeneous multi-agent/multi-task allocation problems on random network structures. The consensus-based bundle algorithm (CBBA) has since been extended to include task time-windows, coupled agent constraints, asynchronous communications, and limited network connectivity. CBBA has been used to plan for both networked UAV and unmanned ground vehicle teams and human-robot teams, and real-time performance has been validated through flight test experiments. Recent path planning research has yielded chance constrained RRT, a robust planning algorithm to efficiently identify trajectories which satisfy all problem constraints with some minimum probability. Finally, in collaboration with professor Nicholas Roy's group, Professor How and student Georges Aoude developed an efficient approach for modeling dynamic obstacles with uncertain future trajectories through the use of Gaussian processes coupled with an RRT-based reachability evaluation.

UAV Mission Technologies

Professor How and students Mark Cutler and Buddy Michini developed a novel hovering vehicle concept capable of agile, acrobatic maneuvers in cluttered indoor spaces. The vehicle is a quadrotor whose rotor tilt angles can be actuated, enabling upside-down hovering flight with appropriate control algorithms. As part of research on long-duration UAV mission planning, the Aerospace Controls Laboratory (ACL), under Professor How's directorship, has constructed an autonomous recharge platform capable of autonomous battery replacement for small UAVs (with students Josh Redding, Tuna Toksöz, and N. Kemal Ure).

Information Gathering Networks

Recent research has addressed how to maximize information gathering in complex dynamic environments through the use of mobile sensing agents (with students Daniel Levine and Luders). The primary challenge in such planning is the computational complexity, due to both the large size of the information space and the cost of propagating sensing data into the future. ACL developed new methodologies that correctly and efficiently quantify the value of information in large information spaces, such as a weather system, leading to a systematic architecture for mobile sensor network design. Recently developed algorithms embed information planning within RRTs to quickly identify safe information gathering trajectories for teams of sensing agents, subject to arbitrary constraints and sensor models.

Multi-Agent Decision Making

Markov decision processes (MDP) are a natural framework for formulating many decision problems of interest; Professor How and his team have identified approximate solution techniques which can utilize this framework while overcoming the curse of dimensionality typically encountered for exact solutions. For example, by exploiting flexible, kernel-based cost approximation architectures, the Bellman residual elimination (BRE) algorithm computes an approximate policy by minimizing the error incurred in solving Bellman's equation over sampled states. For online systems, student Alborz Geramifard introduced incremental feature dependency discovery (iFDD) algorithm, which expands the representation in areas where the sampled Bellman error persists. iFDD is convergent and computationally cheap, hence amenable to systems with restricted thinking time between actions. Finally, student Aditya Undurti has developed fast, real-time algorithms for solving constrained MDPs in uncertain and risky environments while maintaining probabilistic safety guarantees.

Patrick Jaillet

Professor Jaillet's main research has recently concentrated on formulating and analyzing online, dynamic, and real-time versions of classical network and combinatorial optimization problems, such as the shortest path problem, the traveling salesman problem (TSP), and the assignment/matching problem, as well as some of their generalizations. Specific research interests deal with provable results (algorithmic design and analysis) on what can be done to solve such problems under uncertainty, with or without explicit stochastic modeling of the uncertainty. Methodological tools include those from online optimization (competitive analysis), stochastic optimization (robust analysis), and online learning (minmax regret analysis and Bayesian updates), with an eye toward their eventual integration.

Motivating applications include various routing problems that arise from transportation and logistics networks, data communication and sensor networks, and autonomous multi-agent systems, as well as dynamic resource allocation problems in various internet applications (such as search engines and online auctions).

Professor Jaillet's research group in AY2011 included postdoctoral fellow Issmail El hallaoui, now at École Polytechnique Montreal; ORC students Jacob Cates, Brian Crimmel, Maokai Lin, and Xin Lu; EECS graduate students Yin-Wen Chang, Daw-Sen Hwang, and Andrew Mastin; EECS undergraduate Christian Therkelsen; and three interns from France: Pierre Jeremy (École Polytechnique), Antoine Legrain (École Centrale Paris), and Thibault Lehouillier (École nationale supérieure d'informatique et mathématiques appliquées de Grenoble). The research group in Singapore includes postdoctoral associate Ali Oran (SMART) and graduate students from National University of Singapore, Nanyang Technological University, and Singapore Management University.

Examples of recent research activities involve the exhaustive competitive analysis of the online TSP with immediate decisions in various metric spaces (with Lu); competitive and asymptotic probabilistic analysis of the online multi-server TSP problems (with Therkelsen and Lu); competitive analysis of online spatial searching problems (with Hwang and Lehouillier); analysis of the development of best competitive ratio theoretical bounds for the online stochastic matching problem (with Lu); the development and empirical testing of various algorithms for online stochastic assignment problems (with Mastin, Jeremy, and Legrain); the development and analysis of primal-dual algorithms for resource constrained shortest path problems (with Dr. El hallaoui); route optimization under uncertainty for unmanned underwater vehicles (with Cates and Dr. Michael Ricard of Draper Laboratory); development of bounds for the price of anarchy in dynamic congestion games (with Lin).

