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 inference. These disciplines, which span the domain of the analytical information and decision sciences, play a critical and pervasive role in science, engineering, and society more broadly. LIDS serves as a melting pot and focal point for disciplines that share a common approach to problems and a common mathematical base; the laboratory provides an energized environment that both 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.

The faculty members within LIDS are 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 MIT Transportation 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 Media Lab; and the Harvard–MIT Division of Health Sciences and Technology.

LIDS leadership in activities within MIT, nationally, and internationally continues to grow, and LIDS faculty and students continue to receive substantial recognition for their contributions, with numerous national and international awards. The LIDS website contains details on LIDS activities, people, awards, and research accomplishments and directions. Of particular note are several significant leadership positions taken by LIDS faculty and principal investigators (PIs). Professor Emilio Frazzoli has recently taken on the role of PI on the Future Urban Mobility project within the Singapore–MIT Alliance for Research and Technology (SMART), a project that involves faculty from across the Institute. Together with professor Andrew Lo of MIT Sloan, professor Munther Dahleh has led the establishment of the new Institute-wide Center for Systemic Risk, which aims to develop the analytical foundations and tools required to understand and address crucial problems of large-scale cascading disruptions and vulnerabilities in complex, interconnected systems, with financial, energy, and transportation systems as the target areas of concern. Professor Asuman Ozdaglar and professor Sandy Pentland of the Media Lab have taken on the joint leadership of the new virtual center Connection Science and Engineering, which has as its mission bringing together various network initiatives across the Institute, with particular focus on social networks. In addition, LIDS continues to grow its activities in MITEI, with several different thrusts of research within the laboratory, and LIDS faculty are involved in several activities aimed at building and coalescing MIT's research portfolio in the emerging area of so-called "big data."

LIDS will also be the MIT focal point for a recently signed letter of intent between MIT and Los Alamos National Laboratory, with a focus on information science and technology. More broadly, LIDS continues to build on its strong relationships with industrial organizations, which provide funding, collaborators, and challenging problems to drive its research. Among the organizations with which it has or is developing relations are Draper Laboratory, Lincoln Laboratory, Los Alamos National Laboratory, Siemens, Shell Oil Company, Honeywell, Ford Motor Company, Société Nationale des Chemins de fer français, Aurora Flight Sciences, and Microsoft Research. 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-leading researchers as visitors and collaborators.

Professor Dahleh, who previously held the position of co-associate director of LIDS (and acting director during professor Alan Willsky's AY2011 sabbatical), has now taken on the position of associate department head in EECS. Also, LIDS continues to host major workshops and symposia in emerging and important areas. In June 2012, LIDS served as cohost of the tenth international Conference on Stochastic Networks, and, following the success of the first Interdisciplinary Workshop on Information and Decision in Social Networks, held in May/June 2011, a second workshop is being planned for November 2012.

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 in the challenges of the present and the future has led 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
- Machine learning for recommendation systems and social media
- 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
- Foundations of scalable analysis and inference for problems involving “big data,” in which the boundaries between inference, learning, data representation and access, and massively parallel algorithms are essentially nonexistent

Faculty Activities

Much of the major research activities of LIDS faculty not only cuts across the 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 published 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 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 during the past year has continued to examine the biological and computational origins of human cognition and biology, as well as the limits of statistically based methods for language acquisition. In particular, during AY2012, he extended well-known results on the computational intractability of so-called "Bayesian hierarchical models" to proposed methods for approximating the solutions in such cases. Instead, it seems that a theory of structural approximation must be used. Several "toy" examples of verb acquisition were shown to be replaceable by simpler methods using maximum likelihood estimation. Professor Berwick has also continued to extend current linguistic theory to computer applications of natural language processing, specifically, the so-called “minimalist” framework of Noam Chomsky and colleagues, that attempts to reduce the “human specific” component of language. During AY2012, he expanded a probabilistic model for this theory, attaining parsing results comparable to those based on earlier context-free grammars.

Professor Berwick continued research in the area of the core biological foundations of language.
He initiated an analysis of phylogenetic methods that have been previously proposed to analyze the “family tree” organization of languages, using Bayesian Markov chain Monte Carlo methods, and found that most of these have been flawed due to an incorrect choice of features, as well as non-convergence issues. To remedy this, he proposed a new evolutionary model for generation-to-generation language change, along with a closer match to the “underlying features” of language. During the past year, along with colleagues here and abroad, he continued extensive work comparing birdsong learning and human language acquisition. He determined that the lateralization of the brain in humans for language extends to lateralization in vocal learning birds, down to the same basic brain tract wiring. This is evidently an example of independent, convergent evolution. Linking this to computational work, the system developed last year that can acquire rhythmic structure from acoustic input was proved to be in the class of so-called “*k*-reversible” languages, so computable efficiently in polynomial time. This and preceding work was published in both *Nature Neuroscience* and *Frontiers in Neuroscience*.

Munther Dahleh

Professor Munther 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 professor Daron Acemoglu and Professor 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. Most recent developments highlight resiliency conditions for cascaded failures. Such conditions are readily computable from the topology of the network.

Side Information in Decision-making Problems

In collaboration with his 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.

Study of Rare Events

With his student Mesrob Ohannessian and professor Sanjoy Mitter, Professor Dahleh led a study of rare events that focused on the question of when one can make meaningful statistical inference about events that have very little data, or even none. In particular, they considered the problem of events determined by discrete outcomes that appear a fixed small number of times in the data, which is known as the Good-Turing estimation problem. They showed that regularity of the tail of the distribution is crucial for estimation to be non-trivial. By doing so, they established a relationship with the tail estimation problem, which is traditionally studied in the area of extreme value theory. As a consequence, 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. In light of this, 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 Ohannessian and Ali Faghih, 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; second, the monetary value of storage might not justify the investment costs, particularly in the presence of ramp rate constraints, resulting in under-investment 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 their 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 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) for uniqueness versus multiplicity of game-theoretic equilibria.

