Signals, Information, and Algorithms

RLE Group
Signals, Information and Algorithms Laboratory

Faculty
Professor Gregory W. Wornell

Visiting Scientists and Research Affiliates
Giovanni Aliberti, Prof. Sae-Young Chung[1], Dr. Uri Erez[2], Hiroyuki Ishii[3], Dr. Emin Martinian[4], Prof. Ram Zamir[5]

Postdoctoral Scholars
Dr. Vijay Divi[6], Dr. Yuval Kochman[7]

Graduate Students
Anthony Accardi, Venkat Chandar, Qing He, Ying-Zong Huang, James Krieger, Maryam Shanechi, Urs Niesen, Charles Swannack, Da Wang

Visiting Students
Si-Hyeon Lee[8]

Technical and Support Staff
Tricia O'Donnell

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.

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[1] KAIST, Korea Advanced Institute of Science and Technology, Daejeon, South Korea
[2] Department of Electrical Engineering, Tel-Aviv University, Israel
[3] NEC Corporation, Intelligence Systems Department, Tokyo, Japan
[4] Mitsubishi Electric Research Laboratories, Cambridge, Mass.
[5] Department of Electrical Engineering, Systems Division, Faculty of Engineering, Tel-Aviv University, Israel
[6] Research Laboratory of Electronics, MIT, Cambridge, Massachusetts.
[7] Department of Electrical Engineering, Systems Division, Tel-Aviv University, Israel
[8] KAIST, Korea Advanced Institute of Science and Technology, Daejeon, South Korea

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 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
- sensing and imaging technologies
- information-theoretic and signal processing aspects of neuroscience, and computational and systems biology

1. Generating Pictures from Waves: Aspects of Image Formation

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Microsoft Research
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Semiconductor Research Corporation through the FCRP Center for Circuits and System Solutions

Project Staff
Anthony Accardi and Professor Gregory Wornell

The research communities, technologies, and tools for image formation are diverse. On the one hand, computer vision and graphics researchers analyze incoherent light using coarse geometric approximations from optics. On the other hand, array signal processing and acoustics researchers analyze coherent sound waves using stochastic estimation theory and diffraction formulas from physics. The ability to inexpensively fabricate analog circuitry and digital logic for millimeter-wave radar and ultrasound creates opportunities in comparing diverse perspectives on image formation, and presents challenges in implementing imaging systems that scale in size. We present algorithms, architectures, and abstractions for image formation that relate the different communities, technologies, and tools. We address practical technical challenges in operating millimeter-wave radar and ultrasound systems in the presence of phase noise and scattering.

We model a broad class of physical phenomena with isotropic point sources. We show that the optimal source location estimator for coherent waves reduces to processing an image produced by a conventional camera, provided the sources are well-separated relative to the system resolution, and in the limit of small wavelength and globally incoherent light. We introduce quasi light fields to generalize the incoherent image formation process to coherent waves, offering resolution tradeoffs that surpass the traditional Fourier uncertainty principle by leveraging time-frequency distributions. We show that the number of sensors in a coherent imaging array defines a stable operating point relative to the phase noise. We introduce a digital phase tightening algorithm to reduce phase noise. We present a system identification framework for multiple-input multiple-output (MIMO) ultrasound imaging that generalizes existing approaches with time-varying filters. Our theoretical results enable the application of traditional techniques in incoherent imaging to coherent imaging, and vice versa. Our practical results suggest a methodology for designing millimeter-wave imaging systems. Our conclusions reinforce architectural principles governing transmitter and receiver design, the role of analog and digital circuity, and the tradeoff between data rate and data precision.

2. The Capacity Region of Asynchronous Channels

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Project Staff
Venkat Chandar, Dr. Aslan Tchamkerten and Professor Gregory Wornell

A formulation of the problem of asynchronous point-to-point communication is developed. In the system model of interest, the message codeword is transmitted over a channel starting at a randomly chosen time within a prescribed window. The length of the window scales exponentially with the codeword length, where the scaling parameter is referred to as the asynchronism exponent. The receiver knows the transmission window, but not the transmission time.

