# 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. LIDS emphasizes pursuit of basic knowledge as the foundation for innovation. While maintaining roots in fundamental research related to information science, LIDS has also 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 from various parts of the world visit LIDS to participate in its research programs. Twenty faculty members, a number of research staff, research affiliates from the industry, postdoctoral fellows, and approximately 130 graduate students are presently associated with the laboratory. Undergraduates also participate in research and thesis activities through the Undergraduate Research Opportunities Program (UROP).

## Highlights, Awards, and Events

The 2004–2005 academic year has been an exciting and successful one for LIDS. Research volume remains strong at over $6.5 million. This has been the first year in our new location at the Stata Center, which promotes visibility and increased interaction within the lab and with the larger community. LIDS continues to host various events—notably, weekly colloquia that feature leading scholars from the laboratory's research areas. The 10th annual LIDS Student Conference, organized by a student committee and showcasing current student work as well as keynote speakers, took place in January 2005. Also, a new laboratory publication, *LIDS-all,* was launched in the spring. These and other events reflect the laboratory's commitment to building a vibrant, interdisciplinary research community.

The following LIDS members have received honors and awards for their work during the past year.

### Faculty

Professor Munther Dahleh won the George S. Axelby Outstanding Paper Award of the Institute of Electrical and Electronics Engineers (IEEE) Control Systems Society in 2004 for his paper "Distributed Control of Spatially Invariant Systems," written with Professors Barmieh and Paganini. The award recognizes up to three outstanding papers published in the IEEE *Transactions on Automatic Control* during the two years preceding the date of the award.

Professor Pablo Parrilo received the Donald P. Eckman Award for pioneering contributions to the integration of algebraic and numerical techniques as computational tools for the optimization and robustness of control systems.

Professor Alan S. Willsky was awarded the doctorate honoris causa from Université de Rennes. This was one of two honorary doctorates awarded in conjunction with the 25th anniversary of the establishment of the Institut de Recherche en Informatique et Systemes Aléatoires, a joint laboratory of Institut National de Recherche en Informatique et en Automatique, Centre National de la Recherche Scientifique , and the Université de Rennes. Professor Willsky will receive his honorary doctorate in October 2005, at which time there will be a two-day symposium in his and the other recipients' honor. Professor Willsky also delivered the keynote address at the 2005 Air Force Office of Scientific Research's Workshop on Sensing and Signal Processing.

Professor Moe Win was awarded the Presidential Early Career Award for Scientists and Engineers (PECASE) from the White House "for pioneering work on novel ultra-wide band radio communication systems." The PECASE award is the highest honor bestowed by the US government on scientists and engineers at the outset of their independent research careers.

### Students

Emily M. Craparo received the 2004–2005 Zonta International Amelia Earhart Fellowship.

Emily Fox has been awarded a National Defense Science and Engineering Graduate Fellowship for her doctoral studies. She was the top-ranked applicant for this fellowship. Ms. Fox was also the recipient of a National Science Foundation (NSF) Graduate Fellowship and was awarded the Chorafas Foundation Award and the David Adler Memorial 2nd Place Prize for her thesis.

Tracey Ho received a Best Student Paper Award at the International Workshop on Wireless Ad Hoc Networks for her paper "On the Utility of Network Coding in Dynamic Environments," written with B. Leong, M. Médard, R. Koetter, Y. Chang, and M. Effros. Ms. Ho was also awarded the George M. Sprowls Award honorable mention for her thesis "Networking from a Network Coding Perspective," supervised by Muriel Médard.

Alex Ihler received an Outstanding Student Paper Award at the 2004 Neural Information Processing Systems Conference.

Jay Kumar Sundararajan was awarded a Morris J. Levin Award at the MIT Masterworks for his thesis "Extending the Birkhoff–von Neumann Switching Strategy to Multicast Switching," supervised by Muriel Médard and Supratim Deb.