An Ergodic Theory Approach to Control Under Communication Constraints

The problem of stabilizing a linear time-invariant plant when measurements are obtained via a discrete memoryless channel has received considerable attention from the research community. In the case of a noiseless channel, several practical algorithms have been derived that demonstrate asymptotic stability of the system. In the more general case of a noisy channel, only theoretical bounds on its minimum Shannon capacity to ensure stability are available. In fact, there does not exist a characterization of a practical finite memory encoder/controller that guarantees asymptotic stability of the closed loop system in the presence of such noisy channels.

Professor Dahleh's research, in collaboration with professor Alexandre Megretski and their student Giancarlo Baldo, focuses on almost sure asymptotic stabilization of a deterministic first order plant through a (noisy) discrete memoryless channel. Their goal is to provide a practical algorithm to achieve almost sure asymptotic stability where the memory of the encoder and controller is restricted to a finite number of real valued variables. This restriction makes the algorithm extremely simple and implementable on any modern digital platform. They show how the parameters defining the model can be tuned by solving a suitable optimization problem, and they compare the performance of the obtained control scheme with the theoretical rate constraints. The main idea of the solution is the utilization of ergodic theory for the underlying Markov chain, as opposed to finding a Lyapunov function directly from the state space.

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

Planning and controlling the motion of an autonomous, agile vehicle in a dynamic environment is a very complex (PSPACE-hard) problem, especially when the vehicle is required to use its full maneuvering capabilities. Recent efforts aimed at using randomized sampling-based algorithms for planning the path of kinematic and dynamic vehicles have demonstrated considerable potential for implementation on future autonomous platforms—achieving computational tractability by relaxing deterministic completeness requirements to probabilistic ones.

During the past year, Professor Frazzoli and his students have made a number of fundamental contributions that dramatically increased the robotics community's understanding of sampling-based motion planning algorithms and of their properties, as well as their applicability to a much broader class of problems. These contributions are based on a novel connection that was made between the field of robotic motion planning and the theory of random geometric graphs. Remarkably, both fields date their origin in 1961, i.e., the year of the first installation of an industrial robot, and of the publication of Edgar Gilbert's seminal paper "Random Plane Networks." During the past 50 years, the two fields evolved independently; in 2011, however, graduate student Sertac Karaman and Professor Frazzoli published an article showing that the fields are intimately related. They were able to show, using the theory of random geometric graphs (e.g., percolation and connectivity), that a number of state-of-the-art algorithms for robotic motion planning have undesirable properties, such as excessive computational complexity or failure to converge to optimal solutions. They were able to use this theory to design new algorithms, such as rapidly exploring random tree (RRT), rapidly exploring random graph, and probabilistic road map, which provably combine optimality and computational efficiency. This is the first case in which the theory of random geometric graphs has been used not only for analysis of a natural (or social) phenomenon, but also for algorithm design. The impact of the discovery went beyond the "standard" motion planning problem: they are currently developing extensions enabling "anytime" solutions to many important problems, from decision making under uncertainty and stochastic optimal control, to differential pursuit/evasion games.

The expertise developed in percolation theory was also instrumental in another recent result that received considerable attention from the media, i.e., the discovery of what has been called a "speed limit for birds." Professor Frazzoli and his students found that there exists a critical velocity threshold such that if a "bird" flies through an infinite ergodic "forest" at supercritical speed, it will eventually collide with a tree, whereas if the "bird" flies at subcritical speed, there exists an unbounded trajectory along which the bird can fly without ever colliding with a tree. In addition to its intellectual merit, this discovery allows precise benchmarking and tuning of motion planning algorithms enabling robotic vehicles to move safely through stochastic clutter.

Analysis and Control of Robotic Networks and Transportation Systems

Building on years of work on the control of networks of unmanned aerial vehicles (UAVs) or mobile robots, during the past year Professor Frazzoli and his group have been able to leverage their expertise to model, analyze, and ultimately control transportation networks and mobility-on-demand systems. They introduced a new modeling approach to transportation networks, based on the concept of "dynamical flow network," allowing analysis of the stability of equilibria under a multi-scale model of driver decisions, combining slow updates on the global state of the network with fast myopic reactions to observed traffic. They were able to derive rigorous results on the resilience of such networks under disruptions that reduce link-wise capacity, showing that standard notions (such as Wardrop equilibria) may be efficient but not resilient—and derived game-theoretic approaches to ensure user convergence towards resilient equilibria.

Recently, Professor Frazzoli and his group introduced new distributed and adaptive algorithms for controlling traffic signals. The algorithm is adapted from back-pressure routing, which has been mainly applied to communication and power networks. They formally proved that the proposed algorithm ensures global optimality as it leads to maximum network throughput, even though the controller is constructed and implemented in a completely distributed manner. Third-party, large-scale simulation results show that the algorithm significantly outperforms state-of-the-art solutions such as the Sydney Coordinated Adaptive Traffic System, an adaptive traffic signal control system that is being used in many cities. An invention disclosure has been filed, and the Singapore Land Transport Authority is showing interest in testing and implementing the algorithm in Singapore.