Current funded research programs come from the operations research program of NSF (Online Optimization for Dynamic Resource Allocation Problems); the operations research division of the Office of Naval Research (ONR) (Large-scale Online and Real-time Optimization Problems Under Uncertainty); the optimization and discrete mathematics division of the Air Force Office of Scientific Research (AFOSR) (Data-driven Online and Real-time Combinatorial Optimization); and SMART (Future Urban Mobility [FUM], a large project with nine other MIT principal investigators).

Within the FUM project, Professor Jaillet is leading subprojects entitled Real-time Paths Tracking/Prediction and On-demand Route Guidance Under Uncertainty. The goals are to develop algorithms using real-time data (from many heterogeneous sources) in order to: (1) track and predict paths in dynamic transportation networks, and (2) provide on-demand route guidance under uncertainty, based on a combination of optimization, data fusion, machine learning, and novel behavioral techniques.

Alexandre Megretski

Professor Megretski and his students work on identification and model reduction of nonlinear dynamical systems, as well as on optimization of discrete decision making in dynamical analog control systems, and analysis of distributed nonlinear systems.

Professor Megretski's approach to system identification and model reduction is based on combining nonlinear dynamical system analysis tools with convex relaxation techniques in addressing some major unsolved challenges in the field, such as efficient optimization of the output error and automated certification of robustness of the resulting models. The theory and resulting algorithms, implemented in the system polynomial optimization matrix laboratory (Matlab) toolbox, are used extensively in two application areas: (1) modeling of analog integrated circuit components, where the need for converting large amounts of measurement or simulation data into reliable compact dynamical models is strong; and (2) modeling of live neurons and small live neural networks, where a number of approaches are available for designing nonlinear systems to mimic neural behavior but where generation of models to accurately match the actual input/output relations remains a challenge. The applications in circuit modeling are pursued with professors Luca Daniel, Vladimir Stojanovic, and Joel Dawson. The applications in neural modeling are conducted in collaboration with professor Russell Tedrake.

The research on optimization of discrete decision making in dynamical analog control systems is concentrated on discovery of special analytical properties of the associated optimal control tasks, with the aim of enabling the finding of either analytical or efficient numerical solutions. One application of this effort is optimization of analog-to-digital converters.

Sanjoy Mitter

Professor Mitter's research has spanned the broad areas of systems, communication, and control. Although his primary contributions have been in the theoretical foundations of the field, he has also contributed to significant engineering applications, notably in the control of interconnected power systems and pattern recognition. His current research interests are theory of stochastic and adaptive control; mathematical physics and its relation to system theory; image analysis and computer vision; and structure, function, and organization of complex systems. In particular, he has been working on systems aspects of power systems (smart grids) during the past year.

Professor Mitter has continued his long-standing collaboration with Dr. Charles Rockland (RIKEN Brain Science Institute, Tokyo) on issues of autonomy and adaptiveness in neural systems. There is renewed interest in studying the nematode from the viewpoint of understanding the structure-to-function map, a program the two proposed in the 1980s.

In joint work with Emery Brown (BCS), professor Peter Doerschuk (Cornell University), and professor Bud Mishra (New York University), Professor Mitter has been investigating topological properties of large data sets, using ideas from differential geometry and algebraic topology. New results on manifold learning have been obtained in joint work with postdoctoral associate Hariharan Narayanan and professor Charles Fefferman of Princeton University.

In addition, Professor Mitter has continued his collaboration with Dr. Nigel Newton (University of Essex) on the relation between statistical mechanics, statistical inference, and information theory. In recent work, they have given a proof of the noisy channel coding theorem (including error exponents) from the variational point of view of Bayesian inference.

Investigations on the subject of the interaction of information and control have continued with Anant Sahai (University of California, Berkeley) and Sekhar Tatikonda (Yale University).

Also with Dr. Sahai, Professor Mitter has shown for the first time that unstable processes generate two fundamentally different kinds of information, one requiring Shannon capacity for its reliable transmission, and one requiring anytime capacity for its reliable transmission. Completion of this work required developing new rate distortion theory for a family of channels. This work constitutes part of doctoral candidate Mukul Agarwal's thesis, in which a new result on source channel separation for networks has been presented.

With Professors Bertsekas and Dahleh and Dr. Roozbehani, Professor Mitter continues to work on various systems aspects of smart grids and has obtained new results on volatility of networks when dynamic pricing is implemented..

Eytan Modiano

Professor Modiano leads the Communications and Networking Research Group (CNRG), consisting of eight graduate students and two postdoctoral associates. The primary goal of CNRG is the design of architectures for aerospace networks that are cost-effective, scalable, and meet emerging needs for high data-rate and reliable communications. In order to meet emerging critical needs for military communications, space exploration, and internet access for remote and mobile users, future aerospace networks will depend on satellite, wireless, and optical components. Satellite networks are essential for providing access to remote locations lacking in communications infrastructure, wireless networks are needed for communication between untethered nodes (such as autonomous air vehicles), and optical networks are critical to the network backbone and in high-performance local area networks (LANS). The group is working on a wide range of projects in the area of data communication and networks with application to satellite, wireless, and optical networks.

Over the past year, CNRG continued to work on a Department of Defense–funded project toward the design of highly robust telecommunication networks that can survive massive disruption that may result from natural disasters or intentional attack. The project examines the impact of large-scale, geographically correlated failures on network survivability and design, an important aspect of robust network design that has received little attention in the past. Professor Modiano and his team developed mechanisms for assessing the vulnerability of networks to geographical failures. These mechanisms can be used to identify the most vulnerable parts of the network, and give insights to the design of network architectures that are robust to natural disasters or physical attacks.