In the first scenario we consider, communication rate is defined as the ratio between the message size and the elapsed time between when transmission commences and when the decoder makes a decision. Under this model, several aspects of the achievable tradeoff between the rate of reliable communication and the asynchronism exponent are quantified. First, the use of generalized constant-composition codebooks and sequential decoding is shown to be sufficient for achieving reliable communication under strictly positive asynchronism exponents at all rates less than the capacity of the synchronized channel. Second, the largest asynchronism exponent under which reliable communication is possible, regardless of rate, is characterized. In contrast to traditional communication architectures, there is no separate synchronization phase in the coding scheme. Rather, synchronization and communication are implemented jointly, and it can be rigorously proved that for low communication rates, training based schemes that perform synchronization and communication separately are suboptimal. Finally, inner and outer bounds are given on the capacity region of a general asynchronous DMC.

The second scenario considered is when data rate is defined in the traditional way, i.e., as the ratio of the message size to the blocklength of the code. We consider the error exponents associated with the events of false detection of a codeword when no codeword is present and missing the sent codeword, and provide inner and outer bounds on the achievable error exponent region as a function of the rate.

The results are relevant to a variety of sensor network and other applications in which intermittent communication is involved.

3. Locally Encodable and Decodable Source Codes

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Project Staff
Venkat Chandar, Professor Gregory Wornell, Professor Devavrat Shah

In a variety of applications, ranging from high-speed networks to massive databases, there is a need to maintain histograms and other statistics in a streaming manner. Motivated by such applications, we establish the existence of efficient source codes that are both locally encodable and locally decodable. In the formulation of interest, N integers are to be stored in a data structure such that: (a) they are represented in an efficiently compressed format; and (b) each of the integers can be both written/updated (encoded) and read (decoded) in essentially constant time. By contrast, existing data structures that have been proposed in the context of streaming algorithms and compressed sensing in recent years (e.g., various sketches) support local encodability, but not local decodability---to read even a single integer requires decoding the entire data structure.

Our solution is an explicit construction in the form of a (randomized) data structure that: (a) utilizes minimal possible space, and (b) takes near constant time (on average and with high probability) to read (decode) or write/update (encode) any of the N integers. Our construction uses multi-layered sparse graph codes based on a combination of Ramanujan graphs and the zigzag product. Our construction also leads to a simple message-passing algorithm providing a robust (L1/L1) recovery guarantee for compressed sensing of nonnegative signals.

4. Underwater Acoustic Communication System Design

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Project Staff
Qing He and Professor Gregory Wornell

In the past twenty years, extensive techniques were invented for wireless communication in the air. Nevertheless, communication in the underwater environment is still a great challenge to the existing technology. As 70 percent of the earth is covered in ocean, advancement in underwater communication will contribute significantly in the studying of ocean-geographic and in the development of applications underwater.

The goal of the project is to research methods for transmitting information in the underwater channel. While a variety of methods have been developed for wireless communication in the traditional air medium, the water channel introduces a new set of complications that require novel approaches to improve data rates, the range of transmission and communication reliability. In particular, the dynamic ocean environment presents a large amount of inter-symbol interference (ISI) and a rapidly time-varying channel. The channels are time and frequency spread channels, which have wide delay spread and significant Doppler effects.

At the current stage of my research, the communication approach being studied uses faster-than-Nyquist (FTN) signaling, where symbols are transmitted faster than the Nyquist rate and signals are demodulated using adaptive equalizers implemented using the RLS algorithm. This method exploits the fact that the added ISI due to FTN signaling is minimal in comparison to the ISI of the channel. The project focuses on the development of receiver architectures for such systems. By increasing the signaling rate, while decreasing the bits per symbol by incorporating a simpler constellation diagram, FTN signaling can provide an increase in overall rate and allow for low-complexity implementations of acknowledgment messages and multi-rate coding.

