Laboratory for Information and Decision Systems

The Laboratory for Information and Decision Systems (LIDS) is an interdepartmental laboratory for research and education in systems, control, optimization, communication, networks, and statistical signal processing. These disciplines, which span the domain of the analytical information and decision sciences, play a critical and pervasive role in science, engineering, and society more broadly. At its best, LIDS provides a melting pot of disciplines that share a common approach to problems, a common mathematical base, and an energized environment not only to foster the research needed for the future but also to instill in our students the disciplinary depth and interdisciplinary understanding required of research and engineering leaders of today and tomorrow.

LIDS draws its staff principally from the Department of Electrical Engineering and Computer Science and the Department of Aeronautics and Astronautics. However, because the disciplines in which LIDS is involved are also of great interest across the Institute, we maintain—and are in the process of growing—our collaborations and interactions with many other units, including the Operations Research Center; the Computer Science and Artificial Intelligence Laboratory (CSAIL); the Research Laboratory of Electronics; the MIT Energy 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; the Department of Economics; the Sloan School of Management; and the Harvard–MIT Division of Health Sciences and Technology. In addition, LIDS has a strong and growing set of interactions with industrial organizations, which provide funding, collaborators, and challenging problems to drive our research. Among the organizations with which we have or are developing interactions are Draper Laboratory, Lincoln Laboratory, Los Alamos National Laboratory, Siemens, Shell oil company, Ford Motor Company, and Boeing. 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.

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 and 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 future has led us 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 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 disciplines.

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

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

Furthermore, traditional paradigms of sensing, communication, and control are not adequate to address many of the emerging challenges that we see before us. As a result, we have 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 of cyber-physical systems, including architectural design, cross-layer algorithms, and tools for analysis, verification, and performance guarantees
- Foundational theory for multiscale and granularity modeling, including methods for describing complex phenomena at multiple granularities, learning of such models from complex and heterogeneous data, and reduction and simplification of models to levels appropriate for particular questions of analysis or design

Activities of LIDS Faculty

In this section, we summarize the major research activities of faculty in LIDS, noting first that much of this research not only cuts across the disciplines, applications, and emerging areas mentioned previously but also is collaborative with others within LIDS and elsewhere at MIT.

Professor 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 coordination of mobile agents, control in the presence of communication constraints, and distributed computation over networked computational units.

Limitations of Networks on Control and Optimization

With his students Nuno Martins and Sridevi Sarma, he analyzed the effect of noisy channels in standard feedback and feed-forward networks on the achievable performance measured in terms of tracking and disturbance attenuation. These results provided a bridge between information theory (capturing the limitations on maximum transmission rate) and control theory (capturing the limitation of noise cancelation). Professors Dahleh and Devavrat Shah and their student Ola Ayaso collaborated on understanding the effect of finite-capacity multiagent networks on distributed function computation. In this context as well, information theory is linked to distributed computation and optimization of special classes of functions. With his student Michael Rinehart, Professor Dahleh addressed the problem of channel selection when an agent can request certain information about the underlying system to maximize its performance.

Combinatorial Optimization with Dynamic Constraits

In collaboration with their student Sleiman Itani, Professors Dahleh and Emilio Frazzoli addressed optimization problems that arise in trajectory planning of dynamic systems. Examples of such problems include the traveling salesman problem for a real vehicle, the problem of matching a number of real vehicles to a number of targets in minimum time, and the problem of designing roads to maximize throughput. Explicit bounds are provided when such problems are randomized—for example, when the number of cities that need to be visited is large and randomly selected.

Bayesian Learning in Large Complex Networks

In collaboration with professors Asuman Ozdaglar and Daron Acemoglu, Professor Dahleh and his student Ilan Lobel led an effort in understanding sequential learning problems that arise in social networks. Their work focused on analyzing Bayesian learning for sequential decision makers who base their decision on observing a subset of the previous decision makers and external signals sampled from a distribution conditioned on the correct state of the world. Their work provided necessary and sufficient conditions on the observations and external signals that guarantee asymptotic learning of a binary state of the world. They also provided results on the speed of convergence for specific classes of learning problems.

Automotive Application

Along with his students Michael Rinehart and Yola Katsargyri, Professor Dahleh led a collaboration with Ford focusing on using Global Positioning System (GPS) information to minimize fuel consumption in a hybrid car by optimally switching between the electric motor and the engine. The work relies on using information such as road slope, traffic lights, and other road attributes to plan trajectories as well as engine-switching strategies that will generate optimal fuel consumption. The methods produced favorable results on the Ford simulator of a hybrid car.