Autonomy-enabled Mobility-on-demand System

Finally, Professor Frazzoli and his group are integrating all the research areas mentioned above in the development of a mobility-on-demand system demonstration on the campus of the National University of Singapore (NUS). They are developing a small fleet of dual-mode autonomous electric vehicles to provide personal transportation services to students and faculty on campus. The system builds on the standard "car sharing" concept through the ability of the vehicles to drive themselves to the locations where they are most needed. Users will be able to request pickup at a nearby location through a smartphone application; one of the vehicles will autonomously drive to the pickup location. The users will then drive (or let the vehicle drive autonomously) to their destination. Upon drop-off, the vehicle will autonomously drive to a charging station, or to pick up the next customer. Professor Frazzoli's work in this area covers the entire spectrum, from the theoretical analysis of the mobility-on-demand problem to the actual hardware development and integration for the vehicles.

Jonathan How

Professor How leads 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 and unmanned ground vehicles (UGVs); sensor network design; and robust, adaptive, and nonlinear control. Professor How is also the PI of the Aerospace Control Laboratory (ACL). Recent research includes the following:

Real-time Multiagent Planning

Professor How, with students Luke Johnson and Sameera Ponda, developed a distributed task-planning algorithm that provides provably well-performing, conflict-free, approximate solutions for heterogeneous multiagent/multitask allocation problems. The consensus-based bundle algorithm (CBBA) had been previously extended to include task time-windows, coupled agent constraints, asynchronous communications, limited network connectivity, and to function in decentralized environments. Recent work has introduced the capability to use non-submodular score functions in decentralized environments, extending the applicability of CBBA. One instance of this increased capability was utilized in a robust extension of CBBA that is able to explicitly account for uncertainty in the planning problem, producing higher-performing plans for multi-agent teams operating in stochastic and dynamic environments. CBBA was used to plan for both networked UAV/UGV teams and human-robot teams, and real-time performance was validated through flight test experiments.

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, ACL has constructed an autonomous recharge platform, capable of autonomous battery replacement and recharge, enabling long duration missions for small UAVs (work of students Joshua Redding, Tuna Toksöz, and Kemal Ure, with postdoctoral associate Girish Chowdhary).

Information-gathering Networks

Information collection is a fundamental task in sensor networks. Informative motion planning for mobile sensing agents and information quantification in complex probabilistic graphical models are two problems addressed by research at ACL. Recently developed algorithms (work of students Daniel Levine and Brandon Luders) embed information measures within RRT-based motion planners to quickly identify safe, informative trajectories for teams of mobile sensing agents, subject to general dynamic constraints and sensor models. Levine and Professor How have also developed the notion of "focused" information measures as a way to quantify informativeness in the presence of nuisance variables and subsequently optimize (with respect to inferring non-nuisance states) the observation selection process in Gaussian Markov random fields.

Multi-agent Decision Making

Markov Decision Processes (MDPs) are a natural framework for formulating many decision problems of interest; Professor How and his team have identified approximate solution techniques that can utilize this framework while overcoming the curse of dimensionality typically encountered for exact solutions. To enable online replanning in a multi-agent scenario, Redding developed the Group-Aggregate Decentralized Multi-agent MDP-solving Technique (GA-Dec-MMDP). This technique reduces the dimension of the state space significantly by allowing agents to estimate each other's actions. For online systems, student Alborz Geramifard introduced incremental Feature Dependency Discovery (iFDD) algorithm that expands the representation in areas where sampled Bellman errors persist. iFDD is convergent and computationally cheap, hence amenable to systems with restricted thinking time between actions. Ure and Geramifard, with Dr. Chowdhary and Professor How, recently used the iFDD algorithm to build more accurate models used for planning. Empirical results based on the iFDD-based models' performance are better, with fewer number of samples compared to conventional modeling methods.

Integrated Planning and Learning

One of the main challenges in applying learning techniques to real-world problems is the risk involved in allowing learning. For example, a flying robot may crash due to fuel depletion as it attempts to learn about the consequence of exploring a distant region with low fuel. To tackle this problem, Redding, Geramifard, and Professor How introduced a new framework for integrating planning and learning named Intelligent Cooperative Control Planner (iCCA). This framework provides a safe exploration mechanism for learning as risky actions are identified and filtered from the system. Three papers have been published on the iCCA topic, demonstrating its effectiveness for planning in large UAV missions

Nonparametric Adaptive Control for Health-aware Operation

Online adaptation of control policy is often required in real-world applications to ensure that uncertainties do not lead to inefficient or undesired behavior. Traditional approaches in adaptive control have focused on adaptive elements where the number of regression bases functions and their internal parameters are fixed a priori. However, it is often difficult to choose the right set of bases without prior knowledge of the operating domain, which can be particularly hard to characterize in presence of faults or other unforeseen changes. In Professor How's work with Dr. Chowdhary, a nonparametric approach to model reference adaptive control has been developed using online Gaussian Process regression techniques. These adaptive controllers are capable of increasing their complexity in response to the observed data. The online learned models of the vehicle health are being used to create decentralized health-aware planning algorithms for UAVs in Professor How's work with Dr. Chowdhary and Ure.

Value of Information-based Censoring for Decentralized Data Fusion

In many distributed sensing applications, not all agents have valuable information at all times, therefore requiring all agents to communicate at all times; this can be resource-intensive. In Professor How's work with student Beipeng Mu and Dr. Chowdhary, the notion of Value of Information (VoI) is used to improve the efficiency of distributed sensing algorithms. Particularly, only agents with high VoI broadcast their measurements to the network, while others censor their measurements. New VoI realized data fusion algorithms are introduced, and an in-depth analysis of the costs incurred by these algorithms and conventional distributed data fusion algorithms is presented. Numerical simulations were used to compare the performance of the VoI realized algorithms with traditional data fusion algorithms. A VoI based algorithm that adaptively adjusts the criterion for being informative was presented and was shown to maintain a good balance between reduced communication cost and increased accuracy.

