# 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 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

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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. Neural Signal Processing

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**Project Staff**
Anthony Accardi, Professor Gregory W. Wornell

In order to understand the detailed interworkings of many neurological processes, it is necessary to measure the firing patterns realized by individual neurons. Current measuring techniques involve inserting one or more electrodes into the region of interest, which make extracellular voltage recordings derived from the action potentials of nearby neurons. The difficulty is that firing patterns from many different neurons are superimposed at the electrodes, while we are interested in individual neuron behavior. Deriving this information from such measurements is referred to as separating multiple single-unit spike trains from a multi-unit recording.

The problem is therefore one of signal separation, and many approaches have been attempted based on pattern matching and feature clustering. In many of these approaches the inaccurate assumption that different neurons exhibit action potentials with unique waveforms is made. A new instrument called the tetrode was developed in 1994. A tetrode consists of four very closely spaced electrodes, which allows one to drop this assumption and therefore perform a more reliable separation. The best existing separation schemes for the tetrode are computer assisted they present waveform parameters in a graphical manner so that a well-trained user can visually cluster the features as arising from separate neurons. These techniques necessarily prevent a full exploitation of the information available in the tetrode measurements, since decisions must be made in a low enough dimension for human visualization.

We hope to improve upon these existing multi-unit separation schemes, and will then pursue related applications (e.g., action potential coding) of our new knowledge.

## 2. Dual Channel Signal Processing

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**Project Staff**
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Many models for signal estimation systems assume only statistical information about the source signal to be recovered and about the channel through which the source is sent. In some scenarios, however, there also exists deterministic side information about the desired signal which can be used jointly with channel observations to assist recovery. For example an existing full-band, noisy analog communications infrastructure may be augmented by a low-bandwidth digital side channel. Our research is a study of a hybrid channel that is the composition of two channels: a noisy analog channel through which a signal source is sent unprocessed and a secondary rate-constrained digital channel. The source is processed prior to transmission through the digital channel. Using a signal processing framework for low latency and low complexity, we derive optimal encoder and receiver structures for hybrid channels.

## 3. Signal Processing for DNA sequencing

**Sponsors**

**Project Staff**
Petros Boufounos, Alan V. Oppenehim

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.

## 4. Batch-Iterative Channel Equalization

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**Project Staff**
Albert Chan, Professor Gregory W. Wornell

We are currently working on 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) in uncoded systems, 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 powerful error-control codes to approach channel capacity. 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.

## 5. Information Embedding and Digital Watermarking

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Digital watermarking and information embedding, which are also referred to as data hiding and steganography, refer to the process of embedding one signal, called the “embedded signal” or “digital watermark,” within another signal, called the “host signal.” The host signal is typically a speech, audio, image, or video signal, and the embedding must be done in such a way that the host signal is not degraded unacceptably. At the same time, the digital watermark must be difficult to remove without causing significant damage to the host signal and must reliably survive common signal processing manipulations such as lossy compression, additive noise, and resampling. Applications include copyright protection, authentication, transmission of auxiliary information, and covert communication.

In our work we are developing a general framework for designing digital watermarking systems, evaluating their performance, and understanding their fundamental performance limits. In the process we have developed a class of digital watermarking techniques called quantization index modulation, along with a convenient realization called dither modulation, that have considerable performance advantages over previously proposed methods. More information can be found at http://web.mit.edu/bchen/www/wmark-home.html and in the following publications.

[1] B. Chen and G.W. Wornell, “Preprocessed and postprocessed quantization index modulation methods for digital watermarking,” *Proc. of SPIE: Security and Watermarking of Multimedia Contents II* (part of Electronic Imaging 2000), San Jose, CA, Jan. 2000.

[2] B. Chen and G.W. Wornell, “Provably robust digital watermarking,” *Proc. of SPIE: Multimedia Systems and Applications II* (part of Photonics East '99), Boston, MA, Sept. 1999.

## 6. 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.

## 7. Quantum Detection and Signal Processing

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**Project Staff**
Yonina Eldar, Professor Alan V. Oppenheim

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.

## 8. Space-Time Algorithms for Gbit Wireless LANs

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**Project Staff**
Everest W. Huang, Professor Gregory W. Wornell

In 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 as well as a time-varying channel arising from movement of people and objects including the communicating nodes. One way to mitigate these effects is with arrays of antennas at the transmitter or receiver or both. Space-time codes are a class of codes which provide signal diversity 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 space-time codes and designing power-, bandwidth-, and resource-efficient algorithms to achieve gigabit data rates in an indoor wireless environment. The available bandwidth will be divided into several subchannels, each of which will be adaptively coded given the varying signal quality in that frequency band. We are also looking at the effects of the non-idealities that are inevitable in building an actual system, such as channel estimation errors and antenna crosstalk and mismatches, and ways to counteract these effects through coding. We are also constructing a wireless testbed to allow real-time testing and to aid in the development of these algorithms.