Alessandro Tarello won a Best Student Paper Award at WiOpt 2005 for his paper "Minimum Energy Transmission Scheduling Subject to Deadline Constraints," written with J. Sun, M. Zafer, and E. Modiano.

## 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 outline the major current research being conducted in each area.

### Communication and Networks

#### *Optical Networks*

Professors Chan, Gallager, Médard, and Modiano continue to work on future optical network architectures. The focus of the program is to design and prototype the next-generation scalable access and wide area network with an increase in data rate of up to four orders of magnitude but at the same time to decrease the cost of delivery per bit by approximately the same amount.

Professors Chan and Modiano continued a program sponsored by the Defense Advanced Research Projects Agency (DARPA) on all-optical, local, and metro area networks with ultrahigh reliability and performance. The objective of this research is to use optical network technology to build a highly reliable network that services high-end applications such as aircraft control and coherent collaborative sensing. This program emphasizes cross-layer network optimization and nontraditional networks that provide a faster response than current networks, along with arbitrarily high delivery reliability. In the last year, we have found new diagnostic techniques that rapidly find and locate all optical network failures.

Professor Modiano continues to work on an NSF grant to study mechanisms for providing optical bypass in the Next Generation Internet (NGI). The goal of the research is to use Wavelength Division Multiplexing technology together with novel algorithms to reduce the size, cost, and complexity of electronic switches and routers in the network, leading to a dramatic increase in the traffic capacity that can be supported by the NGI. This past year, the group has developed mechanisms for switching traffic together in bundles of wavelengths called wavebands that greatly reduce the switching costs of the network.

Professor Médard, in collaboration with her students, is working on issues of reliability and robustness of backbone and access networks. Her first project is in the area of probabilistic analysis of optical network robustness as part of an Air Force Office of Scientific Research (AFOSR) University Research Initiative with Stanford University, the University of Illinois, and Caltech. Recent results in this area include results for robustness for both regular and nonregular random graphs. Professor Médard and her students are also working on reliability of access networks. She is the MIT member of a recent NSF Information Technology Research (ITR) project with the University of Illinois in the area of robust optical local and metropolitan area networks. This project considers the use of coarse unit of measure and limited signal-to-noise ratios in architecting robust networks.

Professor Chan, with NSF and DARPA support, is working on new optical transport mechanisms to radically change the cost structure of high-speed networks. His team is also exploring transmission of analog microwave signals over optical networks to greatly enhance the performance of microwave sensing and communication systems.

### *Satellite Communications and Networking*

Professors Chan, Médard, Modiano, and Win conduct research in this area, which focuses on architecture designs for efficient data communications over satellites interconnected with terrestrial fiber and wireless systems to form a heterogeneous global internet.

Professor Chan and his students completed a study to reach a baseline understanding of current traditional space-qualified processors and commercial processors. This group, in conjunction with Professor Modiano's group, is also working on resource allocation schemes for satellite channels. Professor Chan's group has concluded that the yet to become fully mature technology of phase array antennas for satellite systems can greatly enhance the throughput and delay performance of modern data networks. They also have analyzed the performance of current transport layer protocols over short- and long-distance optical channels and found all standard protocols inefficient. New protocol developments are under way.

On transport protocols for hybrid networks, Professor Modiano and his students have explored the interaction between protocols at different layers. Using their models, they are able to optimize protocol parameters to achieve significant improvement in network performance. They also developed a novel algorithm for solving the joint problem of flow control, routing, and scheduling in a heterogeneous network that includes both space and terrestrial components. In addition, Professor Modiano continues to work with NASA on developing intelligent architecture and protocols for NASA's future space internet. A particular focus of this project will be the development of communication architectures for supporting NASA's planned space exploration initiative. It is a goal of this project to obtain an understanding of the interactions between network layers so that overall, end-to-end performance can be significantly improved.