Bayesian Nonparametric Models for Planning and Control

Autonomous planning and control typically involves selecting actions that maximize the mission objectives given the available information, such as models of the agent dynamics and the environment. However, such models are typically only approximate, and can rapidly become obsolete, thereby degrading the planning and control performance. Classical approaches to address this problem typically assume that the environment has a certain structure that can be captured by a parametric model that can be updated online. However, finding the right parameterization a priori for complex and uncertain domains is challenging because substantial domain knowledge is required. In Professor How's work with students Ponda and Trevor Campbell, and with Dr. Chowdhary, it was shown that nonparametric hierarchical Dirichlet process priors improves planning performance for a surveillance and tracking problem, and a multi-agent task allocation problem with environmental uncertainties. In Professor How's work with Dr. Chowdhary, a nonparametric adaptive controller has been developed by combining online Gaussian Process regression techniques and stochastic stability theory. The online learned models of the vehicle health are being used to create decentralized health-aware planning algorithms UAVs. Professor How, Campbell, Geramifard, Dr. Chowdhary, and collaborators from Duke University are investigating how Bayesian nonparametric priors can be used in planning and decision-making problems under uncertainty in the framework of dynamic programming and reinforcement learning.

Patrick Jaillet

Professor Jaillet's main research has continued to be 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 one can do 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 this past year included two postdoctoral associates (Vahideh Manshadi, EECS/ORC, and Rico Zenklusen, EECS/Mathematics); graduate students from ORC (Brian Crimmel, Iain Dunning, Swati Gupta, Maokai Lin, and Xin Lu); graduate students from EECS (Daw-Sen Huang, Andrew Mastin, and Shen Shen); an undergraduate student in EECS/Mathematics (Jin Hao Wan); and one intern from France (Alexandre Hollocou, École Polytechnique). The research group in Singapore included a postdoctoral associate (Ali Oran, SMART) and several graduate students (from NUS, Nanyang Technological University [NTU], and Singapore Management University).

Examples of recent research activities involve the competitive analysis of online TSP and spatial searching problems (Huang, Gupta, and Shen); theoretical and empirical analyses of online stochastic matching problems and their applications (Lu, Manshadi, Mastin, Wan, and Hollocou); the analysis of matroidal secretary problems (Zenklusen); route optimization under uncertainty for unmanned underwater vehicles (Crimmel); and development of bounds for the price of anarchy in dynamic congestion games (Lin).

Current funded research programs come from the operations research program of the National Science Foundation (NSF) (Online Optimization for Dynamic Resource Allocation Problems); from the operations research division of the Office of Naval Research (ONR): (1) Online and Dynamic Optimization under Uncertainty, and (2) Decentralized Online Optimization in Multi-agent Systems in Dynamic and Uncertain Environments); from the optimization and discrete mathematics division of the Air Force Office of Scientific Research (AFOSR) (Data-driven Online and Real-time Combinatorial Optimization); and from SMART (Future Urban Mobility [FM], a project with nine other MIT PIs).

Within the FM 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) 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 tools matrix laboratory 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 professors Emery Brown (BCS), Peter Doerschuk (Cornell University), and 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 professors Hariharan Narayanan (University of Washington) and Charles Fefferman (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 professors Anant Sahai (University of California, Berkeley) and Sekhar Tatikonda (Yale University). Also with Professor 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 a new rate distortion theory for a family of channels. This work constitutes part of the recently completed doctoral thesis of Mukul Agarwal, in which a new result on source channel separation for networks has been presented.

With Professor Dahleh and Dr. Roozbehani, Professor Mitter has been working on various systems aspects of smart grids. New results on volatility of networks when dynamic pricing is implemented have been obtained, and the interaction of the market with the dynamics of the power grid is being investigated. Professor Mitter has also been investigating issues of systemic risk in the financial system in collaboration with Professors Dahleh and Lo.

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 the 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 upon 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. 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.

During the past year, CNRG started to work on a new project titled Optimal Control of Wireless Networks: From Theory to Practice, funded by ONR. This project is a collaboration between CNRG and researchers at the Naval Research Laboratory (NRL). Its goal is to design practical network control algorithms based on the theories developed by Professor Modiano and his students over the past decade. The algorithms have been shown to optimize network performance, e.g., maximize throughput and utility, but so far have been largely limited to being a theoretical framework. Through this new project, Professor Modiano and his group are developing practical network control algorithms that make efficient use of wireless resources through the joint design of network layer routing, link layer scheduling, and physical layer power and rate control. The collaboration with NRL will facilitate transitioning this promising technology for use in military communication systems. In a related project, funded by NSF, the group is developing distributed network control algorithms for wireless networks. Such distributed algorithms are needed in wireless networks where it is neither practical nor desirable to use centralized control mechanisms.

CNRG is also working on an Army Multidisciplinary University Research Initiative (MURI) project titled MAASCOM: 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 between MIT, Ohio State University, the University of Maryland, the University of Illinois, Purdue University, and Cornell University. An important aspect of this 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.

The group continues to work on a Department of Defense–funded project toward the design of highly robust telecommunication networks that can survive a 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 very 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. This project explores the impact of layering on network survivability and develops network architectures that are resilient to failure propagation between layers. In spite its importance and practicality, little is understood about network survivability in this complex layered environment. This 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. 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.