## 9. Realizing Cooperative Diversity in Wireless Relay Networks: Algorithms and Architecture

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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, time and frequency, 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 [1], this work builds upon the classical information-theoretic relay channel model [2] 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. We develop cooperative coding and decoding algorithms offering good performance and explore their implementation within standard layered network architectures.

While applicable to any wireless setting, these protocols are particularly attractive in ad-hoc (or peer-to-peer) wireless networks, in which radios are typically constrained to employ a single antenna. Substantial energy-savings and improved robustness to channel variations resulting from these protocols can lead to reduced battery drain, longer network lifetime, or improved network performance in terms of capacity, and other measures.

[1] A. Narula, M.D. Trott, and G.W. Wornell, ``Performance limits of coded diversity methods for transmitter antenna arrays,'' IEEE Trans. Inform. Theory, 45(7): 2418-2433 (1999).

[2] T. Cover and A. E. Gamal, ``Capacity theorems for the relay channel,'' IEEE Trans. Inform. Theory 25: 572-584, (Sept.1979)

## 10. Distributed Signal Processing

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Networks of distributed processors and sensors can offer significant advantages over traditional signal processing platforms through improving resource sharing and fault tolerance. However, for networks in which resource availability changes dynamically, it is important to have a flexible execution strategy which allows algorithms to adapt to the current conditions of the network. Our research studies a number of questions arising from designing signal processing algorithms for dynamically changing networks of processors and
sensors. We propose a framework in which the system is allowed to dynamically and optimally choose an execution strategy for each data block in adaptation to the computing environment. Our formulation of this strategy derives from an interesting interpretation of algorithms as similar to communications networks. A software simulation has been developed to demonstrate the ideas.

## 11. Multiuser Wireless Communication Using Transmitter Antenna Diversity and Feedback

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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.

## 12. Multimedia Authentication

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

In many multimedia applications, there is a need to authenticate sources subjected to benign degradations such as noise, compression, etc., in addition to potential tampering attacks. Authentication can be enabled through the embedding of suitably chosen markings in the original signal. As a motivating example, consider the authentication of drivers' licenses. Many jurisdictions print a hologram on the photograph portion of the license. The presence of the hologram indicates that the license is legitimate but does not add excessive distortion.

Imprinting a hologram on a license is a particular implementation of a larger class of authentication schemes. More generally, special markings are embedded into the photograph. A decoder uses these markings to extract an authentic representation of the original. The special markings should be embedded so that the distortion between the original and embedded photographs is small; thus, someone without the appropriate decoder can still use the license to check the identity of the bearer. In addition, the special markings need to be robust to perturbations in the form of smudges or other degradation due to routine handling: the decoder should still declare the photo authentic if only these are present. Finally the special markings should be inserted so that no other agent can create a successful forgery.

We are exploring these issues from an information-theoretic perspective. For a simple, but reasonable model we have obtained bounds which illustrates the fundamental tradeoffs between robustness, security, and embedding distortion. This allows us to characterize asymptotically achievable schemes which serve as performance bounds and provide insights into the design of practical systems. For example, our analysis suggests that coding plays an important role in achieving the optimal tradeoffs.

## 13. Memoryless Nonlinear Systems

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Andrew Russell, Professor Alan V. Oppenheim

Signal processing applications have typically used linear algorithms to perform processing. This is because linear systems have been well understood for years. Nonlinear techniques are sometimes used, but such algorithms are usually ad hoc or heuristic. We are trying to understand the theoretical properties of certain nonlinear systems, in order to invent new classes of nonlinear processing algorithms. With this theory in place, we will be able to understand the algorithms better, as well as prove optimality. These nonlinear techniques have been used to solve a wide range of problems, from nonuniform sampling reconstruction, to a new kind of pulsewidth modulation. We also hope to contribute to the theory on stochastic signals through nonlinear systems. Unlike with linear systems, higher order statistics play a much more important role when dealing with nonlinear systems. Some work has also been done on inverting certain many-to-one nonlinear mappings, and establishing conditions under which inversion is possible.

## 14. 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 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.

## 15. Approximation and Autonomy in Large Scale Signal Processing Computations

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Matthew J. Secor, Professor George C. Verghese, Professor Alan V. Oppenheim

This research investigates issues related to the operation, dynamics and control of networks of processors performing large-scale DSP (digital signal processing) computations. Two key aspects of our framework are the introduction of approximate processing to provide flexibility in managing system resources effectively for enhanced performance and the use of market-based models for the computational environment on which to build the communication and control algorithms.

