Digital Signal Processing Research Program

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Introduction

The field of Digital Signal Processing grew out of the flexibility afforded by the use of digital computers in implementing signal processing algorithms and systems. It has since broadened into the use of a variety of both digital and analog technologies, spanning a broad range of applications, bandwidths, and realizations. The Digital Signal Processing Group carries out research on algorithms for signal processing and their applications. Current application areas of interest include signal enhancement and detection; speech, audio and underwater acoustic signal processing; and signal processing and coding for wireless and broadband multiuser/multimedia communication networks.

In some of our recent work, we have developed new methods for signal enhancement and noise cancellation, and for implementing signal processing in distributed environments. We have also been developing new methods for representing and analyzing signals based on the mathematics of fractals, chaos and nonlinear dynamics and applying these to various application contexts. We are also exploring some areas of biology and physics as metaphors for new signal processing methods.

In other research, we are investigating applications of signal and array processing to ocean and structural acoustics and geophysics. These problems require the combination of digital signal processing tools with a knowledge of wave propagation to develop systems for short time spectral analysis, wavenumber spectrum estimation, source localization, and matched field processing. We emphasize the use of real-world data from laboratory and field experiments such as the Heard Island Experiment for Acoustic Monitoring of Global Warming and several Arctic acoustic experiments conducted on the polar ice cap.

Another major focus of the group involves signal processing and coding for digital communications applications including wireless multiuser systems and broadband communication networks. Specific interests include commercial and military mobile radio networks, wireless local

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area networks and personal communication systems, digital audio and television broadcast systems, multimedia networks, and broadband access technologies. Along with a number of other directions, we are currently exploring new code-division multiple-access (CDMA) strategies, space-time techniques for exploiting antenna arrays in wireless systems, new multiscale methods for modeling and management of traffic in high-speed packet-switched networks, and new information embedding techniques for digital watermarking of media and related applications.

Much of our work involves close collaboration with the Woods Hole Oceanographic Institution, MIT Lincoln Laboratory, and a number of high technology companies.

1. Signal Processing for DNA sequencing

Sponsors

Texas Instruments, Inc.
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Contract RP6891

Project Staff
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The development of the Human Genome Project and the commercial interest for DNA sequencing has brought a significant pressure to develop large scale equipment with high throughput rates. Traditional methods for DNA sequencing require significant human intervention, which makes them expensive, slow, and error prone. However, the process is very repetitive and straightforward, a very good candidate for automation. Indeed, commercial machines now exist that reduce the human interaction significantly. These machines produce an electrical signal that should be interpreted to complete the sequencing process.

This operation, called base calling, is very crucial in the cost of genome mapping. Genome maps are constructed by carefully sequencing overlapping fragments of the DNA and combining the overlapping sequences to produce the complete map. To increase the accuracy of the map, the genome is sequenced several times and the redundancy is used for error detection and correction. Since the main cost of genome mapping is the materials and the sequencing process, decreasing the number of times the process should run results to a significant reduction in the cost. Therefore, increasing the accuracy of the base calling software will significantly reduce the redundancy required to produce an accurate map, and, thus, the cost.

In this project we are looking into statistical approaches for basecalling. We are taking the view that the problem is very similar to speech--phoneme, specifically--recognition in terms of structure and formulation. Indeed, both problem involve the conversion of a signal to a sequence of symbols (phonemes, in the case of speech, and bases in the case of DNA sequencing). We are trying to use methods that have proved successful in the speech processing domain to tackle the base calling problem. Furthermore, we are trying to adapt and extend these methods to accommodate the specifics of the problem.

Our aim is to extend the accuracy of existing methods, especially in low signal-to-noise ratio conditions. We believe that the limit for base calling has not been reached, and we would like to get one step closer.