Last year, the group started working on a project with the Masdar Institute of Science and Technology dealing with smart grids, and the design of communication networks that would enable future smart grid applications. Future power grids will require rapid and dynamic control of the grid in order to respond to changes in demand, supply, or failures. Such dynamic control requires the ability to monitor the power grid in real-time and rapidly respond to changes by appropriate control actions, and inevitably depends on the availability of a reliable communication infrastructure. The project aims to develop the communication network's architecture for enabling effective control of future smart grids.

CNRG's research crosses disciplinary boundaries by combining techniques from network optimization, queueing 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 Professors Acemoglu (Economics) and 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 project.

Another recent project, in collaboration with professor Pablo Parrilo, student 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 Multidisciplinary University Research Initiative (MURI) grant—joint with the Georgia Institute of Technology and the University of Maryland—and an NSF project.

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 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, and 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 Defense Advanced Research Projects Agency information theory for mobile ad hoc networks program (joint with Stanford University, the California Institute of Technology, and UIUC), and an AFOSR MURI grant.

Pablo Parrilo

Professor Parrilo's research group is focused 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 and their joint student Candogan, Professor Parrilo has developed a structural approach to game theory that makes possible the decomposition of a given game into its "potential" and "harmonic" components. The methods enable the analysis of "near-potential games," and can be used to study many static and dynamical properties of games, such as equilibria or the convergence of fictitious play mechanisms. Current ongoing work is concerned with possible extensions of these techniques to the development of new auction formats, for graphically-structured valuations of the bidders.

Amir Ali Ahmadi (LIDS/CSAIL postdoctoral associate) and Professor Parrilo have analyzed the interplay between sum of squares (SOS) and the 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? They have obtained a complete characterization of the relationships 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.

Recent work in collaboration with student James Saunderson, Professor Willsky, and former LIDS student Venkat Chandrasekaran (now a postdoctoral associate at the University of California, Berkeley) has established new and interesting links between natural questions in statistical model identification, convex geometry, and matrix decompositions. They have shown that low-rank/diagonal decompositions of symmetric matrices are intimately related to a geometry problem (ellipsoid fitting), as well as the facial geometry of a convex set known as the elliptope. They have provided a simple sufficient condition for the success of a convex optimization-based heuristic known as minimum trace factor analysis. These results have led to a new understanding of the structure of rank-deficient correlation matrices.

In collaboration with colleagues from the University of Washington (Seattle), Professor Parrilo is currently investigating the basic geometric questions of when a given convex set is the image under a linear map of an affine slice of a given closed convex cone. Such representations or "lifts" of convex sets are especially useful if the cone admits an efficient algorithm for linear optimization over its affine slices, and are fundamental in the application of conic optimization to a large class of problems. Professor Parrilo and his colleagues have shown that the existence of a lift of a convex set to a cone is equivalent to the existence of a factorization of an operator associated to the set and its polar via elements in the cone and its dual. This generalizes a well-known theorem of professor Mihalis Yannakakis (Columbia University) that established a connection between polyhedral lifts of a polytope and nonnegative factorizations of its slack matrix.

Yury Polyanskiy

Professor Polyanskiy conducts research in the areas of mathematics of information (information theory), coding theory, and theory of random processes. His current work focuses on non-asymptotic characterization of the performance limits of communication systems, optimal feedback strategies, and non-Shannon information measures.

Asynchronous Communication

Recently, professors Aslan Tchamkerten (L'école Télécom ParisTech) and Gregory Wornell, and Dr. Venkat Chandar (Lincoln Laboratory), proposed a novel variation of the problem of joint synchronization and error-correction. Professor Polyanskiy's work considers a strengthened formulation that requires the decoder to estimate both the message and the location of the codeword exactly. It was shown that the capacity region remains unchanged, can be achieved by universal (channel independent) codes, and that the strong converse holds. Comparisons with earlier results on another (delay compensated) definition of rate were made. The finite blocklength regime was investigated and it was demonstrated that even for moderate blocklengths, it is possible to construct capacity-achieving codes that tolerate an exponential level of asynchronism and experience only a small loss in rate compared to the perfectly synchronized setting; in particular, the channel dispersion does not suffer any degradation due to asynchronism. For the binary symmetric channel, a translation (coset) of a good linear code was shown to achieve the capacity-synchronization tradeoff. The results were reported in Professor Polyanskiy's paper "Asynchronous Communication: Universality, Strong Converse and Dispersion," submitted for publication to the Institute of Electrical and Electronics Engineers (IEEE) journal *Transactions on Information Theory.*

Minimax Converse Methods in Communication

A minimax meta-converse has recently been proposed as a simultaneous generalization of a number of the classical results and a useful tool for the non-asymptotic analysis. Under this project, it was shown that the order of optimizing the input and output distributions can be interchanged without affecting the bound. In the course of the proof, a number of auxiliary results of separate interest were obtained. In particular, it was shown that the optimization problem is convex and can be solved in many cases by the symmetry considerations. As a consequence, it was demonstrated that in the latter cases the (multi-letter) input distribution in information-spectrum (Verdu-Han) converse bound can be taken to be memoryless. A tight converse for the binary erasure channel is re-derived by computing the optimal (non-product) output distribution. For discrete memoryless channels, a conjecture of professors Vincent Poor and Sergio Verdú, both of Princeton University, regarding the tightness of the information spectrum bound on the error-exponents is resolved in the negative. Concept of the channel symmetry group is established and relations with the definitions of symmetry by Robert Gallager and Roland Dobrushin are investigated. The results were reported in Professor Polyanskiy's paper "Saddle Point in the Minimax Converse for Channel Coding," submitted for publication to IEEE's *Transactions on Information Theory.*

Mardavij Roozbehani

Dr. Roozbehani led several research efforts with a focus on understanding the fundamental limitations and the tradeoffs in design and operation of smart power grids of the future. These interdisciplinary research efforts are at the interface of control theory and optimization, power systems, economics, and operations research. Particular emphasis was placed on understanding the effects of network topology and heterogeneity of agents on volatility and robustness of power networks, impact of market architecture on robustness and efficiency in complex networks and the corresponding tradeoffs, volatility and efficiency analysis of real-time pricing schemes, and optimal control and sizing of storage. Funding for his research comes from NSF, Siemens AG, and Draper Laboratory.