Professor Emilio Frazzoli

Professor Emilio Frazzoliís 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.

Building on the efforts leading to MITís successful participation in the 2007 DARPA Urban Challenge, Professor Frazzoli and his group have continued to work on developing real-time planning and control algorithms for autonomous vehicles. In particular, in the past year, Frazzoli's group developed planning and control algorithms for autonomous forklifts, in the context of the agile robotics for logistics project (led by professor Seth Teller in CSAIL and in collaboration with professor Jonathan Howís group at LIDS). This project is aimed at automating logistics for the Army in forward deployment areas. In addition to several challenges already faced in design of the DARPA Urban Challenge vehicle, the agile robotics project required new advances due to the ability of the forklift to interact directly with its environment—for example, manipulating pallets. LIDS students Sertac Karaman, Jeong Hwan Jeon, and Brandon Luders (advised by Professor How) have extended the DARPA Urban Challenge planning and control software to the forklift and developed novel algorithms for pallet detection and manipulation. The effectiveness of the autonomous forklift in realistic Army logistics scenarios was successfully demonstrated on June 10, 2009, at Fort Belvoir, VA, in the presence of Army leadership.

As part of a new multiyear collaborative effort on control science with the Air Force Research Laboratory and the University of Michigan, Professor Frazzoli is investigating mission planning and control systems for heterogeneous, mixed-initiative networks of unmanned aerial vehicles (UAVs), piloted aircraft, and human operators. During the past year, a new computational framework has been proposed, enabling the efficient (i.e., polynomial time) incremental computation of mission plans subject to complex logic and temporal constraints. It was accomplished by combining state-of-the-art motion-planning algorithms in robotics with a general class of formal language (e.g., mu-calculus) so far ignored in the context of mission specification languages. The above is joint work with LIDS student Sertac Karaman. Also, Professor Frazzoli and his students are developing strategies for UAV mission planning that embed cognitive models of human operators, explicitly taking into account the effects of human operators, workload, and situational awareness. A theory of queuing systems with humans in the loop is being developed along with queue-control techniques based on the exploitation of human cognitive models. Ketan Savla and Christine Siew at LIDS are involved in this work.

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

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

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

Professor Jonathan How

Professor Jonathan How has led a research effort focused on controlling multiple autonomous agents, with an emphasis on distributed decision making with uncertainty. The work has focused on two application domains: planning for multiple UAVs and agile robotics for Army logistics.

Robust Distributed Planning for Multiple UAVs

Under funding from the Air Force Office of Scientific Research (AFOSR) and Office of Naval Research, Professor How and his team (postdoctoral associates Dr. H.-L. Choi and Dr. Luca Bertuccelli and students Cameron Fraser and Brandon Luders) have developed algorithms to address the issues of robustness and adaptation to parameter uncertainty in Markov decision problems. They have demonstrated that a robust value function that is updated with observations (adaptation) can converge to the true, optimal value function of a Markov decision problem under an appropriate set of assumptions. This new algorithm improves on the conservatism of robust policies and the fragility of adaptive policies in handling uncertainty in the parameters and has been demonstrated to significantly reduce the likelihood of vehicle crashes in hardware experiments.

The team also developed a Bayesian consensus framework to explicitly and rigorously account for uncertainties in agents' beliefs when the local uncertainties are not Gaussian—for example, arrival rate, transition probability, process noise covariance. They have derived consensus protocols for many common parameterized distributions, which allow agents to agree on the correct, Bayesian parameterization of the distributions given all the agents' initial knowledge. The derived methods have been shown to converge to the centralized Bayesian estimate in situations in which traditional consensus methods would produce biased outcomes and the proposed methods maintain flexibility to subsequent measurements.

Finally, the team developed a distributed task-planning algorithm that provides provably good conflict-free task allocations that are robust to poor network connectivity and inconsistencies in the situational awareness over the team. Recent work demonstrated key theoretical properties of this consensus-based bundle algorithm, extended the algorithm to enable tight linkages with a human operator, and demonstrated the algorithm using the indoor multi-UAV testbed called RAVEN (real-time indoor autonomous vehicle test environment).