In a related project, funded by NSF, CNRG is studying survivability in layered networks. Modern communication networks are constructed with one or more electronic layers (e.g., internet protocol) built on top of an optical fiber network. This multitude of layers is used to simplify network design and operations and to enable efficient sharing of network resources. However, this layering also gives rise to certain inefficiencies and interoperability issues. The project explores the impact of layering on network survivability and develops network architectures that are resilient to failure propagation between layers. In spite of its importance and practicality, there is little understanding of network survivability in a complex layered environment. The project aims to develop a fundamental theory for understanding cross-layer survivability and mechanisms for providing survivability in layered networks through the joint design of the network topologies at the different layers. To that end, Professor Modiano and his group developed new metrics for assessing the reliability of layered networks, as well as mechanisms for embedding the electronic layers on top of the optical fiber network in order to maximize reliability.

CNRG is also working on a new Army multidisciplinary university research initiative (MURI) project titled Modeling, Analysis, and Algorithms for Stochastic Control of Multi-Scale Networks. The project deals with control of communication networks at multiple time-scales and is a collaboration among MIT, Ohio State University, University of Maryland, University of Illinois, Purdue University, and Cornell University. An important aspect of the project is to understand the impact of traffic correlation at multiple time-scales (e.g., heavy-tailed traffic statistics) on the performance of network control algorithms. In particular, Professor Modiano and his group have shown that classical network control algorithms, which are widely used in both wireless and wired networks, perform very poorly in the presence of highly correlated traffic, and they have developed network control mechanisms for alleviating the effects of traffic correlation.

In another project, funded by NSF, CNRG is developing efficient network control algorithms for wireless networks. Existing wireless networks are almost exclusively confined to single hop access, as provided by cellular telephony or wireless LANs. While multi-hop wireless networks can be deployed, current protocols typically result in extremely poor performance for even moderate-sized networks. Wireless mesh networks have emerged as a solution for providing last-mile internet access. However, hindering their success is the relative lack of understanding of how to effectively control wireless networks, especially in the context of advanced physical layer models, realistic models for channel interference, and distributed implementations. Professor Modiano and his group are developing effective and practical network control algorithms that make efficient use of wireless resources through the joint design of topology adaptation, network layer routing, link layer scheduling, and physical layer power, channel, and rate control.

CNRG's research crosses disciplinary boundaries by combining techniques from network optimization, queuing theory, graph theory, network protocols and algorithms, hardware design, and physical layer communications.

Asu Ozdaglar

Professor Ozdaglar's research group focuses on modeling, analysis, and optimization of large-scale dynamic multi-agent networked systems, including technological networks (such as communication and transportation networks), social, and economic networks. The research draws on advances in game theory, optimization theory, dynamical systems, and stochastic network analysis. It focuses on both investigating substantive issues in these areas and developing new mathematical tools and algorithms for the analysis of these systems.

A major current research area in Professor Ozdaglar's group is social networks, which are becoming ever more extensive and complex with parallel developments in communication technology. The group works on developing game-theoretic models for studying dynamics of social behavior over complex networks. In collaboration with Professor Acemoglu (Economics), Professor Dahleh, and student Ilan Lobel, Professor Ozdaglar has provided a new framework to study the problem of Bayesian (equilibrium) learning over general social networks. This work identifies conditions on network topologies, information structures, and heterogeneity of preferences that lead to equilibrium information aggregation in large networks. A recent project, in collaboration with Dr. Tahbaz-Salehi, extends this framework to study the effect of adversarial behavior on Bayesian learning.

Another recent project, joint with Dr. Como and professor Fabio Fagnani (Department of Mathematics, Politecnico di Torino), provides models of misinformation and shows how a set of "prominent agents," which may include community leaders as well as media outlets, can spread misinformation and influence average opinion in the society. The work provides conditions on interaction structures under which consensus obtains or persistent disagreements prevail in the society. This research effort is supported by an NSF grant in human and social dynamics, an Army Research Office (ARO) project, and the Draper Directed Research and Development Program.

Professor Ozdaglar's group also works on understanding the role of networks in economics. A recent project, joint with Professor Acemoglu and Dr. Tahbaz-Salehi, investigates the cascade effects that arise in economic and financial markets because of supply or financial linkages among firms. Results show that the traditional economic insight that neglects firm level variations in aggregate economic fluctuations (using law of large numbers type arguments) fails in interconnected systems, and provide a general framework for the analysis of the relationship between the network structure of an economy and its aggregate volatility. This research effort is supported by an AFOSR grant.

Another recent project, in collaboration with professor Pablo Parrilo, student Utku Ozan Candogan, and postdoctoral associate Ishai Menache, provides a novel flow representation for strategic form finite games, which (using Helmholtz decomposition theory from algebraic topology) allows decomposing an arbitrary game into three components, referred to as the potential, harmonic, and nonstrategic components. The decomposition framework provides a systematic approach for the analysis of static and dynamic (equilibrium) properties of general games through their distance to the set of potential games (which admit tractable equilibrium analysis). Another project, in collaboration with Professor Parrilo and student Noah Stein, investigates new equilibrium notions for symmetric strategic form finite games, which lie between the set of Nash and correlated equilibria and admit efficient computation. This research effort is supported by an AFOSR MURI grant, joint with the Georgia Institute of Technology and the University of Maryland, and an NSF grant.

