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 from the Departments of Aeronautics and Astronautics and 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 2006–2007 year has been an exciting and successful one for LIDS. The lab hosted many events—notably, weekly colloquia and the Twelfth Annual LIDS Student Conference. A third edition of LIDS's community-oriented magazine, LIDS All, was launched in May. Our most recent faculty member, Emilio Frazzoli, joined LIDS in summer 2007 and was appointed by the Department of Aeronautics and Astronautics. Many 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:

Chung Chan is co-recipient of the Cisco Graduate Fellowship in Electrical Engineering and Computer Science.

Professor David Forney received an honorary doctoral degree from EPFL (Swiss Federal Institute of Technology), Lausanne, Switzerland.

Dmitry Malioutov and Jason Johnson received a student paper award from ICASSP 2006 for the paper "Low-Rank Variance Estimation in Large-Scale GMRF Models."

Professor Sanjoy Mitter won the 2007 Richard E. Bellman Control Heritage Award for contributions to the unification of communication and control, nonlinear filtering, and its relationship to stochastic control; optimization; optimal control; and infinite-dimensional systems theory.

Professor Muriel Médard was awarded the Gilbreth Lectureship from the National Academy of Engineering.

Pedro Pinto won the "Best Student Paper Award" at the IEEE International Conference on Ultra-Wideband (ICUWB'06).

Mardavij Roozbehani was awarded the AIAA Graduate Award for his research on safety verification of real time software systems.

Professor Devavrat Shah won the ACM SIGMETRIC/Performance Best Paper Award for the paper titled "Maximizing Throughput in Wireless Network via Gossip."

Noah Stein, a LIDS student jointly supervised by Professors Asuman Ozdaglar and Pablo Parrilo, received the Ernst A. Guillemin Thesis Award for best master's thesis in electrical engineering.

Professor John Tsitsiklis was elected to the National Academy of Engineering. He was recognized for his "contributions to the theory and application of optimization in dynamic and distributed systems."

Lav Varshney won the Ernst A. Guillemin Thesis Award for Outstanding Electrical Engineering SM Thesis and the Capocelli Prize at the 2006 Data Compression Conference.

Professor Moe Win is a recipient of the Wireless Educator of the Year Award, presented by the Global Wireless Education Consortium.

Henk Wymeersch won the 2006 Alcatel Bell Scientific Award for "an original study of Information & Communication Technology, Concepts, and Multimedia Applications."

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) and Defense Advanced Research Projects Agency (DARPA) support, with Professors Médard, Ozdaglar, and Shah, is working on new optical transport mechanisms to radically change the responsiveness and cost structure of high-speed networks. His team is actively working on several projects, including new all-optical transport mechanisms with extreme agility, new diagnostic techniques that rapidly locate all optical network failures. A new project on free space optical communication over the turbulent atmospheric channel has started to investigate fading mitigation techniques. They also studied 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 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 has completed a textbook, entitled *Principles of Digital Communication*, which is based on the graduate subject 6.450. He is also continuing research on wireless communication, feedback communication, and data networks.

Professor Muriel Médard

Professor Médard's group works extensively on network coding, in collaboration with the Computer Science and Artificial Intelligence Laboratory (CSAIL), Caltech, UCLA, the University of Illinois Urbana-Champaign (UIUC), Stanford, and the Technical University of Munich (TUM). 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, Professors Médard, Dina Katabi, and Ozdaglar recently obtained a contract with DARPA through BAE 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 a DARPA program and of an Air Force Office of Scientific Research (AFOSR) program with Caltech and UIUC for the application of network coding to protect data under eavesdropping and Byzantine attacks. She investigates the general applicability of network coding to wireless systems through a NSF contract with Professor Katabi.

In the area of information theory, Professor Médard has obtained, with Professors Ozdaglar, Shah, and Lizhong Zheng, a DARPA contract for the study of information theory for mobile ad hoc networks (ITMANET) with UIUC, TUM, Stanford, and Caltech. She also investigates fundamental coding issues in network coding through an 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 multi-input multi-output schemes in ultra-wideband systems as part of an NSF ITR program. In collaboration with UIUC, 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 an NSF Future Internet Design (FIND) contract.

Professor Devavrat Shah

Professor Shah is involved in interdisciplinary research at the interface of statistical inference, statistical physics, and information theory with networks as the primary application area. An important aspect of the research effort has been development of theory for practical networks such as Internet routers, peer-to-peer networks like BiTTorrent, and wireless sensor networks.