Jointly with professor Asu Ozdaglar, student Brett Bethke has developed an approximate dynamic programming approach called Bellman residual elimination (funded by Boeing). Markov decision processes are a powerful and general framework for addressing problems involving sequential decision making under uncertainty. Such problems occur frequently in a number of fields, including engineering, finance, and operations research. Unfortunately, the curse of dimensionality prevents exact solution of most problems of practical interest. They have developed new approximate policy iteration algorithms that exploit flexible, kernel-based cost-approximation architectures to compute an approximation to the cost-to-go function by minimizing the error incurred in solving Bellman's equation over a set of sample states. Unlike other such Bellman residual methods, the approach is guaranteed to find a solution for which the Bellman residuals at the sample states are identically zero. As a result, convergence to the optimal policy in the limit of sampling the entire state space can be proved. Experimental results indicate that the method produces near-optimal policies for several applications, including a multi-UAV coordination and planning problem, in significantly less time than would be required to compute the exact optimal policy. This work appeared in the 2008 Conference on Decision and Control and the 2009 American Control Conference.

Robust Path Planning to Enable Agile Robotics for Army Logistics

Working with Professor Frazzoli and team, student Brandon Luders has developed a planning and control framework capable of autonomous vehicle operations in an environment of unprecedented complexity. This framework was implemented as part the agile robotics for logistics program, funded by the US Army Logistics Innovation Agency. The agile robotics for logistics program seeks to develop and demonstrate semiautonomous robotic capabilities in an unstructured environment through the operation of an unmanned forklift in an outdoor warehouse scenario. The semiautonomous forklift was designed to operate in the presence of cluttered spaces, dynamic obstacles (including humans), and uncertain terrain without being overly reliant on the presence of maps, reliable GPS data, or existing infrastructure. The proposed planning and control framework is two tiered: closed-loop rapidly exploring random trees are used for navigation, while a steering controller coupled with pallet and truck perception filters is used for manipulating pallet loads. In a presentation at Fort Belvoir, VA, in June 2009, this approach demonstrated robust path-planning capabilities in this uncertain environment.

Professor Sanjoy Mitter

Professor Sanjoy 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.

Professor Mitter has continued his long-standing collaboration with Dr. Charles Rockland (RIKEN Brain Science Institute, Tokyo, Japan) 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 they proposed in the 1980s.

In joint work with Emery Brown (Department of Brain and Cognitive Sciences, MIT), professor Peter Doerschuk (Cornell University) and professor Bud Mishra (New York University), Professor Mitter has been investigating topological properties of large data sets using ideas from differential geometry and algebraic topology.

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

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

Also with Anant Sahai, Professor Mitter has shown for the first time that unstable processes generate two fundamentally different kinds of information, one requiring Shannon capacity for its reliable transmission and one requiring anytime capacity for its reliable transmission. Completion of this work required developing new rate distortion theory for a family of channels. This work constitutes part of Mukul Agarwal's doctoral thesis. With doctoral student Lav Varshney, he is studying the problem of reliably transmitting both energy and information over a noisy channel.

Professor Asu Ozdaglar

Professor Asu Ozdaglar's research spans the areas of nonlinear and convex optimization, game theory, and network optimization and control, with current emphasis on distributed optimization methods, network economics, and network science. The research in her group focuses on problems that arise in the analysis and optimization of large-scale dynamic multiagent networked systems.

A major current research area in her group is social network analysis. While the role of social networks as a conduit for information is as old as humanity, recent social and technological developments—such as Facebook, blogs, and Twitter—have added to the complexity of network interactions. Professor Ozdaglar's group works on developing game-theoretic models for studying the dynamics of belief formation and evolution over complex networks. In collaboration with professor Daron Acemoglu (MIT, Department of Economics), professor Munther Dahleh, and graduate student Ilan Lobel, Professor Ozdaglar has provided a 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. In another recent project, together with professor Daron Acemoglu and graduate student Kostas Bimpikis, she developed a model for Bayesian learning based on communication over a general social network and discussed the conditions under which information can be efficiently aggregated via communication and provided a framework for analyzing how the presence of communication affects the formation of endogenous networks. Other research projects, jointly with graduate student Ali ParandehGheibi, study the spread of misinformation in societies and show what features of social networks make them "robust" to misinformation and biases. This research effort is supported by an NSF grant in human and social dynamics, an AFOSR project, and an AFOSR Multidisciplinary University Research Initiative (jointly with Georgia Tech and University of Maryland).