Professor Ozdaglar also studies game-theoretic models for resource allocation problems in communication networks, with a focus on pricing and investment incentives of providers and implications of competition on network performance. A recent project, joint with student Paul Njoroge and professors Nicolas Stier-Moses and Gabriel Weintraub of Columbia University, develops a game theoretic model based on a two-sided market framework to investigate net neutrality issues from a pricing perspective. Results highlight important mechanisms related to internet service providers' investments that play a key role in market outcomes, providing useful insights for the net neutrality debate. This research is supported by an NSF faculty early career development (CAREER) grant.

Professor Ozdaglar's group also works on developing novel decentralized optimization algorithms for resource allocation problems that emerge in communication and sensor networks. In collaboration with students Lobel and Alex Olshevsky, professor Angelia Nedic (University of Illinois at Urbana–Champaign [UIUC]), and Professor Tsitsiklis, this work has developed algorithms that can optimize general performance metrics and operate over dynamic networks with time-varying connectivity and imperfect information. A recent project, joint with Lobel, extends this framework to problems with state-dependent communication. These problems arise when the current information of decentralized agents influences their potential communication pattern, which is relevant in the context of location optimization problems and in social settings where disagreement between the agents would put constraints on the amount of communication among them. Another recent project, joint with student Ermin Wei and professor Ali Jadbabaie (University of Pennsylvania), develops novel Newton-type second order methods to solve network utility maximization problems in a distributed manner, which are significantly faster than the standard first-order (or gradient) approaches. This research is supported by the DARPA information theory for mobile ad-hoc networks program (ITMANET), joint with Stanford University, the California Institute of Technology, and UIUC, and by an AFOSR MURI grant.

Pablo Parrilo

Professor Parrilo's research group focuses on optimization, systems, and control, with emphasis on control and identification of uncertain complex systems, robustness analysis and synthesis, and the development and application of computational tools based on convex optimization and algorithmic algebra.

In joint work with Professor Ozdaglar, their joint student Candogan, and Dr. Menache, Professor Parrilo has developed a structural approach to normal form games that allows for the decomposition of a given game into its "potential" and "harmonic" components. The methods are based on the classical Helmholtz-Hodge theory for differential forms, and constitute a far-reaching generalization of the well-known potential games, which enables the analysis of many static and dynamical properties of games, such as equilibria or the convergence of fictitious play mechanisms.

Student Amir Ali Ahmadi and Professor Parrilo are looking at the interplay of sum of squares (SOS) and the question of deciding convexity of polynomials. Similar to the SOS relaxation for polynomial nonnegativity, an algebraic notion known as SOS-convexity can be proposed as a tractable sufficient condition for polynomial convexity. Many natural questions arise: are there polynomials that are convex but not SOS-convex? If so, for what dimensions and degrees? Are there algebraic analogues of classical analytic theorems in convex analysis? At a theoretical level, the overall goal of this project is to better understand the connections between the geometric and algebraic aspects of positivity and convexity. Practical applications of this work include efficient algorithms for minimizing polynomial functions, parameterizing convex polynomials that best fit given data, or searching for polynomial Lyapunov functions with convex sublevel sets.

In joint work with student Parikshit Shah, the group has developed a complete state-space solution to H2-optimal decentralized control of poset-causal systems with state-feedback. The solution is based on the exploitation of a key separability property of the problem that enables an efficient computation of the optimal controller by solving a small number of uncoupled standard Riccati equations. The group's approach gives important insight into the structure of optimal controllers, such as degree bounds that depend on the structure of the partially-ordered set (poset). A novel element in the state-space characterization of the controller is a remarkable pair of transfer functions that belong to the incidence algebra of the poset, are inverses of each other, and are intimately related to estimation of the state along the different paths on the poset.

In recent joint work with student Stein and Professor Ozdaglar, the rich structure of the set of correlated equilibria of games is analyzed through the simplest of polynomial games: the mixed extension of matching pennies. While the correlated equilibrium set is convex and compact, the structure of its extreme points can be quite complicated. In finite games there can be a superexponential separation between the number of extreme Nash and extreme correlated equilibria. In polynomial games there can exist extreme correlated equilibria that are not finitely supported. In general, the set of correlated equilibrium distributions of a polynomial game cannot be described by conditions on finitely many joint moments, in marked contrast to the set of Nash equilibria, which is always expressible in terms of finitely many moments.

Professor Parrilo is currently investing further extensions of "compressed sensing" techniques that deal with low-rank assumptions as opposed to sparsity. In earlier work with student Venkat Chandrasekaran, professor Sujay Sanghavi (University of Texas, Austin), and professor Alan Willsky, the methodology has been extended to the problem of decomposing a given matrix into a sparse and a low-rank component. In recent work, the results have been applied to the important problem of identification of Gaussian graphical models with hidden variables. The results show that it is possible to simultaneously identify the structure of the underlying graph, as well as the number and features of a set of latent variables, from a relatively small set of samples (i.e., the high-dimensional statistical setting).

