Laboratory for Information and Decision Systems

The Laboratory for Information and Decision Systems (LIDS) is an interdepartmental laboratory for research and education in systems, communication, networks, optimization, control, and statistical signal processing. While maintaining roots in fundamental research related to information science, lab members have initiated work on system architectures and joined with computer scientists and hardware engineers to broaden perspectives in the research, design, prototyping, and tests of systems such as networks and unmanned air vehicles. LIDS draws its staff principally from the Department of Electrical Engineering and Computer Science, as well as the Department of Aeronautics and Astronautics, the Department of Mechanical Engineering, and the Sloan School of Management. Every year, scientists across the globe visit the Laboratory to participate in its research programs. Undergraduate students also participate in research and thesis activities through the Undergraduate Research Opportunities Program.

Highlights, Awards, and Events

The 2005–2006 year has been an exciting and successful one for LIDS. The lab hosted many events, notably weekly colloquia and the 11th annual LIDS Student Conference. A second edition of LIDS' community-oriented magazine, *LIDS-all*, was launched in May. New faculty members have joined the lab and new research directions continue to develop. An increasingly interdisciplinary focus and diverse international partnerships, both academic and industrial, strengthen our vibrant research community.

Several LIDS students and faculty members have garnered recognition for their work this year.

David B. Brown received second place in the 2005 INFORMS George Nicholson Student Paper Competition for his paper "Robust Linear Optimization and Coherent Risk Measures."

Lei Chen, a graduate student in the Stochastic Systems Group, received the Best Student Paper Award at the 8th International Conference on Information Fusion.

Professor Munther Dahleh and LIDS alumnus Nuno Martins (assistant professor at the University of Maryland) are winners of the 2006 American Automatic Control Council's O. Hugo Schuck Award for Theory for the paper entitled "Fundamental Limitations of Performance in the Presence of Finite Capacity Feedback."

Wesley M. Gifford, Watcharapan Suwansantisuk, and Professor Moe Win received a Best Paper Award from the IEEE International Conference on Next-Generation Wireless Systems (ICNEWS'06) for the paper "Rake Subset Diversity in the Presence of Non-Ideal Channel Estimation."

Professors Asuman Ozdaglar and Devavrat Shah received the prestigious National Science Foundation CAREER awards for faculty early career development.

Professor Pablo Parrilo was awarded the SIAM Activity Group/Control and Systems Theory (SIAG/CST) prize at the annual Society for Industrial and Applied Mathematics in July 2005. The prize, given every three years, is awarded to a young researcher for outstanding research contributions to mathematical control or systems theory.

Professor Devavrat Shah was awarded the 2005 Institute of Operations Research and the Management Sciences (INFORMS) George B. Dantzig Award for best dissertation.

Professor Alan Willsky received a Doctorat Honoris Causa from Université de Rennes I as part of the 25th anniversary celebration of the founding of the French laboratory IRISA, which included a two-day workshop in honor of Professor Willsky and his corecipient.

Professor Moe Win is co-recipient of the 2006 IEEE Communications Society Eric E. Sumner Award for distinguished contributions to ultra-wideband radios, along with Professor Robert Scholtz of the University of Southern California.

Research

Research at LIDS falls into four main areas that share common intellectual bases: communication and networks, statistical signal processing, optimization, and control and system theory. The Laboratory explicitly recognizes the interdependence of these fields and the fundamental role that mathematics, physics, computers, and computation play in the research. Below we summarize the major current research our faculty is conducting.

Communication and Networks

Professor Vincent Chan

Professor Chan, under National Science Foundation (NSF), National Reconnaissance Office, and Defense Advanced Research Projects Agency support, is working on new optical transport mechanisms to radically change the cost structure of high-speed networks. His team is actively working on several projects, including new all-optical transport mechanisms with significant cost savings, new diagnostic techniques that rapidly locate all optical network failures, transmission of analog microwave signals over optical networks to enhance the performance of microwave sensing, and communication systems and their applications to space systems. They also study proactive mobile networks where node mobility is predicted and managed, which will lead to much improved performance over ad hoc wireless networks for mobile networks without planned infrastructures.

Professor Chan's group has completed a study to reach a baseline understanding of current traditional space-qualified processors and commercial processors. A new space information network architecture that has been created will allow revolutionary space system architectures that will significantly enhanced space system performance. They are also working on resource allocation schemes for satellite channels.