Other recent research, in collaboration with professor Pablo Parrilo, graduate student Ozan Candogan, and Dr. Ishai Menache, focuses on potential games, which is a special class of finite games with desirable equilibrium and dynamic properties. The goal of this research is to provide a framework that can be used to identify "near-potential" games, which inherit the desirable properties of potential games.

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 (jointly in part with graduate students Kostas Bimpikis and Paul Njoroge, professor Daron Acemoglu from the MIT Department of Economics, and professors Nicolás Stier-Moses and Gabriel Weintraub from Columbia University). A core objective of this work is to quantify and mitigate the losses that result from lack of centralized regulation and provide insights into the important net-neutrality policy debates for the Internet. This research is supported by an NSF career grant.

Her group also works on developing novel decentralized optimization algorithms for resource allocation problems that emerge in communication and sensor networks.

In collaboration with graduate student Ilan Lobel, professor Angelia Nedic from the University of Illinois at Urbana–Champaign (UIUC), professor John Tsitsiklis, and graduate student Alex Olshevsky, this work has developed algorithms that can optimize general performance metrics and operate over dynamic networks with time-varying connectivity and imperfect information. Another recent project, jointly with professor Muriel Médard and graduate student Ali ParandehGheibi, develops iterative gradient projection algorithms that use approximate projections for resource allocation over fading multiple access channels. This research is supported by the DARPA ITMANET program (jointly with Stanford University, California Institute of Technology (Caltech), and UIUC).

Professor Pablo Parrilo

Professor Pablo Parrilo's research group is focused on optimization, systems, and control, with current 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 Utku Ozan Candogan as well as LIDS postdoc Ishai Menache, Professor Parrilo is developing a structural approach to normal form games that allows for the decomposition of a given game into its "potential" and "harmonic" components. The methods are based on the classic Helmholtz–Hodge theory for differential forms and constitute a far-reaching generalization of the well-known potential games that enables the analysis of many static and dynamic properties of games (e.g., equilibria and convergence of fictitious play mechanisms).

In recent joint work with professor Dimitris Bertsimas and their joint student Dan Iancu, Professor Parrilo has shown the optimality of a certain class of disturbance-affine control policies in the context of one-dimensional, constrained, multistage robust optimization. The results cover the finite horizon case, with minimax (worst-case) objective, and convex state costs plus linear control costs and are applicable in inventory-control problems. The results are of interest because they justify mathematically, for the first time, the experimental practical performance of disturbance-affine policies.

Another research direction is the robustness and stability analysis of continuous and hybrid systems. In joint work with LIDS student Amir Ali Ahmadi, a methodology for relaxing the monotonicity requirement of Lyapunov's theorem has been developed. This method significantly enlarges the class of functions that can provide certificates of stability. Both the discrete time case and the continuous time case are covered. A conference paper describing this research was a finalist for the best student paper award at the 2008 IEEE Conference on Decision and Control.

Professor Parrilo is investing further extensions of the "compressed sensing" techniques that deal with low-rank assumptions as opposed to sparsity. In earlier work in collaboration with colleagues from the University of Washington and Caltech, he has shown that the "nuclear norm" optimization heuristic provably recovers the minimum-rank matrix in a given affine subspace, provided a certain restricted isometry property holds. A recent collaboration with Venkat Chandrasekaran (LIDS student), Sujay Sanghavi (former LIDS postdoc, currently faculty at Purdue University), and professor Alan Willsky has extended these techniques to the problem of decomposing a given matrix into a sparse and a low-rank component, an important problem with many applications in areas such as graphic models and computational complexity.

A new research direction in Professor Parrilo's group (in collaboration with H. Meng, N-C. Nguyen, J. Peraire, and R. Freund, all MIT-affiliated) is concerned with optimal design of photonic crystal band structures. This is a problem with many important technological applications and consists of designing a periodic structure with favorable properties for control and manipulation of light propagation. This problem can be posed as an infinite dimensional nonconvex optimization problem but can be reduced to a more tractable formulation with subspace restrictions and notions from semidefinite programming. The numerical results are very encouraging, with the resulting optimized structures exhibiting patterns that go far beyond typical physical intuition on periodic media design.

Professor Devavrat Shah

Professor Devavrat Shah and his research group (http://web.mit.edu/isng/) are involved in designing practical algorithmic solutions with theoretical understanding for problems arising in large networks and large-scale statistical inference. This interdisciplinary research builds on advances in applied probability, stochastic networks, information theory, artificial intelligence, and algorithms. The primary application areas for this research are communication networks such as Internet routers, peer-to-peer networks like BiTTorrent, and wireless ad hoc or sensor networks and large-scale statistical problems such as those arising in revenue management, performance evaluation of complex engineering systems like storage devices, and automated solutions for secure, fault-tolerant system design.