Devavrat Shah

Professor Shah and his research group—Inference and Stochastic Networks Group—are developing understanding of complex networks to better engineer them. This includes communication networks such as the internet, network of statistical dependencies observed in large datasets captured through graphical models, and emerging social networks like Twitter. A salient feature of Professor Shah's work across this variety of networks is the use of distributed, iterative or so-called message-passing procedures: as operational building blocks in communication networks (e.g., medium access), for efficient information processing in statistical networks (e.g., belief propagation), and as behavioral models in a social network (e.g., gossip algorithms). These collective research activities span computer science, electrical engineering, operations research, and management sciences and utilize tools from algorithms, graphs, information theory, Markov chains, optimization, stochastic processes, and queuing theory. The specific applications include algorithms for internet routers, peer-to-peer networks like BiTTorrent, and high-speed wireless networks; models and algorithms for large-scale statistical problems such as those arising in revenue management based on transactions, search engine for Twitter or group decision-making engine; and statistical models of circuits.

Network Algorithms and Stochastic Networks

Algorithms are the essential building blocks of any large communication network. Successful deployment of a network depends primarily on the possibility of implementing high-performance network algorithms. As an algorithm designer, it is important to provide solutions that can lead to tunable network architecture to reach the right trade-off between implementation cost and performance.

Professor Shah and his collaborators have been working towards addressing the impending challenge of developing a methodological framework for designing high-performance implementable algorithms. To provide performance guarantees for such algorithmic solutions, they have developed parsimonious performance analysis methods.

With student Jinwoo Shin, Professor Shah has developed a novel "message-passing" algorithmic architecture to realize totally distributed asynchronous network architecture that utilizes the system resources to the fullest extent possible. The key enabling features for designing such an algorithmic architecture are based on recently emerging revolutionary ideas at the interface of statistical physics and artificial intelligence. As an important application, this leads to resolution of efficient medium access protocol design for wireless networks that has remained unresolved for the past 40 years.

To provide performance guarantees, Professor Shah and his collaborator Dr. Damon Wischik (University College London) have developed novel analytic methods based on asymptotic probabilistic theory of stochastic networks. This method is parsimonious, applies to complex networks, and provides useful design guidelines to enable a good algorithmic solution. This work has laid down foundations for queuing theory of large networks.

In the past year, Professors Shah and Tsitsiklis, with their student Yuan Zhong, led an effort to further develop a methodology for stochastic network analysis for the models of emerging networks—the data center. Initial approaches have led to evaluation of detailed performance bounds of stochastic networks.

These research efforts are primarily supported by an NSF CAREER grant, an NSF theoretical foundations grant, and an AFOSR grant.

Algorithms for Statistical Inference: Circuits, Revenue, and Society

In various collaborations both inside and outside MIT, Professor Shah has been leading efforts to understand algorithmic problems arising in the context of large-scale statistical inference. These problems, on a very large scale, are omnipresent in complex engineering systems, and he has been leading three research projects on this topic.

The first project concerns fundamental understanding of efficient message-passing algorithms, popularly known as the belief propagation. *Professor* Shah and collaborators (Professor Sanghavi; professor David Gamarnik, MIT Sloan School of Management; and Professor Willsky) have found the surprising result that such algorithms solve (a large class of) linear program problems. This collection of results resolves the mystery behind the unexpected empirical success of the seemingly simple and implementation-friendly belief propagation algorithm.

The second project concerns a fast statistical algorithm for evaluating the performance of complex circuits. Professor Shah and collaborators (professor Lara Dolecek, University of California, Los Angeles; professor Anantha Chandrakasan; and student Masood Qazi) have designed algorithms that allow for automated evaluation in a few minutes compared to a few months. This project has led to the design of a Matlab-based tool that can be used in conjunction with a circuit simulator like a simulator program with integrated circuit emphasis to provide a comprehensive computer-aided design tool for designing and evaluating performance of circuits.

The third project concerns algorithms to process partial information about rankings to obtain global information on rankings—for example, polled information in an election scenario, learning customer preference for revenue maximization, and team-ranking a given outcome in league matches. This work is widely applicable and in the past year, Professor Shah, with student Srikanth Jagabathula and professor Vivek Farias (MIT Sloan School of Management), has developed a revenue estimation toolbox for generic application. This work is likely to revolutionize the way data-driven operations management is performed in modern businesses. To test the theory, collaborations are underway with Amazon.com and Ford Motor Company.

The fourth and most recent project concerns understanding the role that network structure plays in the emerging "network science." To develop concrete foundations, Professor Shah and student Tauhid Zaman have started investigation of the following generic problem: given spread of rumor, infection, cascading failures, or spy information, how to find the source or the culprit? The initial theoretical foundations-based practical solutions seem to suggest unusual potential that underlies this approach. Currently, through collaborations with the future social experiences group at Microsoft Research, the impact of this theory is being tested.

These research efforts are supported by an NSF emerging models for technology grant, an NSF social networks grant, and a Ford–MIT alliance grant.

Network Information Theory

In collaboration with professor Gregory Wornell and Dr. Piyush Gupta at Bell Laboratories, Professor Shah and former student Urs Niesen (now at Bell Laboratories) have been leading the effort to understand how to operate wireless networks efficiently, the most important challenge of current information and communication theory. This ambitious research effort has led to a new class of simple cooperative architecture that promises to utilize the wireless medium efficiently in the context of a large networked setup, and it makes a very significant advance in the field of network information theory. The research is supported through the DARPA ITMANET program and an AFOSR grant.