Professor G. David Forney

Professor Forney is conducting research in the areas of syndrome realizations of linear codes and systems, constraint complexity of cycle-free graph realizations of linear codes, and the role of minimum mean square error estimation in approaching the information-theoretic limits of linear Gaussian channels. He has developed new classes of convolutional and tail-biting quantum error-correcting codes, which have higher rates and simpler decoding algorithms than comparable block codes.

Professor Robert Gallager

Professor Gallager continues to work on research with Professor Lizhong Zheng on noise accumulation over successive transmissions and is about to finish his book on introductory communications theory.

Professor Muriel Médard

Professor Médard's group works extensively on network coding in collaboration with the Computer Science and Artificial Intelligence Laboratory (CSAIL), Caltech, the University of California at Los Angeles (UCLA), and the University of Illinois Urbana-Champaign. Network coding provides cost benefits in a variety of settings—for instance, wireless networks, where the cost may be measured in expended energy, or wireline networks, where they reduce congestion. In the area of network coding for wireless networks, she and Professor Ozdaglar have recently obtained a contract with DARPA through BAE Systems National Security Solution, Inc. to apply network coding to mobile ad hoc networks. For distributed, robust algorithms for network coding, Professor Médard is principal investigator of a DARPA program in advanced topics on network coding. In the area of network coding security, she is principal investigator of an Air Force Office of Scientific Research (AFOSR) program with Caltech and the University of Illinois Urbana-Champaign for the application of network coding to protect data under eavesdropping and Byzantine attacks. She also investigates fundamental coding issues in network coding through a NSF Information Technology Research (ITR) project.

Professor Médard conducts research in wireless fading channels as well. With Professor Zheng, she has investigated the use of feedback and multiinput multioutput schemes in ultra-wideband systems as part of an NSF ITR program. In collaboration with the University of Illinois Urbana-Champaign, she has investigated the antijamming resilience of ultra-wideband channels. Lastly, in collaboration with Professor Chan, she conducts research in the area of optical network capacity and optical access networks through a NSF ITR contract.

Professor Eytan Modiano

Professor Modiano works on novel architecture and protocols for heterogeneous networks consisting of satellite, wireless, and optical components. In the area of space networks, his group works to significantly increase the data transmission capacity of hybrid space-terrestrial networks through the use of efficient resource allocation and protocol designs. Along with the Jet Propulsion Laboratory, his group created energy-efficient transmission scheduling schemes for maximizing data throughput over time-varying channels. Using channel measurements for the communication link between the Mars Lander and the Mars Odyssey orbiter, they demonstrated a 10-fold increase in average throughput and a similar decrease in energy consumption. In the area of optical networks, he works to provide optical bypass to the electronic layer of the network using wavelength division multiplexing (WDM) technology. His group has developed algorithms for joint internet protocol (IP) layer routing and WDM logical topology reconfiguration in IP-over-WDM networks with stochastic traffic. The algorithms maximize network throughput by reducing the traffic load on electronic switches and routers in the network.

Professor Modiano continues to work with researchers from the University of Illinois, UCLA, and Stanford University, on projects funded by NSF and a multidisciplinary university research initiative (MURI) from AFOSR to develop efficient resource management schemes, as well as network control schemes, for wireless networks of autonomous air and ground vehicles. The team is studying the interplay between competing requirements for communication, computation, and mobility. His team is working toward a theory for optimally controlling such networks, which includes optimizing performance metrics such as throughput, delay, and fairness and developing centralized and distributed algorithms for this optimization. Their approach takes a holistic view of the network by optimizing performance across multiple layers of the protocol stack, considering both physical layer functionalities such as power and data rate adaptation and higher layer functionalities such as routing and flow control.

Professor Devavrat Shah

The main focus of Professor Shah's work has been the design of implementable algorithms that have provable performance guarantees for large networks, such as the Internet. Specifically, he has been working on designing algorithms for scheduling in IP switches, dynamic routing in the Internet, and bandwidth allocation in ad hoc wireless networks to overcome interference. His work has led to the characterization of fundamental tradeoffs between performance metrics in wireless and wireline networks.