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 toward addressing this impending challenge of developing a methodologic framework for designing high-performance implementable algorithms. To provide performance guarantees for such algorithmic solutions, they have developed parsimonious performance analysis methods. The algorithmic solutions have been developed along with students Jinwoo Shin and Shreevatsa Rajagopalan. These solutions lead to a novel "message-passing" algorithmic architecture to realize a dream of network engineers: totally distributed asynchronous network architecture that utilizes the system resources to the fullest extent possible. The key enabling features for designing such an algorithmic architecture are based on recently emerging revolutionary ideas at the interface of statistical physics and artificial intelligence. On the other hand, to provide performance guarantees, Shah and his collaborator Dr. Damon Wischik (at University College London) have developed novel analytic methods based on asymptotic probabilistic theory (also known as stochastic networks). This method is parsimonious, applies to complex networks, and provides useful design guidelines to enable a good algorithmic solution. In the past year, Professor Shah and Professor Tsitsiklis along with their student Yuan Zhong are leading an effort to further develop a methodology for stochastic network analysis for the models of emerging networks—for example, a data center.

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

Algorithms for Statistical Inference

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

The first project concerns fundamental understanding of efficient, message-passing algorithms popularly known as the belief propagation. Shah and collaborators (Sujay Sanghavi, former postdoc, now a professor at University of Texas at Austin; professor David Gamarnik and Professor Willsky at MIT) have found a surprising result that such algorithms solve (a large class of) linear program problems.

The second project concerns a fast statistical algorithm for evaluating the performance of complex circuits. Shah and collaborators (Lara Dolecek, postdoc and soon to be professor at the University of California, Los Angeles; Professor Anantha Chandrakasan at MIT) have designed algorithms that allow for automated evaluation in less than a few minutes compared with what was a few months.

The third project concerns algorithms to process partial information about rankings to obtain global information on rankings—for example, polled information in an election scenario, learning customer preference for revenue maximization, and team ranking a given outcome in league matches.

These research efforts are supported by an NSF Emerging Models for Technology grant and an NSF Social Networks grant.

Network Information Theory

In collaboration with professor Gregory Wornell, Professor Shah and student Urs Niesen have been leading the effort to understand the problem “how to operate wireless networks efficiently.” In a nutshell, this question is the holy grail of information and communication theory. These ambitious research efforts have 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. This research effort is supported through an ITMANET DARPA program and an AFOSR grant.

Professor John Tsitsiklis

Professor John Tsitsiklis works 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.

Most of the current research of Professor Tsitsiklis deals with decision making, control, and inference in distributed systems, networked agents, and sensor networks, some of it in collaboration with professors Gamarnik, Ozdaglar, Shah, and Win as well as a number of collaborators outside MIT. Current research includes a theoretical analysis of fundamental coordination problems in multiagent systems, such as consensus and averaging, and an analysis of related models of opinion dynamics and consensus that arise in the context of social networks. Another direction involves the development of a mathematical theory for the effects of different architectures (e.g., different kinds of trees) on the detection performance of large-scale sensor networks.

Two new directions of research involve questions about the stability and performance efficiency of communication networks (in collaboration with Professor Shah) and the development of new formulations and techniques in online learning and adaptive resource allocation, resulting in a major extension of the classic theory on multiarmed bandit problems.

Professor Alan S. Willsky

Professor Alan Willsky leads the Stochastic Systems Group (SSG). The general focus is 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, the Army Research Office, MIT Lincoln Laboratory, and the Royal Dutch Shell Group. During the past year Professor Willsky spearheaded a major initiative with Shell oil company, leading to substantial funding for the next three to five years. While most of this funding will be used to support research in LIDS, this program also involves significant collaboration with other units, including the Department of Brain and Cognitive Sciences.