John Tsitsiklis

Professor Tsitsiklis and his research group—Systems, Networks, and Decisions Group—work on system modeling, analysis, optimization, and control in possibly stochastic and dynamic environments, and in the possible presence of multiple agents with conflicting interests. Research activities have focused on developing methodologies, mathematical tools of broad applicability, and computational methods. Motivating applications for recent work have come from domains as diverse as cancer radiation therapy, direct mail marketing, and sensor networks. This work involves collaborations not only with the students in the group but also with Professors Ozdaglar and Shah, Thomas Bortfeld (Massachusetts General Hospital), and Duncan Simester (MIT Sloan).

Distributed Systems and Decision Making

A particular area being investigated by the group involves models of distributed decision making. One direction concerns information fusion and aggregation in sensor networks, which involves the selection of the effective choices of messages, given a particular information processing goal, as well as higher-level architectural choices. A second direction involves an analysis of simple and fast algorithms for prototypical and generic distributed sensing and control problems, with "averaging algorithms" a prominent example. This research also overlaps with the nascent field of "social networks," where under certain assumptions of rational behavior, similar models are receiving a fair amount of attention.

Resource Allocation in Communication Networks

This research concerns the analysis and optimization of resource allocation methods (routing and scheduling) in queuing networks, with communication networks the prime motivation. It involves the development of novel mathematical techniques to address new types of problems (e.g., the effect of heavy-tailed traffic statistics and the effect of a limited amount of scheduling flexibility in server farms), or to better understand well-established models (e.g., the stability of popular scheduling disciplines and game-theoretic models of bandwidth allocation when multiple users are contesting the same resources). Recent work has identified interesting phase transition phenomena caused by a small amount of information sharing in distributed server systems.

Systems Optimization

Professor Tsitsiklis and his students carry out research involving the analysis and optimization of various stochastic system models that are of current practical interest. One example concerns adaptive radiation therapy, whereby the dosage during each fraction of the treatment is adjusted based on information collected in the course of the treatment. Another example concerns the design of experiments (temporary price modifications) that a retailer can make to improve its demand model and its revenue.

Alan Willsky

Professor Alan Willsky leads the Stochastic Systems Group (SSG), whose research focuses on developing statistically based algorithms and methodologies for complex problems of information extraction and analysis from signals, images, and other sources of data. The work extends from basic mathematical theory to specific areas of application. Funding for this research comes from sources including AFOSR, ARO, Lincoln Laboratory, and the Royal Dutch Shell Group. In Spring 2011, while on sabbatical, Professor Willsky was involved in three successful funding efforts, including a new five-year program with AFOSR and two new five-year MURI programs (one through ARO and one through ONR). In addition, Professor Willsky continues to play a major role at MIT, in particular in MITEI’s interactions with Shell Oil Company extending beyond the funded projects already established (which represent the largest current effort under Shell sponsorship) to active involvement with Shell in charting a research collaboration course for the future.

A major thrust of research in SSG continues to be the extension and exploitation of its methodology for statistical inference, information fusion, and estimation for problems involving complex graphical models, such as those that arise in military command and control, mapping from remote-sensing data, and monitoring complex systems. SSG’s work involves discovering and exploiting structure in complex graphical representations that lead to new processing algorithms. This research continues to yield significant advances, including new classes of signal- and image-processing algorithms that have provable performance properties, that can be applied to very large problems in a scalable manner, and that outperform previous methods. Recent applications of these methods have been made to computer vision, the mapping of subterranean surfaces in support of oil exploration, and the tracking of multiple vehicles from networks of small sensors. A number of the methods that have been developed are being or already have been transitioned to research and engineering organizations including Shell Oil Company, Lincoln Laboratory, and BAE Systems. This part of SSG's research portfolio has received considerable international attention, as evidenced by a string of best paper awards as well as extensive citations and influence on the work of others in fields ranging from systems and control to chemical engineering to groundwater hydrology.

An increasingly important component of research in SSG is in the area of machine learning, in particular the extraction of statistical models, usually in graphical form, of complex phenomena. Some of the group's most recent work on object recognition and hidden variables has been highlighted in MIT News. In one of these research efforts, documented in student Myung Jin Choi's recently completed PhD thesis, a new, systematic methodology has been developed for discovering "hidden" variables that provide a hierarchical understanding of the variables that are observed. One of the driving applications for this work is in computer vision, in which the goal is to use—and possibly discover—context that would allow integration of lower-level object recognition with scene understanding (e.g., the recognition of a desk may suggest the scene is an office and one might then expect to find other objects, such as a chair, bookshelves, and possibly a computer, monitor, keyboard, and mouse). This work has also led to theoretical guarantees of the accuracy with which such hierarchically structured hidden models can be discovered. In the second research area, documented in student Chandrasekaran's recently completed PhD thesis, a very different approach to discovering hidden variables has been developed, in this case based on emerging methods and new results in convex optimization. The basic concept is that in many problems the interactions among the observed variables are quite complex; however, most of that complexity is due to the influence of a much smaller number of unobserved hidden variables. In this research, new optimization-based approaches are developed that allow such hidden structure to be recovered (with theoretical guarantees on the accuracy of recovery), leading to models that are easier to understand and exploit. The third area of research is the work documented in student Vincent Tan's recently completed PhD thesis. This work looks carefully at how accurately machine-learning algorithms can recover the structure of graphical models, characterizing how errors in recovery occur, due to noise and limited data, and how those errors diminish in likelihood as more data become available. This work provides clear guidance on how much data needs to be collected for accurate recovery of particular types of models.

