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; advanced beam forming for radar and sonar systems; and signal processing and coding for wireless and broadband multi-user/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 knowledge of wave propagation to develop systems for short time spectral analysis, wave number 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 multi-user systems and broadband communication networks. Specific interests include commercial and military mobile radio networks, wireless local area networks and personal communication systems, digital audio and television broadcast systems, multimedia networks, and broadband access technologies. Along

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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 collaboration with the Woods Hole Oceanographic Institution and a number of high technology companies.

1. Signal Processing for DNA sequencing

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The development of the Human Genome Project and the commercial interest for DNA sequencing has generated significant interest in developing 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 have studied statistical approaches for base calling. We are taking the view that the problem is very similar to speech--phoneme, specifically--recognition in terms of structure and formulation. Indeed, both problems 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 has been 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. Frames, Geometric Algebra and Signal Processing

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The purpose of this research is to explore new mathematical tools and their application in Signal Processing. Specifically we are investigating frame expansions, and geometric (Clifford) algebras. Frame expansions are a very convenient way to generate redundant signal representations, thus creating a representation robust to noise and degradation. We are looking into issues of noise shaping and signal reconstruction using such a representation. Furthermore, we are investigating the application of geometric algebras in signal processing. The algebraic structure of these tools provides a very convenient way to analyze and think about signal processing algorithms. Our objective is to exploit this structure to improve our understanding of existing algorithms, and obtain intuition into creating new ones. We believe that these mathematical tools have the potential to improve significantly our understanding of signal processing methods and create new signal processing paradigms.

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

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The proposed research introduces a new, low-complexity class of nonlinear receivers that detects data symbols distorted by channel interference and noise. Applications of the proposed ``iterated-decision'' detectors in digital communication contexts include the equalization of intersymbol interference (ISI) channels, the cancellation of multiple-access interference (MAI) in typical wireless environments, and the decoding of multiple antenna systems.

Iterated-decision detectors use optimized multipass algorithms to successively cancel interference at the receiver and generate symbol decisions whose reliability increases monotonically with each iteration. The research investigates implementations when the channel is known at the receiver, when the channel is unknown and must be learned at the receiver, and when channel coding is used to approach channel capacity. Strategies are also proposed to ensure that effectively optimal interference cancellation is achieved with arbitrary channels.

4. Multimedia Content Authentication

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In traditional authentication problems, the goal is to determine whether a received message is an exact replica of what was sent. Digital signature techniques are a natural tool for addressing such problems. However, in many emerging applications the message may be an audio or video waveform, and before being presented to a decoder the waveform may experience any of a variety of possible perturbations, including, for example, degradation due to noise or compression; transformation by filtering, resampling, or transcoding; or editing to annotate, enhance, or otherwise modify the waveform. Moreover, such perturbations may be intentional or unintentional, and benign or malicious.

Methods for reliable authentication from such perturbed data are important and so we propose one possible model for the authentication problem, and examine its implications. In terms of performance limits, we assess the inherent trade-offs between security, robustness, and distortion, and develop the structure of systems that make these trade-offs efficiently. We show that under this model, the authentication problem is substantially different from familiar formulations of the digital watermarking and data hiding problems, and has a correspondingly different solution.

5. Multimedia Transcoding and Requantization

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There are a variety of engineering scenarios where the bit rate of a compressed data stream must be decreased further by transcoding/requantization. When a scalable encoder (also known as an embedded encoder) is used in the initial compression step, transcoding can be accomplished by discarding layers of least significant bits, often without sacrificing compression efficiency. By contrast, we study the distortion-rate tradeoffs, which can be guaranteed when scalable encoders are not used in the initial compression step and no provisions have been made for the rate reduction. Specifically, we attempt to quantify the penalty incurred in such scenarios and show that in some practical cases, this penalty is not too large.

6. Compensation for Defective D/A Conversion

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Flat-panel displays such as those found in modern personal computers are made by placing thousands of light emitting diodes (LEDs) on a silicon wafer. Each LED corresponds to one color component of one pixel of the image. Often, one of these LEDs malfunctions and gets permanently set to a particular value. In this case, the entire flat-panel may be considered defective and thus be discarded. However, we may compensate for a defective LED by adjusting the intensity of the neighboring LEDs.