A major thrust of research in SSG continues to be the extension and exploitation of our growing methodology for statistical inference, information fusion, and estimation for problems involving complex graphic models, such as those that arise in military command and control, mapping from remote-sensing data, and monitoring complex systems. SSG’s work involves examining complex graphic representations and developing tractable algorithms based on these representations. This research continues to yield significant advances, including new classes of signal and image-processing algorithms that have provable performance properties, that can be applied to very large problems in a scalable manner, and that outperform previous methods. Recent applications of these methods are to computer vision, mapping of subterranean surfaces in support of oil exploration, and tracking of multiple vehicles from networks of small sensors. Among the most recent advances in this area are new classes of models that represent complex phenomena at multiple resolutions or granularities. These models show great promise for modeling geophysical phenomena that exhibit behavior at a multitude of scales; stock indices, such as the S&P in which our models provide enhancements to the well-established organization of stocks into groups and industries; and computer vision in which the different granularities of representation range from low-level image features to objects (e.g., computer monitors or keyboards) to higher-level characterizations (e.g., workstations). A number of the methods that have been developed are being or already have been transitioned to research and engineering organizations including Shell, Lincoln Laboratory, and BAE Systems. This part of SSG's research portfolio has received considerable international attention, as evidenced by a string of best paper awards as well as extensive citations and influence on the work of others in fields ranging from systems and control to chemical engineering to groundwater hydrology.

SSG's work continues to focus on developing statistically based curve evolution algorithms for segmentation of imagery and extraction of the geometry of regions of interest from complex multimodal data. Recent accomplishments include machine-learning methods that perform segmentation while learning the statistical differences between the regions being segmented, tracking dynamically evolving curves, and capturing the inherent uncertainty in extracted geometry through curve-based Monte Carlo simulation methods. Most recently, and in collaboration with researchers at Shell and Brigham and Women's Hospital, SSG's work focused on developing algorithms that can take user-supplied guidance (e.g., in the form of partial segmentations of slices through three-dimensional data sets) as well as noninvasive indirect measurements (e.g., gravity anomaly measurements in geophysics or CAT scan data in medical imaging) and use them to guide high-performance three-dimensional shape extraction algorithms. Research in this area received considerable recognition, including a recent best paper award.

An increasingly important component of research in SSG is in the area of machine learning, in particular the extraction of statistical models, usually in graphic form, of complex phenomena. One part of this research, which deals with the direct learning of graphic models from data, has led to new methods for learning models for multiple types of behavior, with an eye toward using these models to discriminate among these modes of behavior when presented with new data. A second aspect of this work deals with the learning of "hidden" explanations of the complex behavior of observed data—that is, the learning of coarser descriptions of complex phenomena that explain much of the complexity of the observed data and hence simplify the modeling of the remaining behavior not captured by these hidden causes. Both of these projects have led to significant theoretical advances as well as to new algorithms for applications in fields ranging from computer vision to modeling complex geophysical phenomena. In addition, a major new thrust of work in SSG is in the development of so-called nonparametric methods for the extraction of behavioral models for dynamically evolving phenomena. This research has led to significant advances, developed in collaboration with colleagues at the University of California, Berkeley, and led at MIT by Professor Willsky and especially his student Emily Fox. One method developed in this work was applied successfully to analyzing so-called "dances" of honeybees (in which the motion of bees has been characterized as having several distinct components) and stock market data (in which our methods automatically detect changes in volatility models that match well with detailed analysis by economists). This work has received considerable publicity, including being highlighted in *Tech Talk* and on the MIT home page and in a long article written about our work in the Armed Forces Communication and Electronics Association magazine *Signal.*

Professor Moe Win

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

The group has been working intensively on location-aware networks in GPS-denied environments, which provide highly accurate and robust positioning capabilities for military and commercial aerospace networks. They have developed a foundation for designing and analyzing large-scale location-aware networks from the perspective of theory, algorithms, and experimentation. This work includes deriving performance bounds for cooperative localization, developing a geometric interpretation for these bounds, and designing practical, near-optimal cooperative localization algorithms. They are 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 developing a state-of-the-art apparatus that enables automated channel measurements. The apparatus makes use of a vector network analyzer and two vertically polarized, omnidirectional 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 facilitate the efficient and accurate experimental validation of proposed theories and enable the development of realistic wideband channel models. Work is under way 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 they have developed introduces the notion of a secure communications graph (s-graph), which captures the information theoretically secure links that can be established in a wireless network. They have characterized the s-graph in terms of local and global connectivity as well as the secrecy capacity of connections. They also proposed various strategies for improving secure connectivity, such as eavesdropper neutralization and sectorized transmission. Lastly, they analyzed the capability for secure communication in the presence of colluding eavesdroppers.