2. Block-Iterative Interference Cancellation Techniques for Digital Communication Receivers

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Project Staff
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We are investigating a new and efficient class of nonlinear receivers for digital communication systems. These "iterated-decision'' receivers use optimized multipass algorithms to successively cancel interference from a block of received data and generate symbol decisions whose reliability increases monotonically with each iteration. Two variants of such receivers are being explored: the iterated-decision equalizer and the iterated-decision multiuser detector. Iterated-decision equalizers, designed to equalize intersymbol interference (ISI) channels, asymptotically achieve the performance of maximum-likelihood sequence detection (MLSD), but only have a computational complexity on the order of a linear equalizer (LE). Even more importantly, unlike the decision-feedback equalizer (DFE), iterated-decision equalizers can be readily used in conjunction with error-control coding. Similarly, iterated-decision multiuser detectors, designed to cancel multiple-access interference (MAI) in typical wireless environments, approach the performance of the optimum multiuser detector in uncoded systems with a computational complexity comparable to a decorrelating detector or a linear minimum mean-square error (MMSE) multiuser detector.

3. Source Representation and Encoding for Multimedia Applications

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Project Staff
Stark Draper, Professor Gregory W. Wornell

We are working in the area of source compression for correlated sources. Standard techniques lead to one of two options. One is to entropy encode the two sources into one codeword. This uses minimal memory resources, but leads to complicated decoding procedures. Alternately, the sources can be separately entropy encoded into two independent codewords. This uses greater memory resources, but leads to simple decoding procedures.

We are interested in a third set-up where the sources are encoded into three codewords. One codeword characterizes the "common information" between the two sources, and the other two codewords characterize the "marginal refinements" needed to reconstruct each source. By differentially weighting the cost of the common information rate versus the marginal rate, we can trace out a region bracketed by the two standard techniques described above.

We focus both on the design of algorithms to implement such source coding and their application in such diverse areas as adaptive memory interfaces, coding for networks, and cryptography. Finally, we explore the insights that this tool can provide into dual problems of channel coding.

4. Quantum Detection and Signal Processing

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In our research we are exploring relationships between detection problems that arise in the context of quantum physics, and signal processing methods. One aspect of our research is directed towards developing new methods for quantum detection using signal processing tools. Another aspect of our research is directed towards developing a new framework for signal processing methods by exploiting the fundamental ideas and constraints of quantum mechanics. In particular, we are pursuing some new viewpoints towards matched filter detection that have connections with the quantum detection problem. We are also exploring new techniques for suppressing interference in multiuser wireless settings, that result from this framework.

5. Space-Time Algorithms for Gbit Wireless LANs

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Due to the rich scattering environment of an indoor setting, wireless communication is hindered by signal fading (loss of signal energy) due to multipath propagation of signals from transmitter to receiver. The frequent lack of line of sight signaling and time-varying nature of the communications channel (due to movement of people and objects for instance) limits the amount of data than can be reliably transmitted given power and bandwidth constraints. One way to mitigate these effects is with arrays of antennas at either the transmitter or receiver, or both. Space-time codes are a class of codes which provide signal diversity in both space and time (as their name implies) by "spreading" information bits over many samples in time as well as over the spatially separated antennas to provide redundancy to aid in decoding.

In the context of a wireless indoor LAN, we are looking at developing and designing algorithms for a system to achieve gigabit data rates over an indoor wireless channel. The available bandwidth will be divided into several subchannels , each of which will be 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 spatial diversity of 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. As long as there are

sufficient antennas at the server, adding more nodes in the network does not affect the available bandwidth of the existing nodes.

We are also looking the effects of the non-idealities that are inevitable in building an actual system, such as channel estimation errors and antenna isolation difficulties, and their impact on our ability to reach very high data rates. Additionally, by examining the fundamental characteristics of the analog hardware in the system that are typically abstracted away, we are looking for ways to improve performance in novel ways.