Because of the non-zero pixel size along with the blurring introduced by the eye, properly compensating can minimize the visual distortion caused by the defective LED. We refer to this as the missing pixel problem. In this project we are searching for solutions, which could lead to flat-panel displays that can correct for defective pixels by performing some processing on the image signal.

We have restricted ourselves to the one-dimensional version of the missing pixel problem. A signal is to be reconstructed through an ideal low-pass filter. We know what the reconstructed signal is to be, but because the reconstruction grid has one pixel missing, we cannot achieve the desired reconstruction. Our goal is to find a compensation signal, added before the reconstruction takes place, that minimizes the mean-squared error (MSE) between the actual and desired reconstruction.

The problem naturally formulates itself as finding a compensation signal that has minimum energy in the low-pass band in addition to canceling the value of the missing pixel. A solution using an infinite length compensation was found in work previously done. However, infinite length signals are not practicably feasible, thus our effort focuses on finding optimal finite-length compensation signals. Our aim is to give a thorough theoretical description of the solution to the idealized missing pixel problem in addition to finding practical numerical techniques its computation.

7. Calibration and Correction Techniques for Parallel Analog-to-Digital Converters

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Next-generation wireless LANs will require the ability to sample signals at very high speeds. This sampling allows the system to achieve higher data rates, thus providing more capabilities to the users. One method of high-speed sampling uses parallel analog-to-digital converters (ADCs). In these systems, the analog input signal is sent through multiple branches of ADCs, each which collects a certain fraction of samples. In theory, this process allows for extremely high rates of sampling; in practice, there are many real-world limitations. Because of imperfections and mismatch in the ADCs and circuit design, interleaving ADCs gives rise to a variety of gain, offset and time-skew errors. This research is investigating advanced algorithmic calibration and correction techniques for such systems.

8. Successive Structuring of Source Coding Algorithms for Data Fusion, Buffering, and Distribution in Networks

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Numerous opportunities to improve network performance present themselves when we make communication networks aware of the characteristics of the data content they are handling. In our work, we have designed such content-aware algorithms for a number of applications, focusing on problems of data fusion, buffering, and distribution. These algorithms span traditional network layers and share a common successive structuring. This structure provides the flexibility needed to deal with the distributed processing, the heterogeneous sources of information, and the uncertain operating conditions that typify many networks.

One branch of our research investigates the interplay between signal processing algorithms and communication constraints in the context of estimation and detection in distributed systems. We show how joint design of the estimation and communication subtasks can significantly improve system performance. We decompose general sensor trees into prototype serial (pipeline) and parallel (hub-and-spoke) networks. We develop coding strategies for these prototype networks based on generalized Wyner-Ziv source coding with decoder side information. Combining these strategies gives a good coding approach to arbitrary sensor trees. Under a sum-rate constraint, the parallel network is closely related to what is referred to as the CEO problem. We connect our work to those earlier results. Finally, we apply our results to develop channel-coding strategies for certain classes of relay channels.

We also explore the interactions between source coding and queue management in problems of buffering and distributing distortion-tolerant data. We develop a powerful buffer management algorithm for queues handling distortion-tolerant data under finite memory limitations. When multiresolution source codes are used, overflows can be avoided and significant performance gains realized by reducing the fidelity of signal descriptions in a gradual, controlled, manner. We show that the proposed algorithm is sample-path optimal, i.e., it achieves an average distortion equal to the best achievable by any algorithm, including those designed with full non-causal knowledge of queue arrival and service times.

9. Quantum Signal Processing

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Quantum signal processing (QSP) as formulated in this thesis, borrows from the formalism and principles of quantum mechanics and some of its interesting axioms and constraints, leading to a novel paradigm for signal processing with applications in areas ranging from frame theory, quantization and sampling methods to detection, parameter estimation, covariance shaping and multiuser wireless communication systems. The QSP framework is aimed at developing new or modifying existing signal processing algorithms by drawing a parallel between quantum mechanical measurements and signal processing algorithms, and by exploiting the rich mathematical structure of quantum mechanics, but not requiring a physical implementation based on quantum mechanics. This framework provides a unifying conceptual structure for a variety of traditional processing techniques, and a precise mathematical setting for developing generalizations and extensions of algorithms.