Efficiency and Risk Tradeoffs in Complex Networks

Together with Professor Dahleh and graduate student Qingqing Huang, Dr. Roozbehani developed an abstract model of power networks for examining how different market architectures induce a tradeoff between efficiency and risk. They considered two extreme market architectures: (a) consumers with market power cooperate to minimize the aggregate cost of meeting their demands, and (b) consumers do not cooperate. In both cooperative and non-cooperative architectures, the consumers behave strategically, anticipating their impact on the cost and exploiting their market power to minimize their cost. Their results demonstrate that although the non-cooperative scheme leads to an efficiency loss, it has a smaller tail probability of stationary aggregate demand distribution, whereas the cooperative scheme achieves higher efficiency at the cost of a higher probability of demand spikes, and thus, higher risk. They thus posit that the origins of endogenous risks may lie in the market architecture, which is an inherent characteristic of the system. The implication of these results on issues of efficiency and systemic risk is not limited to the context of real-time pricing and exercising market power by electricity consumers. Extensions of these results to other application areas, such as systemic risk in financial networks, are currently underway. Systematic analysis of the risk implications of the market architecture in complex networks is one of the long-term goals of this research effort.

Network Effects on Volatility

Recent work in which new results on analysis of the network effects and heterogeneity of the agents on price volatility in wholesale electricity markets were obtained is an extension of Dr. Roozbehani's earlier work on price volatility in power networks, which now includes dynamic demand models for the consumers, and also explicitly includes the network parameters. The effects of transmission network constraints on the sensitivity and volatility of the system are formally characterized, and the interplay between price volatility, spatial heterogeneity of consumers/producers, and network parameters is examined. In particular, it is shown that increased heterogeneity induces an asymmetry in the flows over the network, which in turn amplifies volatility. This work has applications in architecture design, storage investment, and transmission planning, as well as in designing market rules and pricing mechanisms in power networks. This research has attracted the attention of power systems and network communities, as evidenced by several invited talks by Dr. Roozbehani at workshops, conferences, and seminars across the country.

Reliability Value of Energy Storage

In collaboration with student Ali Parandehgheibi and Professors Ozdaglar and Dahleh, Dr. Roozbehani conducted a research effort that examined the "value" of storage in securing the reliability of a system with uncertain supply/demand, and supply friction. It is shown that when the objective is to minimize the expected cost of blackouts over a long period of time, it is often optimal to allow a small blackout to occur in the interest of maintaining a higher level of reserve, which may help avoid a large blackout in the future. A particularly interesting result is that as the "volatility" of the supply side increases, there is a critical level of storage capacity, above which the value of having additional capacity quickly diminishes, and below which, storage capacity provides very little value. Increased level of volatility can take away the value of storage significantly, and as volatility increases, storage may become less valuable. Results also show that for all control policies, there appears to be a critical level of storage size, above which the probability of suffering large blackouts diminishes quickly.

This work provides the groundwork for understanding the reliability value of storage. The economic value of storage is dictated by its arbitrage value in the energy market. Therefore, mechanism design for striking a tradeoff between the reliability and economic values, and aligning such objectives, is important. In light of the results discussed above on efficiency and risk tradeoffs under different market architectures, the risk implications of cooperative operative agents with access to storage must be understood and mechanisms for mitigating risk must be designed. These constitute directions for further and future research.

Devavrat Shah

Professor Shah and his research group—Inference and Stochastic Networks Group—are involved in 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 messagepassing 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, and 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 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.

Processing Social Data

Unlike human conversations, most interactions on "social networks" are recorded. This provides a tremendous opportunity to learn about people, and it also poses the challenge of tackling information overload. Professor Shah has developed methodology to capture people's choices from seemingly innocent data like electronic transactions or clicking on one of many options displayed, with interest in improving business enterprise, providing recommendations, and helping make collaborative decisions. He has taken theory to practice and demonstrated its utility in running businesses by better predicting car sales (20 percent better than state-of-the-art alternatives) at dealerships using transactions from Ford Motors (via the MIT-Ford alliance). This collection of contributions, along with the collaborative decision-making tool Celect, were featured in the *New York Times* (July 2011) and recognized through best paper awards at the Neural Information Processing Systems Foundation Conference, and at the Institute for Operations Research and the Management Sciences (INFORMS) Conference. To help tackle information overload, Professor Shah's group has developed theory for searching the information trail of people, e.g., Tweets on Twitter. Students involved in these projects have recently completed their doctoral theses and have joined faculties at New York University and MIT.

NSF, ARO, MURI, and Ford-MIT alliance grants primarily support the research effort.

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 this 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.

In the past year, Professors Shah and Tsitsiklis, along 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. This has resulted in resolution of a long-standing problem of delay optimal algorithm design for stochastic networks. The problem remained unresolved for a long time because it requires understanding optimal algorithms for highly complex MDPs with objective function-spanning long time horizons. Upon completion of his doctoral thesis, Zhong will join the faculty of Columbia University.