6. Cooperative Diversity in Wireless Relay Networks: Algorithms and Architecture

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Project staff
J. Nicholas Laneman, Professor Gregory W. Wornell

In wireless networks, signal fading arising from multipath propagation is a particularly severe form of interference that can be mitigated through the use of *diversity*---transmission of redundant signals over essentially independent channel realizations in conjunction with suitable receiver combining to average the channel effects. Space, or multi-antenna, diversity techniques are particularly attractive as they can be readily combined with other forms of diversity, *e.g*., time and frequency diversity, and still offer dramatic performance gains when other forms of diversity are unavailable. In contrast to the more conventional forms of single-user space diversity with physical arrays---co-located antenna elements connected via high-bandwidth cabling---this work builds upon the classical relay channel model and examines the problem of creating and exploiting space diversity using a collection of distributed antennas belonging to multiple users, each with their own information to transmit. We refer to this form of space diversity as *cooperative diversity* because the users share their antennas and other resources to create a "virtual array" through distributed transmission and signal processing.

Our work to date has developed low-complexity cooperative diversity protocols that take into account certain implementation constraints in the relay mobiles. We develop and analyze a variety of cooperative protocols in which the relay either amplifies what it receives, or fully decodes, re-encodes, and re-transmits the source message. We refer to these options as *amplify-and-forward* and *decode-and-forward*, respectively. Each of our cooperative protocols achieve *full* space diversity; that is, the outage probability decays proportional to $1/SNR^2$ in the case of two users cooperating, where SNR is signal-to-noise ratio of the channel, while it decays proportional to 1/SNR without cooperation. Our schemes are close to optimal in certain regimes and offer big power savings over direct transmission. More broadly, the relative attractiveness of amplify-and-forward and decode-and-forward, and adaptive versions thereof, can depend upon the network architecture and implementation considerations, which we continue to explore.

7. Multiuser Wireless Communication Using Transmitter Antenna Diversity and Feedback

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Project Staff
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We investigate the use of transmitter antenna diversity in multiuser wireless communications. In particular, we propose an amount of integration between the physical layer, feedback of channel side information, and properties of the data itself. We believe that transmitter arrays are particularly well-suited to gaining these efficiencies when data (either common or receiver-specific) must be delivered to multiple users. Our research is in contrast to most space-time coding and array processing, in which strict layering is maintained and channel knowledge at the transmitter is often not present at all.

8. Multimedia Authentication

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Project Staff
Emin Martinian, Brian Chen, Professor Gregory W. Wornell

Low latency communication is a key requirement for next generation interactive applications such as voice and video conferencing, tele-medicine, games, etc. Traditionally, latency and delay have usually been dealt with by either assuming infinite delay is allowed or absolutely no delay is allowed. Instead we plan to look at delay as a parameter, such as transmission power, and study the fundamental trade-offs inherent in low delay communication as well as developing new techniques to achieve the best delay trade-offs.

9. Efficient Algorithms for Resampling

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Project Staff
Andrew Russell, Professor Alan V. Oppenheim

This research is focusing on developing efficient algorithms for performing resampling on a digital computer. Resampling is viewed as a change of the sampling grid, where the input and output grids may be regular or irregular. The results derived have been applied to various problems including sampling rate conversion, nonuniform sampling and pulse-position modulation. The algorithms being derived can be implemented in real time and assume sequential input and output data streams.

10. Biological Signal Processing

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Project Staff
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Biological Signal Processing (BSP) defines a framework that lies at the intersection of Signal Processing and Molecular Biology. Our goal is to define and explore the basis for a meaningful and potentially paradigm-shifting interaction between the two fields. In a first stage, signal processing tools are used to develop signal processing models for functional steps involved in biological information processing. In a somewhat parallel manner, biological processing operations are used as a metaphor to develop novel signal processing algorithms and filtering techniques. Finally, at a later stage, BSP emerges as a discipline where biological systems are used as actual hardware for performing signal processing. In this context, meaningful elementary operations, rules of associations, and signal transmission constraints are defined.

