Signals, Information, and Algorithms Laboratory

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Introduction

Our laboratory formulates, examines, and develops algorithmic solutions to a wide spectrum of problems of fundamental interest involving the manipulation of signals and information in diverse settings. Our work is strongly motivated by and connected with emerging applications and technologies.

In pursuing the design of efficient algorithm structures, the scope of research within the lab extends from the analysis of fundamental limits and development of architectural principles, through to implementation issues and experimental investigations. Of particular interest are the tradeoffs between performance, complexity, and robustness.

In our work, we draw on diverse mathematical tools—from the theory of information, computation, and complexity; statistical inference and learning, signal processing and systems; coding and communication; and networks and queuing—in addressing important new problems that frequently transcend traditional boundaries between disciplines.

We have many joint projects and collaborate closely with faculty, staff, and students in a variety of other labs on campus, including the Laboratory for Information and Decision Systems, the Microsystems Technologies Laboratories, and Computer Science and Artificial Intelligence Laboratory.

Much of our activity over the last few years has centered around a variety of different types of problems arising naturally in the context of wireless, sensor, multimedia, and broadband networks.

Some topics of current interest include:

- cross-layer design techniques and architectural considerations for resource-efficient wireless networks
- coding for multiple-element antenna arrays in wireless networks, and interactions with other

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layers; advanced antenna designs
- new classes of source and channel codes, and decoding algorithms, particularly for new applications
- diversity techniques and interference suppression and management algorithms for wireless networks
- distributed algorithms and robust architectures for wireless networks, especially ad-hoc networks and sensor networks
- algorithms and fundamental limits for multimedia security problems, including digital watermarking, encryption, and authentication of multimedia content
- algorithms and architectures for multimedia and streaming media networks
- algorithmic and coding techniques for generating reliable advanced systems from aggressively scaled devices, circuits, and microsystems.
- information-theoretic and algorithmic aspects of learning, inference, and perception; universal algorithms
- information-theoretic and signal processing aspects of neuroscience, and computational and systems biology

1. Signal Recovery in Distributed Sampling Systems with Application to Time-Interleaved A/D Converters

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Project Staff
Vijay Divi, and Professor Gregory W. Wornell

Many modern applications need high-speed distributed sampling systems such as time-interleaved analog-to-digital converters. Calibration is a serious challenge in the design of such systems. A lack of synchronization between separate converters yields gain mismatches and non-uniform timing, leading to a poor sampling of the original input.

We investigate alternative approaches for signal recovery. In particular, we develop blind calibration techniques which focus on the estimation of the associated unknown gain and offset parameters, from which the calibrated signal is reconstructed. Estimation algorithms are considered for both deterministic and random input signal models. For deterministic signals, a least squares estimation of input is examined; for random signals, the Maximum Likelihood (ML) parameter estimate is obtained via the Expecation-Maximize (EM) algorithm. Tradeoffs in reconstruction quality between varying calibration times, oversampling factors, and number of converters are studied.

2. Coding Techniques for Multicasting

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The problem of sending independent messages to different receivers from a single transmitter has received much attention in the literature. However little work has been done in finding fundamental limits of sending a common message to multiple receivers. In this work we study two scenarios for multicasting. In the first scenario, the sender wishes to communicate a common message to multiple receivers, when each receiver experiences an additive interference sequence.

These additive interferences are known only to the sender but not to the receivers. This is a multi-user generalization of the writing on dirty paper problem. For the special case of binary channels, we propose some coding schemes and outer bounds on the achievable rate. We also study achievable rates for the Gaussian case and some other channel models.

The second setting is when a base station with multiple antennas sends a common message to several users. We show that even with moderate size of antenna arrays dramatic gains can be achieved, similar to the well-known single user MIMO link.

3. A Framework for Low-Complexity Iterative Interference Cancellation In Communication Systems

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Communication over channels with interference poses challenges not present for additive white Gaussian noise (AWGN) channels. This research develops practical schemes for mitigating the effects of the interference in order to approach the information limits of the channel. We focus on the channel model in which the received vector is r = H*x + w, where H is a matrix, x is a vector of symbols chosen from a finite set, and w is a Gaussian noise vector. Scenarios consistent with this model include the equalization of intersymbol interference (ISI) channels, the cancellation of multiple-access interference (MAI) in CDMA systems, and the decoding of multiple-input multiple-output (MIMO) systems in fading environments.

We develop mode-interleaved precoding, a transmitter precoding technique that conditions the interference matrix H so that the interference becomes as benign as possible. The transmitter does not require knowledge of the channel, and yet maximum-likelihood (ML) detection in combination with mode-interleaved precoding achieves the pairwise error probability of the corresponding AWGN channel. The disadvantage of mode interleaving, however, is that the precoding dramatically increases the complexity of ML detection.

We investigate the iterated-decision detector, which avoids this complexity problem by using optimized multipass algorithms to successively cancel interference from the received vector and generate symbol decisions whose reliability increases monotonically with each iteration. Iterated-decision detectors asymptotically achieve the performance of ML detection (and hence the AWGN channel bound) for uncoded systems with considerably lower complexity. We can explain the excellent performance of these detectors by interpreting them as approximations to popular message-passing algorithms.