Professor Médard, with her students, has considered practical means of performing universal distributed compression. One of the main reasons for the significant gap between the performance of current streaming compression systems and theoretical limits in this domain is the difficulty of performing rapid decoding for sources with complicated and often poorly understood statistics. Universal decoding allows decoding for a wide range of source statistics through the use of a single decoder. However, the practice of universal decoding has heretofore remained solely in the theoretical domain, owing to the perceived complexity of implementing known theoretical approaches. Our recent research has established that universal decoding is actually implementable as a polynomial-time algorithm. Such an implementation runs altogether counter to the prevailing wisdom regarding the excessive complexity of universal decoding methods. Our results are based on the method of types and use recent results from polytope projection theory as well as linear programming relaxation for error-correction decoding.

### Wireless Communications and Networking

Professor Win and his graduate students are working on the application of mathematical and statistical theories to communication, detection, and estimation problems. Specific current research topics include measurement and modeling of time-varying channels, design and analysis of multiple antenna systems, ultrawide bandwidth (UWB) communications systems, optical communications systems, and space communications systems. Projects include developing analytical frameworks for transmitted-reference signaling for UWB communications and diversity with practical channel estimation. This group has been actively equipping the new Wireless Lab and maintains dynamic collaborations with the University of Oulu in Finland and the University of Bologna in Italy, among other research partnerships.

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 squared 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 Zheng, along with Professor Médard, as part of the UWB NSF program led by Professor Moe Win and comprising LIDS, Microsystems Technology Laboratories, and the Computer Science and Artificial Intelligence Laboratory (CSAIL), has made progress in the study of wideband communication over wireless fading channels. A novel approach has been 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. Professor Zheng is also conducting research with Professor Gallager on noise accumulation over successive transmissions for the NSF Career Project and an NSF project on wireless/wireline interface in collaboration with professors Médard, Wornell (Research Laboratory of Electronics), and Tonguz (Carnegie Mellon University). This research is useful in the study of multi-hop communication schemes over relay networks, especially in a wireless fading environment. The goal of this research is to build fundamental frameworks to study the costs of performance for using simple and distributed algorithms.

Professor Chan and his students, under sponsorship of NSF and DARPA, have been working on proactive mobile networks where node mobility is predicted and managed, as well as providing relay node insertion when needed. This study will lead to much improved performance over wireless ad hoc networks for mobile networks without planned infrastructures.

### Wireless Ad Hoc Networks

This year, Professor Modiano, along with Professors Deyst, Ozdaglar, Win, and Roy, has continued work on a project with Draper Laboratory aimed at the development of robust distributed sensor networks. This project will develop advanced communication technologies that can enable ad hoc sensor networks to operate effectively in hostile environments. The approach is unique in that it combines, in an integrated manner, the ground-breaking efforts at LIDS in ultrawide bandwidth transmission technologies, management and control of mobile ad hoc networks, and inertial system concepts to create a novel technical capability that can address the national need for surveillance in hostile environments.

### Network Codes

Professor Médard, in collaboration with Professor Koetter of the University of Illinois–Urbana-Champaign and Professor Effros of Caltech, as well as their students, collaborate on network coding through an NSF ITR project on network coding and a DARPA project on secure and robust network coding. Until now, network schemes have considered transmission of information in networks in terms of flows—networks are used in a manner akin to any transportation system. Network coding takes a very different approach. Rather than considering information as a good to be distributed, we actively make use of the fact that information—unlike goods in a transportation network—is composed of algebraic entities such as bits that can be manipulated. Without network coding, switches map inputs onto outputs. The traffic from an input is copied onto one or more outputs at a time, with an output being mapped at any time to at most one input. The cleverness of the way in which these mappings from inputs and outputs are done lies at the heart of the operation of modern routers. In a network coding setting, functions of inputs are copied onto outputs. Such copying can be done over virtual overlay networks and need not be done in routers. While the difference between placing data or functions of that data onto outputs may seem slight, the flexibility afforded by having a rich set of functions to choose from has profound consequences on network performance.