Emulating the probabilistic nature of quantum mechanics in the QSP framework gives rise to probabilistic and randomized algorithms. As an example we introduce a probabilistic quantizer and derive its statistical properties. Exploiting the concept of generalized quantum measurements we develop frame-theoretical analogues of various quantum-mechanical concepts and results, as well as new classes of frames including oblique frame expansions, that are then applied to the development of a general framework for sampling in arbitrary spaces. Building upon the problem of optimal quantum measurement design, we develop and discuss applications of optimal methods that construct a set of vectors with a given inner product structure that are closest in a least-squares sense to a given set of vectors. We demonstrate that, even for problems without inherent inner product constraints, imposing such constraints in combination with least-squares inner product shaping leads to interesting processing techniques that often exhibit improved performance over traditional methods. In particular, we formulate a new viewpoint toward matched filter detection that leads to the notion of minimum mean-squared error covariance shaping. Using this concept we develop an effective linear estimator for the unknown parameters in a linear model, referred to as the covariance shaping least-squares estimator. Applying this estimator to a multiuser wireless setting, we derive an efficient covariance shaping multiuser receiver for suppressing interference in multiuser communication systems.

10. Elements of an Efficient Wireless Gigabit LAN System Architecture

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In the context of a wireless indoor LAN, we are looking at developing space-time codes and algorithms for a system to achieve gigabit data rates over an indoor wireless channel. By utilizing an antenna array on a central server with a virtual array formed by the mobile nodes, the network is able to simultaneously support many nodes communicating over the same frequencies without cooperation or collisions between nodes. The central server allocates and directs communications such that the nodes in the network do not need to be aware of each other.

We are also looking the effects of the nonidealities that exist in an actual system, such as channel estimation errors, antenna and circuit crosstalk, and their impact on the network's ability to reach high data rates. For crosstalk in particular, a system has to be designed to function properly given the worst-case crosstalk performance. With the proposed architecture of multiple RF chains on a single chip, designing for the worst case may require an overly conservative design. A randomization of the crosstalk phase can greatly improve the worst-case performance by ensuring that a particular instance of a circuit does not get "stuck" in a bad configuration. This can open the door to novel circuit designs which have what would otherwise be unacceptable amounts of signal leakage between components.

11. Multicasting in Wireless Networks with Multi-Antenna Base Station

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Multiple antenna base stations can dramatically increase the capacity of wireless networks. In this research project we study efficient transmission schemes over multi-antenna channels in a wireless network where there are many different multicast groups. All users within a multicast group want the same message while users in different groups want different messages.

We have studied an achievable rate region using beam-forming technique. This is a linear interference suppression technique that optimizes transmission to each group while minimizing the interference caused to other groups. When the number of multicast groups is small, we have shown that this technique performs better than treating all the users as independent and applying the best-known technique for independent users. These preliminary results suggest that it is important to exploit common information in a network to improve system performance.

12. Multiplexing, Scheduling, and Multicasting Strategies for Antenna Arrays in Wireless Networks

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A transmitter antenna array has the ability to direct data simultaneously to multiple receivers within a wireless network, creating potential for a more integrated view of algorithmic system components. In this thesis, such a perspective informs the design of two system tasks: the scheduling of packets from a number of data streams into groups; and the subsequent spatial multiplexing and encoding of these groups using array processing. We demonstrate how good system designs can help these two tasks reinforce one another, or alternatively enable tradeoffs in complexity between the two. Moreover, scheduling and array processing each benefit from a further awareness of both the fading channel state and certain properties of the data, providing information about key flexibilities, constraints and goals.