Moe Win

The Wireless Communication and Network Sciences Laboratory, led by Professor Win, is involved in multidisciplinary research that encompasses developing fundamental theories, designing algorithms, and conducting experiments for a broad range of real-world problems. Current research topics include location-aware networks, network synchronization, aggregate interference, intrinsically secure networks, time-varying channels, multiple antenna systems, ultra-wide bandwidth systems, optical transmission systems, and space communications systems. Details of a few specific projects are given below.

The group has been working intensively on location-aware networks in global positioning system (GPS)–denied environments that provide highly accurate and robust positioning capabilities for military and commercial aerospace networks. It has developed a foundation for the design and analysis of large-scale location-aware networks from the perspective of theory, algorithms, and experimentation. This includes derivation of performance bounds for cooperative localization, development of a geometric interpretation for these bounds, and the design of practical, near-optimal cooperative localization algorithms. The group is currently validating the algorithms in a realistic network environment through experimentation in Professor Win's laboratory.

Professor Win and one of his students have been engaged in the development of a state-of-the-art apparatus that enables automated channel measurements. The apparatus makes use of a vector network analyzer and two vertically polarized, omni-directional wideband antennas to measure wireless channels over a range of 2–18 GHz. It is unique in that extremely wide bandwidth data, more than twice the bandwidth of conventional ultra-wideband systems, can be captured with high-precision positioning capabilities. Data collected with this apparatus facilitates the efficient and accurate experimental validation of proposed theories and enables the development of realistic wideband channel models. Work is underway to analyze the vast amounts of data collected during an extensive measurement campaign that was completed in early 2009.

Professor Win's students are also investigating physical-layer security in large-scale wireless networks. Such security schemes will play increasingly important roles in new paradigms for guidance, navigation, and control of UAV networks. The framework developed introduces the notion of a secure communications graph, which captures the information-theoretically secure links that can be established in a wireless network. The students have characterized the secure communications graph in terms of local and global connectivity, as well as the secrecy capacity of connections, and have also proposed various strategies for improving secure connectivity, such as eavesdropper neutralization and sectorized transmission. Lastly, they analyzed the capability for secure communication in the presence of colluding eavesdroppers.

Professor Win and a team of undergraduate and graduate students competed in the Institute of Soldier Nanotechnologies soldier design competition. In this contest they demonstrated the first cooperative location-aware network for GPS-denied environments, using ultra-wideband technology, leading the team to win the L-3 Communications Prize. The group is now advancing the localization algorithms in terms of scalability, robustness to failure, and tracking accuracy.

To advocate outreach and diversity, the group is committed to attracting undergraduates and underrepresented minorities and to giving them exposure to theoretical and experimental research at all levels. For example, the group has a strong track record for hosting students from both the Undergraduate Research Opportunities Program and the MIT Summer Research Program. Professor Win maintains dynamic collaborations and partnerships with academia and industry, including the University of Bologna and the University of Ferrara in Italy, the University of Lund in Sweden, the University of Oulu in Finland, the National University of Singapore, Nanyang Technological University in Singapore, Draper Laboratory, Jet Propulsion Laboratory, and Mitsubishi Electric Research Laboratories.

Highlights, Awards, and Events

AY2011 was an eventful and important year for LIDS. In addition to a continuing record of research accomplishments and intellectual excitement, the laboratory has grown in every meaningful dimension. Research volume has exceeded LIDS's ambitious strategic plan (with excellent prospects for the future). The laboratory welcomed, and will be welcoming, additional faculty as members of the community; made major strides in engaging other units across MIT; took major steps in several new initiatives; continued the series of events and activities that have added so much to LIDS's environment; and hosted a major international event that has helped LIDS reaffirm and extend its position of leadership in the international research community.

Continuing successful activities within LIDS include the colloquium series and the 16th annual LIDS student conference. A sixth edition of LIDS's community-oriented magazine, *LIDS-ALL*, was produced, and the seventh edition is being readied for the start of AY2012. LIDS also completed several major components of its long-term plan, including the launch of an enhanced website and expanded outreach to other units across MIT, such as CSAIL and ORC. A new faculty member, Yury Polyansky, will join LIDS in September 2011. In addition, LIDS faculty have played significant roles in several major research thrusts that align well with the intellectual agenda and areas of expertise that define its research. These include a major initiative in energy systems and smart grids, as well as a significant LIDS role in FUM, the long-term research program funded by SMART that focuses on the future of urban mobility. The Singapore–MIT program tackles problems of exploiting fine-grained information through the increasingly powerful internet and the explosion of personal devices and devices located on individual vehicles. The program includes developing integrated models for planning land, resource, and energy use, as well. Finally, LIDS is playing a critical role in the MIT-wide initiative on systemic risk.

One of LIDS's major events this past year was the Interdisciplinary Workshop on Information and Decision in Social Networks (WIDS), cited at the start of this report. Numerous enthusiastic comments and words of thanks were received from those who attended, and many requested that the workshop be made an annual event. WIDS highlighted the role LIDS is playing in defining research directions in new and emerging fields in information systems.