These research efforts are primarily supported by an NSF CAREER grant, an NSF Theoretical Foundations grant, and AFOSR grant.

Network Information Theory

In collaboration with Professor 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 in 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. This work makes a very significant advance in the field of network information theory, and is supported through 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 among the students in the group but also with professors George Verghese, Thomas Bortfeld (Harvard Medical School), and Duncan Simester (MIT Sloan), and Professors Dahleh, Ozdaglar, Shah, and Modiano.

Distributed Systems and Decision Making

A particular area being investigated 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. Recent activities concern modeling, inference, and control of interagent influences in social networks.

Resource Allocation in Communication Networks

This research concerns the analysis and optimization of resource allocation methods (routing and scheduling) in queueing networks, with communication networks being 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 Analysis and 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. A new activity has been recently initiated, on data-driven modeling of sleep apnea.

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, ONR, and the Royal Dutch Shell Group.

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. A recent highlight in this area is the research of one of Professor Willsky's current students, Ying Liu, who has developed a new suite of inference algorithms for graphical models that can be scaled to extremely large problems and data sets, and which has been proven to work on complex problems that have defeated well-established algorithms. Recent applications of these methods are to computer vision, mapping of subterranean surfaces in support of oil exploration, analysis of power flow signals into homes, and analysis of financial data. 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, BAE Systems, and several small companies in Massachusetts. This part of SSG's research portfolio has received considerable international attention, as evidenced by a string of best paper awards, recent plenary and invited talks by Professor Willsky and his recently graduated students, 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. Together with work on scalable inference algorithms, this work is of particular current relevance as the challenges of "big data" represent some of the most important problems in information technology. This research arcs across the EECS boundary at MIT, bringing together new perspectives on these challenges. Current work in this area includes research by student Matthew Johnson on so-called Bayesian nonparametric methods for discovering complex behaviors in temporal or spatio-temporal data. This work has been demonstrated in very challenging applications, including the so-called "power disaggregation" problem in which, by monitoring power flow into a home, the aim is to discover the pattern of power usage, including the number and types of appliances and the temporal patterns in which they tend to be used. In addition, Johnson has attracted the attention of other researchers at MIT working in very different areas, including speech analysis, and has demonstrated the power of his framework by devising nonparametric algorithms that represent very new approaches to long-standing and well-studied problems, such as extracting characterizations of phonemes in speech. In addition to these research thrusts, SSG is actively involved in developing highly parallelizable inference algorithms, motivated in large part by application to very large and possibly distributed data sets, and to discovering hidden structure in complex data, a problem of central importance in social network analysis, as well as in devising very fast computational algorithms that can take advantage of this structure.

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. Following are details of a few specific projects.

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 demonstrated the first cooperative location-aware network for GPS-denied environments, using ultra-wideband technology. 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, NTU in Singapore, Draper Laboratory, Jet Propulsion Laboratory, and Mitsubishi Electric Research Laboratories.

Highlights, Awards, and Events

AY2012 was another successful 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 continues to grow, exceeding LIDS's ambitious strategic plan, and is anticipated to more than double over the 4-year period ending with the next academic year. The laboratory welcomed additional faculty as members of the community; made major strides in engaging other units across MIT; took leadership roles in several major Institute-wide initiatives and centers; continued the series of events and activities that have added so much to LIDS's environment; and continued to lead and host major research symposia and workshops, enhancing its position of leadership in the international research community.

Continuing successful activities within LIDS include the colloquium series, the 17th annual LIDS student conference, and a second visit of its advisory committee. A seventh edition of the LIDS community-oriented magazine, *LIDS-ALL*, was produced, and the eighth edition is being readied for the start of AY2013. A new faculty member was welcomed, Professor Polyanskiy, and LIDS faculty are playing leadership roles in several major Institute-wide initiatives, including the Future Urban Mobility program within SMART, the newly formed Center for Systemic Risk, and the equally new virtual center Connection Science and Engineering. All bring together researchers cutting across many schools at MIT and bridging disciplines from engineering to economics to social sciences.

LIDS also continues to host major workshops and symposia in emerging areas, including network science, analysis of social networks, and game theory.

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

Awards

- Amir Ali Ahmadi received the 2012–2013 IBM Goldstine Fellowship. He is supervised by Professor Parrilo.
- Elie Adam was awarded a Xerox Fellowship for 2012. He is advised by Professors Dahleh and Ozdaglar.
- Ozan Candogan was awarded a Microsoft Research PhD Fellowship for 2012. He is advised by Professors Ozdaglar and Parrilo.
- Ali Faghih received the Best Poster Award, MITEI Energy Research Seed Fund Program, March 2012.
- Debbie Wright, LIDS's assistant director for administration, received the School of Engineering's 2012 Infinite Mile Award for Excellence.
- Pablo Parrilo is the recipient of the 2011 Antonio Ruberti Outstanding Young Researcher Award of the IEEE Control Systems Society. This award recognizes distinguished cutting-edge contributions by a young researcher to the theory or application of systems and control.
- Jonathan How was awarded the 2011 National Instruments Graphical System Design Achievement Award (education category).
- David Forney was awarded the 2011 Aaron D. Wyner Distinguished Service Award of the IEEE Information Theory Society. The Wyner Award honors an individual who has shown outstanding leadership in, and provided long-standing exceptional service to, the information theory community.

- Moe Win was awarded the IEEE 2011 Kiyo Tomiyasu Award, an IEEE Technical Field Award for fundamental contributions to high-speed reliable communications over optical and wireless channels.