Recently, Professor Shah has been working on the application of algorithmic methods emerging at the interface of statistical physics and artificial intelligence. The application of such methods in the context of switch scheduling has led to a one-parameter class of scheduling algorithm that provides a continuous trade-off between performance and "implementability:" the currently implemented simple (but poor in performance) algorithm is at one extreme, while the performance optimal (but complex) algorithm is at the other extreme of the trade-off curve. Application of these methods in the context of networks is likely to provide a handle on performance and implementation for algorithms, which is usually an implementer's dream.

Professor Moe Win

Professor Win works on the application of mathematical and statistical theories to communication, detection, and estimation problems. Current research topics include inference problems in sensor networks, diversity with practical channel estimation, ultrawide bandwidth (UWB) communications, cooperative localization with wideband signaling, and space communications systems. His projects include measurement and modeling of time-varying channels, the development of an analytical framework for

UWB transmitted-reference systems, techniques for rapid acquisition of wideband signals, and distributed algorithms for sensor networks.

Professor Win and his group are also developing a state-of-the-art wideband wireless experimentation facility, which includes a Cartesian positioning experimental platform and a high-performance vector network analyzer used to systematically characterize wideband propagation channels. Finally, the group maintains dynamic collaborations with the University of Bologna in Italy and NTS and NTU in Singapore, among other research partnerships in academia and industry.

Professor Lizhong Zheng

Professor Zheng's research spans the area of wireless communications, information theory, and networks, with a focus on developing a fundamental theory of communications over dynamic and networked environments. Working on a NSF career project and an AFOSR research program, he developed novel techniques of asymptotic analysis and used them in the designs of new, layered coding structures. The goal of this research is to develop the theoretical foundation of coding for dynamic channels, which may provide the new generations of communication systems and networks with higher flexibility and adaptability. He also participates in the UWB NSF program led by Professor Win and comprising LIDS, Microsystems Technology Laboratories, Research Laboratory of Electronics (RLE), and CSAIL; he has made progress in the study of wideband communication over wireless fading channels. A novel approach was developed to understand the interactions among a number of system parameters, including the signal-to-noise ratio, the energy and spectral efficiency, constraints on the peak power for the signaling, and different channel modeling assumptions. He is also conducting research with Professor Gallager on noise accumulation over successive transmissions and has completed work on an NSF project about wireless/wireline interface with Professors Médard, Gregory Wornell (RLE), and Ozan Tonguz (Carnegie Mellon University).

Control and System Theory

Professor Robert Berwick

Professor Berwick is conducting work along with his colleagues, Professors Sanjoy Mitter, Munther Dahleh, and Steve Massaquoi, on the general question of how control systems might evolve over time to manage complex control problems. The hope is to understand principles common to self-optimizing control systems across multiple scales of time and space. Biology is used as the guiding example, with analysis of systems ranging from molecular biological control of metabolism to organ system interaction to ecological regulation.

Professor Munther Dahleh

Professor Dahleh has led a research effort focused on control of networked systems, with emphasis on the problem of coordination of mobile network of robots. 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. In collaboration with Professor Shah and student Holly Waisanen, he utilized scaling results to derive polynomial time algorithms that achieve near-optimal performance (in terms of average delay) for a class of vehicle routing problems with network constraints. With his student Sleiman Itani, he showed how to incorporate kinematics constraints into such vehicle routing problems and still achieve near-optimal performance. This work drew from various areas including control and information theory, stochastic processes and queuing theory, and geometric optimization techniques.

Professor Dahleh, in collaboration with Professor Alexandre Megretski and their students Danielle Tarraf and Georgios Kotsalis, has also led an effort to develop a robust control framework for systems with finite alphabets. This research comprised three components: (1) modeling of such systems in terms of finite-state machines interconnected with a hybrid system, (2) estimating coarse error bounds on the uncertainty and deriving computable certificates for stability and performance robustness, and (3) synthesis of controllers utilizing such certificates. A major part of this work focused on model reduction of discrete automata or hidden Markov models. This work has provided the first set of results of such reduction with computable guaranteed bounds on the error. Along with his student Michael Rinehart, Professor Dahleh also led a collaboration with Ford on the design of hybrid controllers for multiple-mode engines to devise the optimal switching strategy for minimizing fuel consumption.