11. Communication Metrics for Signal Processing Algorithm Design

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Project Staff
Charles Sestok, Professor Alan V. Oppenheim

Traditionally, the efficiency of a signal processing algorithm is measured by the amount of computation it requires. Trends in implementation technology are challenging the validity of this cost measure. In semiconductor technology, for example, the cost of computation continues to decline exponentially, and the cost of transporting data, in both time delay and power dissipation, does not decrease so quickly. As the delay and energy necessary to drive a signal across a chip becomes unacceptable, it is likely that multi-processor architectures will become more prevalent. Its reasonable to predict that the cost of implementing a signal processing algorithm on these new DSPS will be dominated by the amount of data communication. Additionally, there is interest in distributed systems, such as sensor networks that collaboratively process data. the sensors must communicate data long distances to process it effectively, requiring significantly more energy and time than local computation.

In light of these systems with cost structures dominated by communication, we are investigating the design of signal processing algorithms under communication cost measures. We are pursuing the problem on two fronts. First, we are examining traditional signal processing algorithms such as LTI filtering and Fourier transforms to determine the fundamental limits on the amount of communication required to implement them on distributed processor architectures. Second, we are investigating algorithms for estimation And detection on sensor networks. We are developing algorithms that perform well when the amount of data available for processing is limited by the communication capacity of the network.

12. Generalized Frequency Modulation

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Project Staff
Wade Torres, Professor Alan V. Oppenheim

We have developed generalized theory of frequency modulation in which state trajectories of dynamical systems are used as carrier waves. This freedom to choose the carrier wave has several potential advantages. For example, a carrier wave can be chosen that satisfies a given optimality criterion for a particular channel. Also, because the systems can be non-linear, components used in their realizations are not restricted to operate in a linear regime. This leads to less complex and more efficient circuitry. Another potential application is in the area of private communications. Chaotic systems are among the class of systems to which generalized frequency modulation is applicable. Because chaotic signals are noise-like and difficult to predict, they are not easily distinguished from background noise nor are they easy to demodulate without complete knowledge of the parameters of the transmitter.

The primary focus of our work is the design and analysis of modulators and demodulators for generalized frequency modulation systems. In particular, a systematic procedure for demodulator design is developed that depends on the underlying dynamical system in a simple manner. These demodulators are analyzed to ascertain their tracking capability and their robustness to additive noise.

13. Decoding For Wireless Communication Systems With Multiple Antennas Using Lattice Reduction

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It has been shown theoretically that using multiple transmit and receive antennas in a wireless communication systems can significantly increase the capacity of the system and its robustness against fading. The capacity increase is linear with the number of antennas used, with no extra cost of bandwidth nor time. All the antennas can transmit in the same bandwidth and at the same time.

However, one major problem with utilizing multiple antennas is the interference between the transmission from the different antennas. Theoretically, the decoder should be able to extract the transmitted information. But in practice, even if we assume the channel is known, a optimal maximum likelihood decoder would take exponential time to operate. One conventional technique is to use the decorrelator, which is a linear decoder. The component of each signal that is orthogonal to all the others is used for detection. The disadvantage of this method is that the SNR becomes very low when the signals are highly correlated. The effect is that the diversity gain, the rate at which error rate decreases with SNR, is very low compare to what the optimal ML decoder can achieve.

Lattice reduction techniques can greatly improve the performance of the decorrelator by changing to a more orthogonal basis when the original signals are highly correlated. The effective SNR is increased and the decision regions becomes closer to the optimal one the ML decoder achieves. Preliminary results have shown that with lattice reduction, the performance of the new decorrelator can achieve the same diversity as ML decoder does. For the two antenna case, the choice of the optimal basis has been precisely defined, an iterative algorithm for finding the optimal basis has been designed, its convergence property and complexity analyzed, and the performance sub-optimality compared to ML is bounded.

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