Professor Win and a team of undergraduate and graduate students competed in the Institute for Soldier Nanotechnologies Soldier Design Competition. In this contest, they demonstrated the first cooperative location-aware network for GPS-denied environments, using ultra-wideband technology, leading to the team winning the L3 Communications Prize. They are 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, 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 Universities of Bologna and Ferrara in Italy, University of Lund in Sweden, University of Oulu in Finland, National University of Singapore, Nanyang Technological University in Singapore, Draper Laboratory, the Jet Propulsion Laboratory, and Mitsubishi Electric Research Laboratories.

Highlights, Awards, and Events

The 2008–2009 year has been one of continuing accomplishment, activity, and intellectual excitement. LIDS hosted many events, including a significantly enhanced Colloquium Series and the Fourteenth Annual LIDS Student Conference. A fourth edition of LIDS's community-oriented magazine—*LIDS-ALL*—was produced, and the fifth edition is being readied for the start of academic year 2009–2010. LIDS also took major steps in acting on the strategic plan put together during the preceding year. These steps include readying an enhanced website to be launched by the end of summer 2009; engaging in outreach to other units across MIT, including CSAIL and the Operations Research Center; extending LIDS's leadership position and profile across the international community; and using these activities to enhance the sense of collective and inclusive community within LIDS.

During this year we established and had the first visit of a LIDS Advisory Committee, composed of four distinguished and world-recognized intellectual leaders:

- Dr. Henrique Malvar, Microsoft distinguished engineer and managing director of microsoft tesearch in Redmond, WA.
- Professor Manfred Morari, head of the automatic control laboratory and head of the Department of Information Technology and Electrical Engineering, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland.
- Professor H. Vincent Poor, Michael Henry Strater university professor of electrical engineering and dean of the School of Engineering and Applied Science, Princeton University.
- Professor Pravin Varaiya, Nortel Networks distinguished professor and professor in the graduate school, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley.

The committee visited LIDS in May 2009, a visit that included meetings with faculty, students, and postdocs as well as presentations by faculty and a student poster session, activities that added significantly to the sense of community within LIDS and that led to a very positive and constructive informal report on LIDS and its prospects.

In addition, LIDS is in the process of organizing and hosting a major international meeting, "Paths Ahead in the Science of Information and Decision Systems," to be held at MIT in November 2009. We have already confirmed sponsorship from a number of government agencies (NSF, Army Research Office, AFOSR) as well as from a number of industrial and research laboratories, and our invitations for participation have been accepted by recognized research leaders from major institutions across the United States and Europe. It promises to be a very important event.

Finally, LIDS students and faculty members have garnered recognition for their work during this year:

Amir Ali Ahmadi was one of four finalists in the best student paper award competition at the 2008 IEEE Conference in Decision and Control.

Professor Müjdat Çetin, a LIDS visiting research scientist and faculty member at Sabanci University, Istanbul, Turkey, received the 2008 Turkish Academy of Sciences Young Scientist Award.

Professor David Forney, together with coauthor Daniel Costello, has been awarded the 2009 IEEE Donald G. Fink Prize Paper Award for their paper "Channel Coding: The Road to Channel Capacity," which appeared in *Proceedings of the IEEE* in June 2007. Professor Forney is the only two-time recipient of this award.

Emily Fox's research, under the supervision of professor Alan Willsky, on nonparametric methods in discovering patterns of behavior in dynamic phenomena, has received considerable publicity, including being highlighted in *Tech Talk*, on MIT's home page, in an extensive article reporting on her work in the June 2009 issue of the Armed Forces Communications and Electronics Association magazine *SIGNAL*, and in a feature on Emily in the April 29–May 12, 2009 issue of *The Improper Bostonian.*

Professor Frazzoli presented work at the 2009 German-American Frontiers of Engineering meeting, organized by the National Academy of Engineering.

Professor Frazzoli presented work at the NSF Cyber-Physical Systems Research Expo at the US Senate, Capitol Hill, 2009.

The Guillemin Electrical Engineering SM first place prize was given to Srikanth Jagabathula for "Scheduling Algorithms for Arbitrary Commmunication Networks," which was supervised by Devavrat Shah.

Srikanth Jagabathula received the Best Student Paper Award at NIPS 2008 for the paper "Inferring Rankings Under Constrained Sensing," coauthored with Devavrat Shah.

Junmo Kim, Mujdat Cetin, and Alan S. Willsky received the Elsevier Signal Processing Journal Best Paper Award, presented at the EUSIPCO2008 16th European Signal Processing Conference in Lausanne, Switzerland, in August 2008, for their paper titled "Nonparametric Shape Priors for Active Contour-Based Image Segmentation."