Numerical simulations based on experimental data are being conducted to explore the performance of the proposed FTN signaling scheme, along with conventional error correction coding and equalization techniques. Experimental data for the FTN transmit method was obtained during the SPACE08 experiments. Using a single transmit hydrophone and multiple receive hydrophone arrays, data was collected underwater over a month period at distances of 60m, 200m, and 1000m. The current multiple hydrophone receivers we have developed show promising results for providing advancement in underwater communication rate by using FTN methods.

5. Low Latency Delivery of Lossless and Degradable Streams

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Project Staff
Ying-zong Huang, Dr. Yuval Kochman and Professor Gregory Wornell

We investigate the zero-delay joint coding and transmission of a colored Gaussian source over an unreliable channel, with application to video streaming. The system constraints limit what can be done in response to channel errors, in light of the fact that typical channel coding methods are unavailable. We propose a linear predictive quantization system similar to and generalizing the standard differential pulse code modulation (DPCM). By optimizing within this structure, we derive an achievability result for distortion performance in the high-rate limit and compare it to an upper bound, which we also produce. A comparison is made to DPCM and PCM systems that operate under the same conditions. While typically DPCM performs well without erasures and PCM suffers less with many erasures, we show that the proposed solution improves performance over both under all severities of erasures, with unbounded improvement in certain cases.

We also continued the research on the hybrid FEC-ARQ protocol for lossless streaming over an unreliable channel, with application to cloud computing. While previously we considered the queued source to take absolute priority in transmission over error correction, we consider, in this continuation, the pre-emption of the source under a more general scheme incorporating decoding likelihood. Through simulations, we show better delay performance for cases where application traffic is bursty, the bandwidth is oversubscribed, the loss rate is high, or the delay is high.

6. Delay-Throughput Tradeoff for Streaming over Blockage Channels with Delayed Feedback

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Project Staff
Dr. Huan Yao, Dr. Yuval Kochman and Professor Gregory Wornell

We consider the problem of real-time streaming over a blockage channel with long feedback delay, as arises in real-time satellite communication from a comm-on-the-move (COTM) terminal. For this problem, we introduce a definition of delay that captures the real-time nature of the problem, which we show grows at least as fast as $O(\log(k))$ for memoryless channels, where k corresponds to the number of packets in the transmission. Moreover, we show that a tradeoff exits between this delay and a natural notion of delay-throughput tradeoffs within this framework which we show can be augmented with coding for additional performance gains. Simulations validate the new protocols on channels with and without memory.

7. Mitigating Phased Array Quantization Errors via Spatial Over-sampling

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Semiconductor Research Corporation through the FCRP Center for Circuit & System Solutions (C2S2)

Project Staff
James Krieger, Professor C.-P. Yeang, Professor Lizhong Zheng and Professor Gregory Wornell

A novel approach to the design of phased array antennas is introduced in which the element to element spacing is reduced beyond the distance prescribed by conventional design practices. The conventional approach is based on the well-established understanding that the radiation characteristics of the array are ultimately limited by the available physical aperture. As the density of the array elements is increased past the point at which the element spacing is approximately one-half of the radiation wavelength, little to no improvement with regard to the ability to control the radiation is achieved. However, the conventional wisdom that takes this to imply that there is no advantage whatsoever to increased element density is somewhat fallacious.

The above conclusion is based on an ideal case in which precise control of the excitation at each element is allowed, but in reality this precision comes at a cost that generally dominates the overall cost and complexity of the entire array. This work describes a method in which the need for precise control is relaxed while the number of array elements is increased and studies the trade spaces of array cost, complexity, and performance.

8. Design and Implementation of Real-time Brain-machine Interface (BMI)

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Project Staff
Maryam Shanechi, Professor Gregory Wornell, Professor Emery Brown, Dr. Ziv Williams

Brain Machine Interfaces (BMIs) aim to restore lost motor function in patients with various neurological disorders by creating a new communication link from the functioning brain to outside devices. BMIs work in part by mapping the noisy observations of the neural signal to the intended movement. This process is also known as 'decoding'. There are various states of a movement that could potentially be decoded and used in reconstructing the intended trajectory. These include the intended target of the movement and its kinematic states such as speed or direction. In this work we build a novel decoder using an optimal feedback control design that combines both kinematic and target related neural activity and jointly estimates the target and trajectory of the movement. We test this decoder by implementing it in a real-time BMI in primates.