Professor Médard's research team has also shown that multicast connections, such as media downloading over the web, in which one or more nodes receive information from a set of sources, can be operated in an optimal fashion if we use a distributed and random approach. The functions performing the input to output mappings are chosen in a random fashion, using a mixture of techniques from random algorithms and finite field algebra. Moreover, the coded network lends itself, for multicast connections, to a cost optimization that not only outperforms traditional routing tree–based approaches, it also lends itself to a distributed implementation that can be updated dynamically when changing conditions arise, such as mobility in wireless networks. While the ability to manage connections optimally in a distributed way is in itself attractive, there are other significant and quantifiable performance advantages to network coding. Network coding provides cost benefits that can be found across a variety of different settings; for instance, in wireless networks, where the cost may be measured in expended energy, or in wireline networks, where they reduce congestion. These types of advantages in operation and cost have prompted the recent announcement that network coding will be incorporated in Microsoft downloading software, based on the kinds of randomized network coding approaches we have developed. Network coding is thus well poised to become a valuable tool for a wide variety of network applications.

### Sensor Web, Interference, Coding, and Statistical Mechanics

Recent research on turbocoding, decoding of low-density parity check codes, and statistical mechanisms of disordered systems has shown that there are deep connections between those subjects. Professor Sanjoy Mitter, in collaboration with Dr. Nigel Newton, has given an information theoretic view of maximum-likelihood decoding and nonlinear estimation of diffusion processes. Professor Mitter is developing a theory of interconnections that has applications in distributed control, coding, and inference on graphs. Professor Mitter and his students also analyzed stability in a single-loop scenario with linear, time-invariant plants, in collaboration with research scientist Professor Elia from Iowa State University. A new notion known as "any-time capacity" was introduced to capture moment stability in a nonconservative way.

### *Interaction between Information Theory and Control*

Shannon's theory of information transmission through noisy channels provides a powerful paradigm for the analysis and synthesis of point-to-point communication systems. Unfortunately, this notion does not extend to networked communication systems and as a result we are left without a universal notion of "information" for general networked systems. In the case of interconnected systems (e.g., feedback systems), information transmission plays a critical role in their stability and performance. Recent applications such as the remote control of aerial vehicles require that output measurements as well as warning signals and reference signals be transmitted through a wireless network. These new challenges require revisiting the output feedback problem under a more general framework; however, as we mentioned above, the paradigms associated with control and communication seem incompatible. This spurred intensive research of feedback loops in the presence of communication constraints. Here we summarize some of the work relevant to this project and highlight one of our recent results that directly captures the performance-transmission tradeoff in the context of disturbance rejection.

Professor Munther Dahleh and his student Nuno Martins focused on the question of fundamental limitation of disturbance rejection (or noise cancellation) in the presence of noisy channels in the loop. In the early warning case discussed above, noise cancellation was shown to be limited by the capacity of the channel through which the measured signal is transmitted. For the feedback case, it is well known that the Bode integral inequality provides the fundamental limitation on shaping the frequency response of the closed loop map between disturbance to output. Dahleh and Martins's work showed that this inequality can be interpreted as a conservation inequality of the information flow in the feedback loop. As a result, new fundamental limits were derived that directly connect the desired frequency response with the channel capacity present in the loop.

## Control and System Theory

### *Multivariable and Robust Control*

Various theoretical and applied studies in this area are being carried out by Professors Dahleh, Eric Feron (chair of the IEEE Technical Committee on Robust Control), Steve Massaquoi, Alexandre Megretski, and their students. Theoretical research deals with issues of robustness, aggregation, and adaptive control. The aim of the research is to derive a computer-aided design environment for the design of control systems that can address general performance objectives for various classes of uncertainty. Recent application-oriented studies include the control of large space structures, helicopters, and submarine control systems; issues of integrated flight control; control of chemical processes and distillation columns; automotive control systems; and the modeling and analysis of biological control systems. New applications for robust and programmed (finite state-based) control theory are also emerging at LIDS, including the real-time, agile guidance of single and multiple unmanned aerial vehicles, as well as vehicle anticollision problems arising in air traffic control. Some of these concepts are implemented and tested on small helicopter systems.