Algorithms are the essential building blocks of any large 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 a tunable network architecture to reach the right trade-off between implementation cost and performance. Professor Shah has proposed a novel message-passing-based algorithmic architecture to realize this dream of a network engineer. 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 (AI). A distinctive feature of Professor Shah's research has been, in addition to providing practical algorithmic network architecture, in providing theoretical guarantees for the high performance of such algorithms.

Professor Shah's research efforts have not only applied ideas from statistical physics and AI to networks but also brought new insights to these communities. Specifically, his work has brought precise understanding of these novel message-passing algorithms, which remained mysterious for more than a decade, using methods of applied probability, optimization, and combinatorics. This research is primarily supported by an NSF CAREER grant.

Through the ITMANET DARPA program, Professor Shah has been leading the effort in understanding the question "what makes it hard to operate wireless networks very efficiently?" Under an NSF FIND program (principal investigator Vincent Chan), Professor Shah has been looking at a new hierarchical architecture that can seamlessly merge a moderate bandwidth electronic network with a very high bandwidth optical network.

During the past year, Professor Shah has been collaborating with Professors Munther Dahleh, Médard, Tsitsiklis, Alan Willsky, and Gregory Wornell at MIT as well as with researchers at Microsoft research, IBM research, Bell-Alcatel labs, Stanford University, and University College of London.

Professor Moe Win

Professor Win and his graduate students (http://wgroup.lids.mit.edu/) are working on applying mathematical and statistical theories to communication, detection, and estimation problems. Their research focuses on various systems and networks and combines theoretical analysis for determination of fundamental performance limits; the design of practical algorithms that approach such ultimate limits; and experimentation, both for validation and for developing realistic statistical models.

Current research topics include inference in sensor networks, synchronization and interference analysis for ultra-wide bandwidth (UWB) communications, diversity with practical channel estimation, cooperative localization, channel identification, aggregate network interference, and signal processing for space and optical communication systems. Professor Win is also completing a state-of-the-art wideband wireless experimentation facility that enables automated channel measurements with an accuracy and scale far beyond existing systems, allowing him to systematically characterize wideband propagation channels and to develop tractable channel models.

Professor Win maintains dynamic collaborations and partnerships with academia and industry, including the University of Bologna and Ferrara in Italy, National University of Singapore, Nanyang Technological University in Singapore, and NTT DoCoMo USA Laboratories.

Professor Lizhong Zheng

Professor Zheng's research spans the areas of wireless communications, information theory, and networks, with a focus on developing a fundamental theory of communications over dynamic and networked environments. Working on an NSF CAREER project and an AFOSR research program, he developed novel techniques of asymptotic analysis and used them in 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 and has made progress in studying wideband communication over wireless fading channels. He developed a novel approach 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 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 on wireless/wireline interface with Professors Médard, Wornell (RLE), and Ozan Tonguz (Carnegie Mellon University).

Control and System Theory

Professor Robert Berwick

Professor Berwick completed an extensive theoretical and empirical analysis of all current models for inducing large-scale grammars from large amounts (>30 MB) of text. He carried out the first cross-validation study on these methods, which uncovered several important gaps in the way these systems operate, particularly for practical natural language-processing systems. These weaknesses previously escaped attention despite the work of many dozens of researchers in this area. By repairing them, we should be able to significantly improve human-computer natural language systems.

Professor Berwick also completed the first large-scale evolutionary computational analysis of the avian flu ("bird flu") virus found in Southeast Asia, determining the key points in the virus that would need to mutate for it to become more virulent in humans. This work is critical to understanding how a new influenza pandemic might develop, as well as developing targeted drugs to combat it.

Professor Munther Dahleh

Professor Dahleh has led a research effort focused on control of networked systems, with emphasis on the problem of coordination of a 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 cancellation). In collaboration with Professor Shah and student Holly Waisanen-Hatipoglu, he used 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 Alex 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 of 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 deriving 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'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, Noah Stein, Professor Parrilo has developed a novel characterization of Nash and correlated equilibria for multiplayer games, where the payoff functions are a polynomial function of the players' pure strategies. The methods, and resulting computational techniques, generalize a number of earlier works on low-rank games. Related work in collaboration with another student, Parikshit Shah, has yielded an innovative technique for computing equilibria of polynomial stochastic games, under the "single-controller" assumption.

Additionally, in collaboration with colleagues from Caltech, Professor Parrilo recently developed an extension of the "compressed sensing" techniques that deal with low-rank assumptions as opposed to sparsity. Their results show that a particular "nuclear norm" optimization heuristic provably recovers the minimum-rank matrix in a given affine subspace, provided a certain restricted isometry property holds. Furthermore, this condition holds with overwhelming probability if the equations are randomly chosen and the number of equations is sufficiently large.