Our development focuses on techniques that lead to high performance even with very low-complexity receivers. We first consider spatial precoding under simple scheduling and propose several extensions for implementation, such as a unified time-domain precoder that compensates for both cross-channel and intersymbol interference. We then show how more sophisticated, channel-aware scheduling can reduce the complexity requirements of the array processing. The scheduling algorithms presented are based on the receivers' fading channel realizations and the delay tolerances of the data streams. Finally, we address the multicasting of common data streams in terms of opportunities for reduced redundancy as well as the conflicting objectives inherent in sending to multiple receivers. Our channel-aware extensions of space-time codes for multicasting gain several dB over traditional versions that do not incorporate channel knowledge.

13. Regular and Irregular Signal Resampling

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We consider three main resampling problems. The first is the sampling rate conversion problem in which the input and output grids are both regularly spaced. It is known that the output signal is obtained by applying a time-varying filter to the input signal. The existing methods for finding the coefficients of this filter inherently tradeoff computational and memory requirements. Instead, we present a recursive scheme for which the computational and memory requirements are both low. In the second problem that we consider, we are given the instantaneous samples of a continuous-time (CT) signal taken on an irregular grid from which we wish to obtain samples on a regular grid. This is referred to as the nonuniform sampling problem. We present a noniterative algorithm for solving this problem, which, in contrast to the known iterative algorithms, can easily be implemented in real time. We show that each output point may be calculated by using only a finite number of input points, with an error which falls exponentially in the number of points used. Finally we look at the nonuniform lowpass reconstruction problem. In this case, we are given regular samples of a CT signal from which we wish to obtain amplitudes for a sequence of irregularly spaced impulses. These amplitudes are chosen so that the original CT signal may be recovered by lowpass filtering this sequence of impulses. We present a general solution which exhibits the same exponential localization obtained for the nonuniform sampling problem. We also consider a special case in which the irregular grid is obtained by deleting a single point from an otherwise regular grid. We refer to this as the missing pixel problem, since it may be used to model cases in which a single defective element is present in a regularly spaced array such as the pixel arrays used in flat-panel video displays. We present an optimal solution which minimizes the energy of the reconstruction error, subject to the constraint that only a given number of pixels may be adjusted.

14. Data Selection Techniques for Binary Hypothesis Testing

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In any signal processing system, scarce resources restrict potential performance. Traditionally, computational resources have provided significant constraints on signal processing systems. In an increasing number of situations, however, communication or movement of data dominate the cost of implementing and operating a signal processing system.

This research focuses on the impact of scarce communication resources on a specific signal processing procedure, binary hypothesis testing. We suggest data selection as a technique for coping with the resource limitations. Data selection algorithms select a subset of the available signal measurements for subsequent processing, resulting in the decision between the two hypotheses.

We develop models for data selection in several cases, considering both random and data-dependent selection algorithms. Our considerations are divided into three classes depending upon the amount of {\em a priori} information available about the competing hypotheses. In the first class, the target signal is precisely known. In the second class, the target signal is characterized by a probability density. In the third class, the target signal is unconstrained save for restrictions on its symmetry and variance. For each situation considered, we describe optimal and suboptimal selection algorithms and compare them to ultimate performance limitations.

15. Efficient Constructive Space-Time Block Codes for Multiple Antenna Channels

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In the past few years, it has been shown that using multiple antennas can tremendously increase the capacity of the communications channel, in particular, capacity increases linearly with the number of antennas used. This means using two antennas, we can communicate twice the information without spending any extra time, bandwidth, nor power. It has also been shown that using multiple antennas can increase the robustness of communication in the case where the wireless channel experiences fading, i.e., channel quality variation due to, for example, movement of the transmitter or the receiver. There has been much work done toward achieving each type of gain.

However, recently, it was discovered that there is an inherent tradeoff between these two types of gains. It was termed diversity-multiplexing tradeoff by Zheng and Tse. They evaluated the optimal tradeoff curve and showed availability using Gaussian random codes.

We recently constructed a deterministic space-time block code for two transmit and two receive antennas systems with code length two that can effectively achieve the optimal tradeoff curve for two by two systems. The deterministic nature of the code suggests practical system designs that bring both types of promised gains of using multiple antennas into reality.

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