Professors Feron and Massaquoi are involved in a collaboration regarding the internal mechanisms that underlie the brain's ability to acquire programs that manage external dynamics and communication. In a separate research track, Professor Feron has been investigating the real-time decision issues arising in highly dynamic, multiagent environments, using partner dancing as a case study. Together with a graduate student, Professor Feron has uncovered the essential role of gaming in competitive partnered dancing.

In a recent initiative, Professors Megretski and Feron have begun a new investigation about applying the tools of robust control systems analysis to real-time software analysis, with a specific focus on run-time error. They have established a collaboration with the group of Professor Patrick Cousot, École Normale Supérieure, France, to facilitate this activity.

### *Evolutionary Control*

Another new thrust regards the general question of how control systems might evolve over time to manage complex control problems. Professors Mitter, Dahleh, Massaquoi, and Berwick conduct this work. 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.

### *Unmanned Air Vehicles*

Professors Dahleh and Feron and their students are working on developing control architectures for unmanned vehicles, in part sponsored by the Boeing Company. They have derived an architecture for the autonomous controller that enables the vehicle to perform agile maneuvers. The researchers have developed a complete simulation/animation environment, and their software (based on the above architecture) is now in use at Draper Laboratory, Barron Associates, Inc., and the Air Force Research Laboratory. A recent development in this problem is deriving efficient algorithms for performing real-time motion planning (contrasted from path planning, where vehicle dynamics are not taken into account) in a cluttered environment. This research entails the development of a hierarchical control system that replaces the human pilot in order to perform agile maneuvers. Much of this work has been or is in the process of being transitioned to industry (Nascent Technology, Lockheed Martin, Boeing) and users (Natick Army Laboratories).

With sponsorship from Draper Laboratory, Professor John Deyst and his students are developing new guidance and control methods for operation of intelligent unmanned air vehicles (UAVs). This work addresses the coordinated action of groups of UAVs that operate together to accomplish complex tasks. Such coordinated action is required to accomplish tasks that are impossible or would take excessively long periods of time for a single vehicle to complete. Significant issues being addressed are the safe and effective flight of UAVs near each other, including rendezvous and docking of one vehicle with another.

### *Identification and Learning of Complex Systems*

Professor Dahleh has led a research effort in developing a theoretical framework for learning and identification of complex systems. To accurately define such a problem, one needs to make assumptions about the generation of data; choose a model class from which a model will be selected; and choose a metric that captures the distance between the model and the actual system. One can also choose multiple model classes and derive a metric to evaluate which model class to choose.

Professor Dahleh and his students have developed a new theoretical framework in which undermodeling is explicit in the problem formulation. Equivalently, the process that generates the data is not a member of the model classes considered. This work began with Dr. Saligrama Venkatesh’s thesis several years ago. Recently, Dr. Soosan Beheshti developed a new measure of model quality evaluation named Model Description Complexity (MDC) that is computed from finite data. MDC is the correct generalization of AIC and MDL methods used heavily for evaluating model sets. Recent work connects Beheshti’s results with learning theory and universal coding.

### *Control, Communication, and Computation*

Communication channels impose constraints on feedback systems that limit the achievable closed-loop stability and performance. Control theory has focused on characterizing the fundamental limitations and capabilities of closed-loop systems in the presence of both plant and input uncertainty. Communication constraints introduce a new class of uncertainty (e.g., quantization, average bit rate, or capacity) that existing theory deals with only indirectly. Professor Dahleh and his students, in collaboration with Professor Elia, have derived new results for computing stability limitations of feedback systems in the presence of various channels, using both deterministic and probabilistic models.