Shreevatsa Rajagopalan and Jin Woo Shin received the Outstanding Student Paper Award at the ACM Signmetrics/Performance Conference for their paper coauthored with Devavrat Shah.

Professor Tsitsiklis received the IEEE/ACM (MIT chapter) best advisor award (2009). He received the doctor honoris causa from Université Catholique de Louvain, Belgium, October 2008, and gave a plenary talk at the 2009 Information Theory Workshop on Networking and Information Theory, Volos, Greece, June 2009. He also gave a plenary talk at the ICST Valuetools Conference, Athens, Greece, October 2008.

Kush Varshney was recognized for an outstanding student paper, "Learning Dimensionality-Reduced Classifiers for Information Fusion," coauthored with professor Alan Willsky, to be presented at the 12th International Conference on Information Fusion held in Seattle, WA, July 2009.

Professor Moe Win received the L3 Communications Prize from the Institute for Soldier Nanotechnologies (ISN) Soldier Design Competition, the first practical demonstration of cooperative ultra-wideband location-aware networks for GPS-denied environments by a team of undergraduate and graduate students, 2009. Professor Win also received the Technical Recognition Award of the IEEE ComSoc Radio Communications Committee "for exceptional technical contributions to radio communications," 2008. He received the Guglielmo Marconi Best Paper Award of the IEEE Communications Society "for an original paper in the field of Wireless Communications published in the *IEEE Transactions on Wireless Communications*," 2008, and the Laurea Honoris Causa, Dottore "Ad Honorem" in Ingegneria e Tecnologie per le Telecomunicazioni e l'Elettronica, awarded by the Università degli Studi di Ferrara, with the approval of the Ministro dell'Università e della Ricerca, Italy, 2008. He was an IEEE Distinguished Lecturer, selected by the IEEE Communications Society, 2008 to present; he received the IEEE ICC'08 Best Paper Award, IEEE International Conference on Communications, 2008; and he received the IEEE VTC'08 Best Paper Award, IEEE 67th Vehicular Technology Conference, 2008.

Future Outlook

During the past year, LIDS began its ambitious plan for realizing its mission and for implementing its plans, as articulated in the course of its strategic planning process in spring 2008 and reinforced by the LIDS Advisory committed, which convened in April 2009. These efforts resulted in an even greater sense of purpose and an increasingly energized and enthusiastic community of students, staff, and faculty. LIDS has been and remains an internationally recognized home for cutting-edge and seminal fundamental research and for the education of research and engineering leaders of the future. We have embarked on an ambitious set of activities aimed not only at sustaining this position but also at enhancing it considerably. Our efforts involve the new research initiatives outlined previously that represent major challenges for the future in our increasingly information- and distributed system-dominated world as well as partnerships with other groups at MIT, in industry, and at other leading institutions. We are also engaged in activities aimed at increasing LIDS's profile within MIT and across the broader community, including sponsoring workshops, extending invitations to world leaders to spend time with us and deliver high-profile colloquia, and conducting outreach activities to some of our most ardent supporters—namely, those who were students in LIDS in the past and were enriched by their time with us. LIDS is an exceptional cadre of leaders and accomplished researchers and engineers, many of whom have expressed their strong and positive feelings about what LIDS has meant to them, and we are intent on building on this sentiment and extending the LIDS community to once again include them as well.

A major event has been planned for November 2009, a symposium on the "Paths Ahead in the Science of Information and Decision Systems." There will be more than 20 invited participants who represent a unique collection of eminent, internationally recognized leaders in the field. The response to this symposium has been overwhelmingly positive and offers the promise of a landmark event in the field. Through presentations and panel discussions, to be followed by position papers, the event is aimed at defining and articulating the key challenges in the fields covered by LIDS and signaling to the community at large that LIDS, newly energized, will continue to play its role as a leading entity, setting the direction for the field.

As the 2008–2009 academic year closes, LIDS stands out as a singular organization for innovation and true impact in the information and decision sciences. Our people are energized by an environment that allows them to develop and pursue research and educational activities of great substance, and our intentions are to make things better and more exciting in the future.

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

Munther A. Dahleh
Co-Associate Director
Professor of Electrical Engineering and Computer Science

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Co-Associate Director
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More information about the Laboratory for Information and Decision Systems can be found at http://lids.mit.edu/.