Statistical Signal Processing

Professor Sanjoy Mitter

Professor Mitter's research has spanned the broad areas of systems, communication, and control. Although his primary contributions have been on 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 relationship 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 that they proposed in the 1980s.

In joint work with Emery Brown (Department of Brain and Cognitive Sciences, MIT) and former doctoral student L. Srinivasan, Professor Mitter has been investigating the role of point process theory in representing the spiking response of premotor dorsal cortex (PMd). A quantitative theory of the role of PMd in movement control requires that the whole delay period spiking response of PMd be understood as well as specific features that describe it in part. An adequate mathematical model of PMd must capture the effects of a physical system governed by local neuronal properties and anatomical connections with numerous cortical and subcortical areas.

Professor Mitter continues to explore brain-driven interfaces that depend on estimation procedures to convert neural signals to inputs for prosthetic devices that can assist individuals with severe motor deficits. Previous estimation procedures were developed on an application-specific basis. A coherent estimation framework is detailed that unifies these procedures and motivates new applications of prosthetic devices driven by action potentials, local field potentials, electrocorticography, electroencephalography, electromyography, or optical methods.

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 theory (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). In biological systems, the plant, sensors, and actuators will be linked by noisy communication channels (synapses). An information storage view of the role of noisy synapses was undertaken in the completed SM thesis of Lav Varshney.

Also with A. 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. The completion of this work required the development of an inverse rate distortion theory, which shows that, under appropriate conditions, end-to-end rate distortion theory is equivalent to a communication problem.

Professor Alan S. Willsky

Professor Willsky leads the Stochastic Systems Group (SSG). The general focus is on the development of 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 Association for Research in Otolaryngology; the Air Force Research Laboratory; the Office of the Director, Defense Research and Engineering; MIT Lincoln Laboratory; and the Royal Dutch Shell Corporation. SSG is investigating how to extend and exploit its methodology for problems involving complex graphical models, such as those that arise in military command and control, mapping from remote sensing data, and the monitoring of complex systems. SSG's work involves examining complex graphical representations and developing tractable algorithms based on these representations. 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, mapping of subterranean surfaces in support of oil exploration, and tracking of multiple vehicles from networks of small sensors. This work has also been extended to a variety of machine learning problems in which tractable models are sought for high-dimensional data and phenomena.

SSG's work also continues to focus on the development of statistically based curve evolution algorithms for the 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 simultaneously 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 Oil and Brigham and Women's Hospital, SSG's work has 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 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 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 Department of Economics, 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 (e.g., fictitious play), and computation of equilibrium in nonzero-sum games with potentially infinite strategy spaces. More recent research in her group focuses on the development of novel decentralized algorithms for large-scale constrained optimization with explicit performance guarantees.

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 the development of 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 generating electric power. 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.

Professor Emilio Frazzoli

Professor Frazzoli's main research interests are in the area of control of autonomous vehicles and large-scale mobile robotic networks. He is currently leading an effort in developing a formal modeling framework, enabling the development of a rigorous complexity theory for robotic networks. With such modeling tools, his research group is currently analyzing a broad class of multiple-vehicle motion coordination problems, ranging from dynamic vehicle routing to path coverage and traffic deconfliction.

In addition to the design of provably efficient, scalable, robust, and adaptive algorithms for such problems, he is interested in understanding how the performance and complexity characteristics of the system change as its dimension grows, in terms of the number of agents and the nature of the tasks. Notable results include (1) development of the first polynomial-time approximation algorithm for traveling salesman problems with curvature constraints, (2) exact characterization of traffic volume/congestion trade-offs in general mobile networks, (3) development of the first algorithm for collision avoidance in air traffic control that is provably safe for general aircraft encounters, and (4) recognition that intervehicle communication is not necessary for optimal performance in a certain class of multiple-vehicle routing problems.

In addition, he is part of the team developing the MIT entry to the 2007 DARPA Urban Challenge, with collaborators from CSAIL and the Department of Aeronautics and Astronautics. In particular, he is leading, jointly with Professor Jonathan How, development of the planning and control software, which will ensure that the autonomous vehicle navigates an unknown urban environment safely and efficiently, while obeying traffic laws and avoiding collisions with other vehicles.

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 with 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 and 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 2006–2007 academic year draws to a close, we will continue to emphasize expanding connections to industry, host events, and recruit new members. LIDS remains a thriving, interdisciplinary community both within MIT and among other leading universities.

Vincent W. S. Chan
Director
Joan and Irwin M. Jacobs Professor of Electrical Engineering and Computer Science and Aeronautics and Astronautics

Muriel Médard
Associate Director
Edgerton Associate Professor of Electrical Engineering and Computer Science

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