### *Analysis and Synthesis of Hybrid Systems*

Many applications involve the interaction of both discrete (logic) and continuous systems. A feedback system with bit constraints is an example of such interaction. The motion planning problems of UAVs is another example. Professors Dahleh and Megretski are leading an effort 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.

### *Model Reduction of Discrete and Hybrid Systems*

Professors Dahleh and Megretski and their students pioneer this work. The objective is 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.

### *Systems Aspects of Biology*

Professor B. Mishra (Courant–New York University), Professors Peter Doerschuk and Saul Gelfand (Purdue University), and Professors D. Bertsekas and S. K. Mitter (MIT) initiated a collaborative research project involving an integrative view of systems biology, with special emphasis on the study of viruses interacting with E. coli.

## Statistical Signal Processing

### *Stochastic Systems Group*

Professor Alan S. Willsky leads the Stochastic Systems Group (SSG), with the assistance of Dr. Mujdat Cetin of LIDS and Dr. John Fisher of CSAIL. SSG includes 10 to 12 graduate students, visitors, and participants from other groups within LIDS and from other MIT laboratories and departments. The general focus of research within SSG 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 in the group extends from basic mathematical theory to specific areas of application. Funding for this research comes from a variety of sources, including the Office of Naval Research (ONR), AFOSR, the Army Research Office (ARO), the Office of the Director, Research & Engineering (through AFOSR, ARO, and ONR), the National Institutes of Health, NSF, MIT Lincoln Laboratory, and Royal Dutch Shell Corporation.

In addition to directing these research activities, Professor Willsky is very active in supporting government and in particular Department of Defense organizations in assessing and planning technology investments. He previously served as a member of the Air Force Scientific Advisory Board and continues to support that organization informally. Each of the following research areas being pursued within SSG involves both theoretical development and applied studies in the application areas mentioned previously.

### *Multiresolution Statistical Signal/Image Processing and Graphical Models*

The key to SSG's previous (and some of its current) research in this area is the direct statistical modeling of phenomena at multiple resolutions using graphical models on trees and other graphs, in which each level on a tree corresponds to a particular resolution. Using these models, the group has developed highly efficient algorithms for estimation, data fusion, and other image analysis tasks and has also demonstrated that a wide variety of real phenomena and applications can be captured within this framework. They continue to work on expanding the domain of applicability of this methodology by pursuing additional applications and by developing tools for constructing multiresolution models needed as the basis for applying their results.

Major new thrusts involve the investigation of how SSG can exploit its methodology for problems involving much more complex graphical models, such as those that arise in military command and control or in problems of monitoring complex systems—

problems of great national concern because of the need to make critical national infrastructure secure. SSG's work involves the examination of graphical structures more complex than trees; in particular, graphs containing (typically many) loops. The group's approach aims at the exploitation of acyclic tree structures embedded in these graphs.

SSG has had several major successes in this area, including a new class of signal and image processing algorithms that expands the range of applicability of the group's method considerably; and new sets of algorithms for inference on loopy graphs that have provable performance properties, outperform previously developed methods, and have led to several awards for recent SSG graduate, Dr. Martin Wainwright. In addition, the group is now heavily involved in extending these methods to problems of distributed fusion in sensor networks, in which the relevant graphical structure captures both the statistical relationships among the variables of interest and the network connectivity among sensing, processing, and communication nodes.

### *Nonlinear and Geometric Image Analysis*

During the past year, SSG has continued its efforts in the area of nonlinear/non-Gaussian image analysis. These include the explicit estimation/extraction of geometric information, such as object boundaries and segmentation. The group's work continues to focus on the development of statistically based curve evolution algorithms. Such algorithms involve explicitly defining and dynamically evolving curves in ways that lead to accurate and efficient segmentation of images. The group's work aims at developing first-principles statistical approaches to curve evolution that deal with noise and variability in a statistically optimal way. Recent accomplishments include methods that use training examples to build and then 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 the tracking of dynamically evolving curves.