Professor Alexandre Megretski

In a recent initiative, Professor Megretski began an investigation about applying the tools of robust control systems analysis to real-time software analysis, with a specific focus on run-time error. Professor Megretski is also leading an effort, along with Professor Dahleh, to derive a formal theory for modeling, analysis, and synthesis of pure discrete systems. This work is the first step toward the derivation of a complete formal theory for hybrid systems. He also pioneers work with his colleagues to develop a theory for model reduction of discrete systems represented by hidden Markov chains. Such systems arise frequently in enterprise models as well as hybrid systems.

Professor Pablo Parrilo

Professor Parrilo has developed, in collaboration with Professor Jean-Jacques Slotine and student Erin Aylward, techniques for analyzing uncertain nonlinear systems based on the computation of contraction metrics via sum-of-squares programming. The results naturally extend classic techniques such as Krasovskii's method and can be used to study the performance and robustness properties of nonlinear polynomial systems.

He has also led a research effort toward developing semidefinite-programming (SDP)-based computational methods for games with an infinite number of pure strategies. The initial results deal with a class of zero-sum semialgebraic games, for which the optimal strategies have been shown to be computable using SDP. In collaboration with Professor Ozdaglar and their joint student Noah Stein, he is currently extending these results to the case of correlated equilibria. Besides these efforts, there have been several other publications on topics related to polynomial-time approximation schemes for optimization and analysis of symmetric reversible Markov chains. Professor Parrilo's team is also in the last stages of a novel application of SDP to the design of quantum algorithms.

Statistical Signal Processing

Professor Sanjoy Mitter

Professor Mitter and his collaborator Nigel Newton (University of Essex, UK) investigate the information theoretic properties of Kalman-Bucy filters in continuous time, developing notions of information supply, storage, and dissipation. By introducing a concept of *energy*, they developed a physical analogy in which the unobservable signal describes a statistical mechanical system interacting with a heat bath. The abstract "universe" comprising the signal and the heat bath obeys a nonincrease law of entropy; however, with the introduction of partial observations, this law can be violated. The Kalman-Bucy filter behaves like a Maxwellian demon in this analogy, returning signal energy to the heat bath without causing entropy increase. This is made possible by the steady supply of new information. The analogy thus provides a quantitative example of Landauer's principle, operating in reverse. The filter sets up a stationary nonequilibrium state, in which energy flows around the loop comprising the heat bath, the signal, and the filter. A rate of interactive entropy production is defined, isolating the statistical mechanics of this flow from the marginal mechanics of the signal and filter. This leads naturally to a dual filtering problem in which information flows are reversed.

Along with Anant Sahai (UC Berkeley), Professor Mitter also reviews how Shannon's classic notion of capacity is not sufficient to characterize a noisy communication channel if the intention is to use that channel as a part of a feedback loop to stabilize an unstable scalar linear system. While classic capacity is not enough, a parametric sense of capacity called "anytime capacity" was shown to be both necessary and sufficient for the stabilization of an unstable process over that channel. The rate required is the log of the open-loop system gain, and the sense of reliability required comes from the desired sense of stability. This is sufficient even in cases with noisy observations and without any explicit feedback between the observer and the controller. In addition, the vector-state generalizations are established and the magnitudes of the unstable eigenvalues play an essential role. To deal with such systems, the concept of the anytime rate region is introduced, which is the region of rates the channel can support while still meeting potentially different anytime reliability targets for the parallel bitstreams. For cases in which there is no explicit feedback of the noisy channel outputs, the intrinsic delay of the control system tells what the feedback delay needs to be while evaluating the anytime-rate-region for the channel.

Professor Alan S. Willsky

Professor 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; Air Force Research Laboratory; Office of the Director, Research & Engineering (including two recently awarded MURIs); NSF; MIT Lincoln Laboratory; and the Royal Dutch Shell Corporation. SSG is investigating how to extend and exploit its methodology for problems involving complex graphic models, such as those that arise in military command and control, mapping from remote sensing data, or monitoring complex systems. SSG's work involves examining graphic structures more complex than trees—in particular, graphs with (typically many) loops. They continue to have major successes in this area, 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 (recognition of multiple objects in complex scenes and tracking of hand motion in image sequences), mapping of subterranean surfaces in support of oil exploration, and tracking of multiple vehicles from networks of small sensors.