In AY2011, LIDS hosted extended visits by three visiting professors: Vincent Blondel, Universite catholique de Louvain; Tom Luo, University of Minnesota; and Martin Wainright, University of California, Berkeley. All three are well-recognized leaders in their respective disciplines, contributed to graduate teaching in EECS, and carried out collaborative research. In addition, Professor Blondel was instrumental in setting up the MIT–Belgium seed fund through the MIT international science and technology initiatives and in organizing the WIDS conference.

Finally, LIDS students and faculty members continue to receive awards and significant recognition for their accomplishments:

Animashree Anadkumar, former LIDS postdoctoral researcher, received the Association for Computing Machinery Special Interest Group SIGMETRICS 2011 Best Paper Award for her paper "Topology Discovery of Sparse Random Graphs with Few Participants."

The 2010 George Axelby Outstanding Paper Award was given to Munther Dahleh and Nuno Martins for their paper "Feedback Control in the Presence of Noisy Channels: 'Bode-Like' Fundamental Limitations of Performance."

Administrative assistant Jennifer Donovan received the 2011 School of Engineering Infinite Mile Award for Excellence.

Kimon Drakopoulos received the second place Ernst Guillemin Award for best electrical engineering master of science thesis. His thesis was co-supervised by Professors Ozdaglar and Tsitsiklis.

Jon How and LIDS alumnus Han-Lim Choi won the best application paper published over the last three years in *Automatica*, a journal of the International Federation of Automatic Control, for their paper "Continuous Trajectory Planning of Mobile Sensors for Informative Forecasting."

Srikanth Jagabathula, jointly supervised by Professors Shah and Farias, received the Manufacturing and Service Operations Management Society student paper competition first prize during the 2010 Institute for Operations Research and the Management Sciences (INFORMS) annual meeting.

Patrick Jaillet was named the new co-holder of the Dugald C. Jackson Chair.

Sertac Karaman was awarded a 2011 Nvidia Graduate Fellowship. He also received the 2011 American Institute of Aeronautics and Astronautics Orville and Wilbur Wright Graduate Award. He is supervised by Professor Frazzoli.

Asu Ozdaglar was selected as a 2011 Kavli Fellow of the National Academy of Sciences.

Pablo Parrilo was invited to speak at the International Congress of Mathematicians (ICM) 2010 in Hyderabad, India, for the section on control theory and optimization. The ICM is organized every four years and is the largest congress in the mathematics community.

Devavrat Shah was announced as the recipient of the prestigious Erlang Prize at the 2010 INFORMS annual meeting.

Yuan Shen received the Marconi Society Young Scholar Award for his work on the fundamental limits of wideband cooperative localization. He is supervised by Professor Win.

Jinwoo Shin received a 2010–2011 George M. Sprowls Award, given every year for the best PhD thesis in computer science at MIT.

David Staelin was awarded the John Howard Dellinger Medal "for seminal contributions to the passive microwave remote sensing of planetary atmospheres and the development of remote sensing of the atmosphere and environment of the Earth from space" by the International Union of Radio Science (Union Radio-Scientifique Internationale).

Vincent Tan received the 2010–2011 EECS Jin-Au Kong Award for best electrical engineering PhD thesis. His thesis was supervised by Professor Willsky.

Lav Varshney received honorable mention for the 2010–2011 Jin-Au Kong Award for best electrical engineering PhD thesis. His thesis was jointly supervised by professor Vivek Goyal and Professor Mitter.

Alan Willsky, LIDS alumnus Dmitry Malioutov, and research scientist Mujdat Cetin were awarded the 2010 IEEE Signal Processing Society Best Paper Award.

Kuang Xu, supervised by Professor Tsitsiklis, was awarded the first place Ernst Guillemin Award for best electrical engineering masters of science thesis.

Future Outlook

During the past year, LIDS met and exceeded nearly all of the goals set in the strategic plan developed in Spring 2008. LIDS research has always been of the highest quality and now that research is complemented by an energized community, a greatly strengthened funding base, a reaffirmed and strengthened international presence, significantly enhanced engagements and interactions with other units at MIT, and substantial roles in several major research initiatives at the Institute, including energy and transportation.

All of these accomplishments lay the foundation for a very bright future. The prospects for additional growth are substantial: LIDS expects to welcome at least one additional faculty member in September 2011; initiatives in energy (with support from various funding agencies, industry, and MITEI) are expected to grow; and LIDS's role in the recently initiated transportation initiative funded by the Singapore–MIT program has been substantial. Future symposia and workshops are planned and will continue to position LIDS as both a catalyst and source of cutting-edge research in areas of considerable international importance.

As AY2011 closes, it is extremely gratifying that the efforts of all in LIDS have led to so much success in realizing the vision articulated several years ago. LIDS is an energized and welcoming community and is recognized as a leading center for research in the information and decision sciences. LIDS is an exciting and fulfilling environment for all who are part of its community, and it intends to build on its successes to ensure continued growth and fulfillment of its promise.

Munther A. Dahleh
Acting Director
Professor of Electrical Engineering and Computer Science

John N. Tsitsiklis
Co-associate Director
Clarence J. Lebel Professor of Electrical Engineering

Alan S. Willsky
Director (on sabbatical AY2011)
Edwin Sibley Webster Professor of Electrical Engineering and Computer Science