This work is being pursued in the context of several significant interdisciplinary efforts. The first of these involves collaboration with clinicians and researchers at Brigham and Women's Hospital toward applications in automatic interpretation of medical imagery and image-guided therapy procedures. Another major interdisciplinary effort involves problems of dynamically estimating and tracking curves, with applications including both 4-D medical imaging of the heart and the tracking of major fronts in meteorology and oceanography (e.g., the Gulf Stream).

### *Machine Learning and Information-Theoretic Methods for Multisensor Fusion*

A third component of SSG's research program involves the development of statistically based algorithms for the fusion of information from multiple sensors in the presence of substantial uncertainties—for example, in the nature of the signals being sensed (such as acoustic signatures of unknown character), in the number of sources generating those signals, in the locations and calibration of the sensors themselves, and in the relationships among the signals being sensed by sensors of very different modalities.

The group's work has found application in medical image analysis, in particular in functional magnetic resonance imaging and in a variety of multisensor fusion applications. These include fusion of audio and video sensors (e.g., for the localization of acoustic sources in video scenes) and fusion of multiple acoustic sensors for the detection and localization of multiple sources in complex and highly uncertain environments that defeat standard coherent processing methods. SSG has demonstrated that information-theoretic methods can provide robust solutions to such problems without the need for *any* training (i.e., fusion is performed "on-the-fly" as data are collected). Current applications of this work include new methods for "blind" segmentation of imagery (i.e., without prior models for the statistics of foreground and background), as well as methods for detecting dependencies among multiple variables without prior knowledge of the statistical nature of possible dependencies.

### Neurobiological Modeling

Professors Munther Dahleh and Steve Massaquoi are interested in three problems. The first is the development of a hierarchical model of the interaction between the cerebrum and cerebellum that is anatomically justified and that can explain multivariable dynamic stabilization and control. The second problem is deriving a multiscale, multiresolution model that explains electroencephalography (EEG) data, with specific interests in motor control, anesthesia, and evaluation of cortical function and dysfunction. These projects are in collaboration with various laboratories/departments at MIT as well as Massachusetts General Hospital. The third is the development of a circuit model of basal ganglia that describes the basal ganglia's function in both low-level control of movement speed and in motor programming.

Substantial progress was made in the area of developing reduced-order models for the cerebellum and its interactions with the cerebrum and spinal cord. Progress has been made in utilizing these models for interpreting speed and directional information present in actual cerebellar data. In a parallel effort concerning modeling EEG data, professors Dahleh and Massaquoi have developed a basic circuit that constitutes a fundamental cerebral function module. The circuit describes local and global interconnections between the different layers and has been successful in simulating several important states of the brain. This development is unique, and the professors expect several interesting fundamental models to emerge. Progress has also been made in developing a unified model of basal ganglia function that interprets the structure as implementing a logical operator that enables programmed control of behavior ranging from cruising movements to cooperative interaction with the environment.

### Perceptual Systems

Professor Sanjoy Mitter and his collaborators, Professor Stefano Soatto of UCLA and Dr. Horst Haussecker of Intel Corporation, have been working on various aspects of perception and recognition. Perception and recognition involve recovering useful information about the environment from sensed data and prior knowledge about the real world and the sensors. Artificial systems designed to carry out this task are much inferior to biological systems, largely due to the size and intricacy of the knowledge required to carry out reliable inference in unrestricted and uncertain domains. The basic engineering principle of decomposing a complex task into simpler and independent tasks is difficult to apply to perception and recognition due to the extremely complicated and yet unknown patterns of interdependency among the many "acts of perception" involved. What are the components involved in perception and recognition? Into what architecture should these components be organized? How does one minimize the interdependence of these components? How should uncertainty be represented? How does one acquire and represent the knowledge about the real world and the sensors? Several projects are being undertaken to find answers to these questions.