We also consider coded systems and introduce a framework for designing joint detection and decoding algorithms based on the iterated-decision detector. We develop analytic tools to predict the behavior of such systems.

4. Elements of an Efficient Gigabit Wireless LAN System Architecture

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In the context of a wireless indoor LAN, we are looking at developing space-time codes and designing algorithms for a system to achieve gigabit data rates over an indoor wireless channel. The available bandwidth is divided into several subchannels, each of which is adaptively coded given the varying signal quality in the frequency band.

A central server with many antennas is used as a global relay for node-to-node communications, as well as providing resource management and traffic control for the network. By exploiting the richness of the multipath environment and the many antennas available at the central server, the network is able to simultaneously support many nodes communicating simultaneously over the same frequencies without cooperation or collisions. Alternately, the multiple antennas can be used to dramatically reduce the signal power required to communicate, allowing greater range or reducing the requirements of the amplifiers and filters of the RF frontend, which can greatly reduce the area required, reducing cost.

In order to lessen the requirements on the RF frontends, and hence the amount of difficult design time for the analog engineer, we also working on system architectures and processing techniques which are tolerant of nonidealities and variations in analog circuit elements. To keep the costs reasonable, the multiple RF chains run in parallel on a single chip. The isolation required to keep the crosstalk between the parallel chains from affecting the signal quality may require large amounts of area. Measurements on actual parallel power amplifiers has shown that although the phase of the crosstalk signal will determine whether destructive interference will occur, if the isolation is insufficient, then deep nulls can appear inside the frequency band of interest. Phase randomization techniques can reduces the variations between chips, effectively raising the worst-case performance of a circuit to equal its average case performance. Additional gains can be made by analyzing the effects of circuit nonlinearities on the desired data rate, and methods to reduce the amount of linearity required. These methods are examples of over-provisioning of resources, in which some (more difficult) requirements on system design are relaxed by either using processing to reap additional gains elsewhere, or by simplifying design with a larger number of cheaper, less capable components rather than a single, very complicated and difficult design.

5. Comparing Application- and Physical-Layer Approaches to Diversity on Wireless Channels

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Emin Martinian, Professor Gregory Wornell

Diversity techniques often arise as appealing means for improving performance of multimedia communication over certain types of channels with independent parallel components (e.g., multiple antennas, frequency bands, or time slots). Diversity can be obtained by channel coding across parallel components at the physical layer. Alternatively, the physical layer can present an interface to the parallel components as separate, independent links thus allowing the application layer to implement diversity in the form of multiple description source coding. We compared these two approaches in terms of average end-to-end distortion as a function of channel signal-to-noise ratio (SNR).

For traditional on-off channel models, multiple description coding achieves better performance. For more general noise-limited channels, we derived intuitive guidelines for allowing system designers to identify which types of systems are preferable under different scenarios. Specifically, we introduced a new figure of merit called the distortion exponent, which measures how fast the average distortion decays with SNR. For channel models with Rayleigh fading, our analysis shows that optimal parallel channel coding at the physical layer is more efficient than independent channel coding combined with multiple description source coding. Finally, we considered a joint source-channel decoding approach and showed that by using joint decoding multiple description systems achieve performance comparable to parallel channel coding.

6. The Value and Use of Distributed Quality Information in Source Coding

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We consider lossy source coding when quality side information affecting the distortion measure may be available at the encoder, decoder, both, or neither. For example, such quality side information can model reliabilities for noisy measurements, sensor calibration information, or perceptual effects like masking and sensitivity to context. When the quality side information is statistically independent of the source, we show that in many cases (e.g., for additive or multiplicative quality side information) there is no penalty for knowing the side information only at the encoder, and there is no advantage to knowing it at the decoder. Furthermore, for quadratic distortion measures weighted by the quality side information, we evaluate the penalty for lack of encoder knowledge and show that it can be arbitrarily large. In this scenario, we also sketch transform based quantizers constructions, which efficiently exploit encoder side information in the high-resolution limit.

7. Scheduling for MIMO Communication Systems

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Multiple-Input Multiple-Output (MIMO) antenna arrays have been shown to dramatically increase the capacity of the wireless broadcast channel. Recent results have shown that the capacity region can be achieved via a method termed "Dirty Paper Coding". However, this coding strategy has high computational complexity. There exist simpler sub-optimal coding techniques, such as zero-forcing, that can obtain a trade-off between throughput and complexity. From a purely physical-layer point of view, that is, without considering data arrival process dynamics, this trade-off is a fundamental one.

On the other hand, when the input of the broadcast channel is in the form of multiple independent streams of data packets, there is a scheduling question that needs to be answered, in addition to the coding question. Our first observation is that an optimal scheduling algorithm used with sub-optimal coding can achieve close to optimal performance in terms of overall throughput, especially under different data rate demands from the multiple streams. This is striking, because in many applications, streams of data have variable quality of service demands. Thus joint coding and scheduling is very promising from a practical point of view as well as being interesting from a theoretical perspective. We will look for algorithms that achieve the throughput/delay/complexity tradeoff.

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