SSG's work also continues to focus on the development of statistically based curve evolution algorithms. Recent accomplishments include methods that use training examples to build and use statistical models for shapes of interest, learning-based methods that perform segmentation while simultaneously learning the statistical differences between the regions being segmented, and tracking dynamically evolving curves. SSG has demonstrated that information-theoretic methods can provide robust solutions to such problems without the need for *any* training (in other words, fusion is performed "on-the-fly" as data are collected). Most recently and in collaboration with researchers at Shell Oil and Brigham and Women's Hospital, they have begun developing algorithms that can take user-supplied guidance (e.g., in the form of partial segmentations of slices through three-dimensional data sets) and use these to guide high-performance three-dimensional shape extraction algorithms.

Optimization

Professor 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 is writing a textbook on the subject, which involves new research on the fundamental structures that guarantee the existence of optimal solutions, while eliminating duality gaps. Recent effort has focused on separable large-scale convex optimization problems, known as monotropic programming problems, for which special duality results and algorithms are possible.

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, in the context of fully and partially observable Markov decision problems.

Professor Asuman Ozdaglar

Professor Ozdaglar's research interests lie at the interface of optimization theory and game theory. Motivated by the decentralized and multiagent structure of today's large-scale networks, such as the Internet, her group focuses on resource allocation problems among heterogeneous users in networked systems. The goal is to provide a systematic framework for understanding the interactions of economic and performance incentives of service providers and users and traffic engineering aspects of communication networks. This research requires both development of new theoretical tools in convex and nonconvex optimization and use of game theory and economic market mechanisms to model multiagent interactions.

Toward this goal, Professor Ozdaglar's group develops models for resource allocation problems in different types of networks (e.g., wireline/wireless communication networks, transportation networks, electricity markets). A core objective of this research, done in collaboration with faculty in the Economics Department, is to quantify and mitigate the losses that result from lack of centralized regulation. Using tools from convex and nonsmooth analysis, Professor Ozdaglar also studies fundamental problems in optimization theory including optimization duality, Lagrange multiplier theory, and existence/analysis of critical points of equilibrium problems. Applicability of this framework in networking applications also necessitates a study of both the processes by which the game-theoretic equilibria are reached by the agents and how equilibria can be computed for modeling purposes. Consequently, in collaboration with other faculty in LIDS, her group studies learning in dynamic games, including myopic learning rules that were considered for static games (for example, fictitious play) and computation of equilibrium in nonzero-sum games with potentially infinite strategy spaces.

Professor John Tsitsiklis

Professor 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.

On the methodological side, recent activity has focused on understanding distributed methods for multiagent coordination as well as coordinated information processing in distributed sensor networks. Another domain has been the study of simple, market-based mechanisms for resource allocation in various settings. Particular contexts of interest include allocating bandwidth to users in a communication network as well as allocating production levels in day-ahead markets for electric power generation. Different mechanisms are being evaluated in terms of the possible efficiency losses in the presence of strategic (gaming) behavior by market participants holding significant market power.

Future Outlook

As LIDS continues to evolve as a research laboratory at the cutting edge of its fields, committed to roots in fundamental research, our faculty play a major role in realizing our objectives. They spearhead the effort to train our students in the essentials, while increasing efforts to provide every graduate exposure to real-life engineering problems. They also help foster engineering creativity in our students, accomplished via a combination of activities such as partnerships, mentoring, and internships as well as exchanges with other top research institutions around the world. Recruitment of new faculty adds to the already impressive innovation and energy of longer-term members. As the 2005–2006 academic year draws to a close, we are well settled into our new home at the Stata Center and continue to host events, expand connections to industry, and recruit new members. LIDS remains a thriving, interdisciplinary community both within MIT and among other leading universities.

Vincent Chan was on sabbatical leave during the spring semester of 2006. Professor Robert Gallager was the acting director for the duration.

Vincent W. S. Chan, Director and Joan and Irwin M. Jacobs Professor of Electrical Engineering and Computer Science and Aeronautics and Astronautics
Muriel Médard, Associate Director and Edgerton Associate Professor of Electrical Engineering and Computer Science
Robert Gallager, Acting Director and Professor of Electrical Engineering

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