9. Efficient Universal Coding for Parallel Gaussian Channels

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Project Staff
Maryam M. Shanechi, Dr. Uri Erez and Professor Gregory Wornell

The design of practical universal codes for parallel Gaussian channels, when the capacity is known at the transmitter but the channel parameters themselves are not, is of significant interest in a variety of emerging wireless applications and standards.

In this work, we investigate various universal coding approaches for the parallel Gaussian channel in scenarios with very limited or no channel state information at the transmitter. We mainly focus on channels with moderate SNR and seek a practical method that performs well for all channel conditions. We also construct optimal universal codes for low and high SNR regimes.

10. Cross Layer Design of MIMO Downlink Schedulers

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Project Staff
Charles Swannack and Professor Gregory Wornell

It is now well understood that the use of a multiple-element antenna array at the transmitter can, in principle, greatly increase the capacity of wireless systems. However, little is known about the performance characteristics of such wireless systems in a network setting, or about how to optimize the design of such systems, especially when complexity is taken into account as a practical constraint. This project studies the problem of multi-user multiple antenna broadcast system design with an emphasis on the role that channel feedback plays in a network setting. We develop new design principles for channel feedback design in such systems and show that the system designer is afforded extra degrees of freedom in the choice of the channel quantizer due to the multi-user diversity of the system. As such, the system designer may use the extra degrees of freedom to design structured quantizers that aid in user selection and allow the system to adapt to heterogeneous user populations with different fading characteristics. We construct an adaptive quantization framework which, when paired with low-complexity graph algorithms, enables efficient and robust user scheduling for multi-user multiple-antenna broadcast systems.

11. Distinguishing Codes from Noise: Fundamental Limits and Applications to Sparse Communication

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Project Staff
Da Wang, Professor Sae-Young Chung, Venkat Chandar, Professor Gregory Wornell

We investigate the problem of distinguishing codes from noise. We develop a slotted channel model where in each time slot, the channel input is either a codeword or a noise sequence. In this model, successful communication requires both correctly detecting the presence of a codeword and decoding it to the correct message. While the decoding problem has been extensively studied, the problem of distinguishing codes from noise is relatively new, and we ask the following question regarding the "distinguishability" of a channel code: given a noisy channel and a code with a certain rate, what are the fundamental limits of distinguishing this code from noise at the output of the channel?

The problem of distinguishing codes from noise involves both detection and decoding. In our analysis, we first extend the classical channel coding problem to incorporate the requirement of detection, which admits both miss and false alarm errors. Then we investigate the fundamental limits of code distinguishing in terms of the error exponents of miss and false alarm error probabilities. In a scenario that miss probability is required to vanish asymptotically but not necessarily exponentially, we characterize the maximum false alarm error exponent at each rate, and show that an i.i.d. codebook with typicality decoding is sufficient to achieve the maximum exponent. In another scenario that requires certain miss error exponent, we show that for DMC channels, the i.i.d. codebook is suboptimal and the constant composition codebook achieves the best known performance. For AWGN channels, we develop a clustered spherical codebook that achieves the best known performance in all operating regimes.

This code distinguishability problem is strongly motivated by the synchronization problem in sparse communication, a new communication paradigm where transmissions take place intermittently and each transmission consists of a small amount of data. Our results show that, in sparse communication, the traditional approach of conducting synchronization and coding separately is suboptimal, and our approach of designing codes for joint synchronization and information transmission achieves better performance, especially at high rates. Therefore, for systems with sparse transmissions such as sensor networks, it is beneficial to adopt the joint sync-coding architecture instead of the traditional separate sync-coding architecture.

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