Honors

- Sanjoy Mitter was the John von Neumann Visiting Professor in Mathematics at the Technical University of Munich, Germany, May–July 2012; the Ulam Scholar at the Los Alamos National Laboratory, April 2012; a visiting professor at Tata Institute of Fundamental Research, Bangalore, India, January 2012; and a visiting professor at Imperial College, London, October 2011.
- Eytan Modiano was named a fellow by the IEEE board of directors at its November 2011 meeting, effective January 1, 2012, with the following citation: "For contributions to cross-layer resource allocation algorithms for wireless, satellite, and optical networks."
- Robert Berwick gave a lecture series as the Distinguished Helmholtz Lecturer at Utrecht University, Netherlands, January 2012.
- Moe Win was elected a fellow of the Institute of Engineering and Technology, 2011; was elected a fellow of the American Association for the Advancement of Science, for distinguished contributions to the foundations of network navigation and communication; and received the Copernicus Fellowship at the Universita degli Studi di Ferrara, Italy, 2011.

Paper Awards

- Patrick Jaillet (with Michael Wagner) received the 2010 INFORMS Glover-Klingman Prize (awarded in 2012) for the best paper published in the journal *Networks* during 2010: "Almost Sure Asymptotic Optimality for Online Routing and Machine Scheduling Problems."
- Devavrat Shah, along with Neil Walton (University of Amsterdam) and Yuan Zhong, received the Kenneth C. Sevcik Outstanding Student Paper Award for "*Optimal Queue-size Scaling in Switched Networks"* at ACM SIGMETRICS/Performance, June 2012.
- Vu Huynh, Sertac Karaman, and Emilio Frazzoli were finalists for the Best Student Paper Award at the IEEE International Conference on Robotics and Automation, May 2012, for "An Incremental Sampling-based Algorithm for Stochastic Optimal Control."
- David Gamarnik and his former student Dmitriy Katz (now at IBM Research) received the 2011 Best Publication Award from the INFORMS Applied Probability Society for three papers: "On Deciding Stability of Constrained Homogeneous Random Walks and Queueing Systems"; "On the Undecidability of Computing Stationary Distributions and Large Deviation Rates for Constrained Random Walks"; and "On Deciding the Stability of Multiclass Queueing Networks under Buffer Priority Scheduling Policies."

- Yury Polyanskiy won the 2011 IEEE Information Theory Society Prize Paper Award, jointly with his advisors Professors Poor and Verdú, for "Channel Coding Rate in the Finite Blocklength Regime," IEEE *Transactions on Information Theory*, May 2010.
- Watcharapan Suwansantisuk and Moe Win, together with Marco Chiani (University of Bologna), received the 2011 IEEE Leonard G. Abraham Prize for their paper "Frame Synchronization for Variable-length Packets," IEEE *Selected Areas in Communication*, January 2008.
- Moe Win, with student Damien Jourdan and research colleague Davide Dardari, won the 2011 M. Barry Carlton Award for the best paper published in the IEEE Aerospace and Electronic Systems Society journal *Transactions*.
- Yuan Shen, Santiago Mazuelas, and Moe Win received the Best Paper Award at the 2011 IEEE Global Communications Conference for "A Theoretical Foundation of Network Navigation," and the 2011 Best Paper Award at the IEEE International Conference on Ultra-wideband for "Wideband Cooperative Localization via Belief Condensation."
- Kuang Xu received the First Place prize in the 2011 INFORMS George Nicholson Student Paper Competition for "On the Power of Centralization in Distributed Processing," based on his master's thesis, supervised by Professor Tsitsiklis.
- ACL students Sameera Ponda and Brandon Luders. with Professor How and collaborators from Cornell University, received the Best Paper Award in the 2011 AIAA Guidance, Navigation, and Control Conference for "Decentralized Information-rich Planning and Hybrid Sensor Fusion for Uncertainty Reduction in Human-robot Missions."

Thesis Awards

- Venkat Chandrasekaran received the 2012 EECS Jin-Au Kong Outstanding Doctoral Thesis in Electrical Engineering Award for his thesis, "Convex Optimization Methods for Graphs and Statistical Modeling," supervised by Professors Parrilo and Willsky.
- Myung Jin Choi is the winner of a 2011 George M. Sprowls Award, given to the best computer science theses at MIT.

Future Outlook

During the past year, LIDS has moved well beyond the goals articulated in late 2008 to rebuild its research base, to re-establish its intellectual leadership within and beyond MIT, and to re-energize its community. Looking forward, LIDS expects its research volume to grow in AY2013 to a level more than double that of AY2009, essentially reaching capacity for its size and the nature of its analytical and theoretical research. Efforts over the past 18 months have also led LIDS to take leadership roles in several major Institute-wide initiatives, and the laboratory expects to build on these nascent centers and programs in AY2013 and to establish them as major foci of research within MIT and leading international centers in their respective areas. LIDS also anticipates continuing its pattern of hosting major symposia and workshops in emerging areas, including social networks, network science, and big data.

While it is gratifying that LIDS has established a leading role in all these activities and has cemented its standing as one of the leading international centers in the information and decision sciences, the laboratory is especially proud of the exciting and fulfilling environment it has developed for all those who call LIDS home. LIDS intends to build on its successes to ensure continued intellectual leadership and fulfillment of its promise.

Alan S. Willsky
Director
Edwin Sibley Webster Professor of Electrical Engineering and Computer Science

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

Pablo A. Parrilo
Co-associate Director
Finmeccanica Career Development Professor of Electrical Engineering