A new computational theory for the recognition of occluded deformable templates in a cluttered scene has led to efficient algorithms with guaranteed performance in terms of localization errors and time complexity. Currently, this approach has been applied to features consisting of points in the plane and to affine deformations. Future work will seek to generalize these assumptions. Lastly, early recognition of moving ground targets from an approaching platform is an important task for the military. To enhance the performance of existing systems, it is necessary to combine information from multiple frames that contain the target at different resolutions. This project is still at an early stage, and initial efforts have focused on the incorporation of continuity and smoothness constraints of the relative motion of the target with respect to the camera by means of a geodesic approach.

## Optimization

### *Algorithms*

Professors Dimitri Bertsekas and John Tsitsiklis are working on a project that focuses on analytical and computational methods for solving broad classes of optimization problems arising in engineering and operations research, as well as for applications in communication networks, control theory, power systems, computer-aided manufacturing, and other areas. Currently, in addition to traditional subjects in nonlinear and dynamic programming, there is an emphasis on the solution of large-scale problems involving network flows, as well as on the application of decomposition methods.

### *Neurodynamic Programming*

Professors Bertsekas and Tsitsiklis also perform research on problems of sequential decision making under uncertainty that are pervasive in communication networks, manufacturing systems, and logistics and in the control of nonlinear dynamical systems. In theory, such problems can be addressed using dynamic programming techniques. In practice, however, 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 in real-world stochastic control problems. Application areas currently being investigated include problems in logistics (resource scheduling and assignment), finance (pricing of high-dimensional derivative instruments, dynamic portfolio management in the presence of risk constraints), supply chain management, and communications (dynamic channel allocation).

### *Network Optimization*

This research considers linear/integer multicommodity flow problems for some special types of graphs, such as rings, that frequently arise in practical applications, such as data communication networks. Professors Bertsekas and Ozdaglar and their students show that these problems can be polynomially solved without loss of optimality by relaxing the integer constraints and rounding the solutions.

One important context in which such problems arise is the routing and wavelength assignment (RWA) problem, which is critically important for increasing the efficiency of wavelength-routed all-optical networks. In this work, the researchers propose several novel optimization problem formulations, which can be addressed with highly efficient linear integer programming methods and yield optimal or near-optimal RWA policies.

### *Game Theory and Communication Networks*

Professor Ozdaglar and her students perform this research, focusing on a combined study in which the interactions between economic incentives of service providers and users and traditional network control algorithms are understood to be essential for the design of future networks. This research, done in collaboration with faculty in the Department of Economics, requires the combination of classical techniques of optimization theory with new tools from game theory, the study of multiagent decision making.

The goal in this research is twofold. First, it is to provide a theoretical framework for understanding the interactions of service providers, users, and traffic engineering aspects of communication networks. Second, it is to develop and evaluate new computationally feasible algorithms and pricing schemes that can be implemented in practice for allocation of resources in the presence of users with variable quality of service (QoS) requirements. Toward this goal, the research analyzes different networks (treating the wired and wireless networks separately) and different pricing schemes (flat, usage-based, various QoS pricing schemes). The large scale and complexity of the systems under study also necessitate the development of new tools in optimization theory and advances in game theory.

### *Game Theory in Resource Allocation*

Professor Tsitsiklis, together with his students and coworkers, has been studying 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 have been evaluated in terms of the possible efficiency losses in the presence of strategic (gaming) behavior by market participants that hold significant market power. Models of network formation that capture negotiation and certain types of contractual agreements are also being studied.

## Future Outlook

LIDS's faculty and student numbers has grown threefold in the last five years, together with a commensurate degree of funding growth, largely from the government sector.

In the past few years, LIDS has also recruited three women and one minority faculty member. We will continue to target the recruitment of both junior and senior women and minority faculty members in the next few years, as we replace some of the retiring faculty. Additionally, our increasing participation in research agenda-setting in Washington and service to the engineering community allows us to influence the direction of research and enhances our ability to raise funds. The research themes of choice in LIDS are increasingly cross-disciplinary in nature, and we envision further collaborations with other MIT departments and laboratories as well as other leading universities.

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