In a typical scenario, an individual user partitions a large problem into task packets that can be distributed on the network. Other processors attend to these task packets as best they can, and then approximate results are gathered back at the user's node for re-assembly into an approximate answer to the problem of interest. Associated with such a scenario are research challenges related to characterizing DSP algorithms appropriately for this form of approximate processing, developing partitioning and re-assembly methods that are robust to differential delays and varying levels of completion in the returned task packets, and managing the communication and computation on the network so that congestion and delay instabilities are avoided. The research focuses on the latter set of problems, dealing with the dynamics and control of the network.

Specifically, we are reformulating queuing network models and load balancing strategies for networks of processors, using richer models for jobs. Our models includes the ability to use approximate processing methods to trade off the resources required to process a job against the quality of the results. We have used such models to investigate the relationship between the stability of a queue and the distribution of the quality of the jobs after being processed by the queue.

Additionally, we have investigated the use of economic models and mechanisms for the efficient allocation of resources of computations. We have developed analytical models for the dynamic behavior of an existing implementation of an auction-based resource allocation system, in order to determine the fairness and stability properties of the scheme. Some numerical pitfalls in naive approaches to the simulation of such systems have also been exposed. We are also exploring the use of game-theoretic models in order to model the strategic aspects of the interaction between independent participants in the computational marketplace in their attempts to acquire computational resources.

## 16. Communication Metrics for Signal Processing Algorithm Design

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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, 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, its likely that multi-processor architectures will become more prevalent. Its reasonable to predict that the cost of implementing a signal processing algorithms 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 the advent of 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 three 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 detection and estimation on sensor networks. Since sensor measurements may be highly correlated, we anticipate that carefully designed signal quantizers can reduce the amount of communication required for detection and estimation algorithms.

## 17. Generalized Frequency Modulation

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**Project Staff**
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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.

## 18. Coding for Transmission Using Multiple Antennas Over Unknown Flat Fading Channel.

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**Project Staff**
Huan Yao, Professor Gregory W. Wornell

Traditionally, people have been using single antennas for wireless communications. Recent research has shown that by using multiple transmitter and receiver antennas, significant increase in capacity can be achieved. (For example, two transmitter and receiver antennas can typically achieve twice the capacity.) There is no extra cost in power or bandwidth, only complexity and possibly some space.

There has been a lot of research done in the field of coding for additive white Gaussian noise (AWGN) channels since the 1950's. However, those results are all for single antennas. The key idea there, is that information is represented by a waveform, or in the discrete time world, a vector indexed by time. The goal of coding is to separate the vectors from each other as much as possible to maximize tolerance to additive noise.

In the multiple antenna realm, very little has been developed before the last five years. In this case, information is represented, not by a simple vector, but a subspace spanned by many vectors, one for each antenna. The goal for coding is to separate the subspaces from each other as much as possible. The distance between the subspaces is defined by the angles formed between them. The intuition is quite different from the AWGN coding problem. We are currently working on solving this coding problem and constructing some practical and efficient encoding and decoding schemes.

## Publications

### Journal Articles, Published

Eldar, Y. C. and Oppenheim, A. V. "Filterbank Reconstruction of Bandlimited Signals from Nonuniform and Generalized Samples," *IEEE Trans. Signal Processing*, 48(10): 2864-2875, (2000).

Russell, A. I. "Efficient Rational Sampling Rate Alteration Using IIR Filters," *IEEE Signal Proc. Letters* 7(1): 6-7 (2000).

### Journal Articles, Accepted for Publication

Papadopoulos, H. C., Wornell, G. W. , and Oppenheim, A. V. "Sequential Signal Encoding from Noisy Measurements Using Quantizers with Dynamic Bias Control," *IEEE Trans. Inform. Theory*. Forthcoming

Eldar, Y. C. and Forney, G.D., Jr. "On Quantum Detection and the Square-Root Measurement," to appear in *IEEE Trans. Inform. Theory*, Forthcoming

Chen, B. and Wornell, G. W. "Quantization Index Modulation: A Class of Provably Good Methods for Digital Watermarking and Information Embedding," *IEEE Trans. Inform. Theory.* Forthcoming

Chen, B. and Wornell, G. W. "Implementations of Quantization Index Modulation Methods for Digital Watermarking and Information Embedding," *J. VLSI Signal Processing Systems for Signal, Image, and Video Technol*. (Special Issue on Multimedia Signal Processing) Forthcoming

### Journal Articles, Submitted for Publication

Eldar, Y. C., Oppenheim, A. V., and Egnor, D. E. "Orthogonal and Projected Orthogonal Matched Filter Detection," submitted to *IEEE Trans. Inform. Theory*.

Barron, R. J., Chen, B., and Wornell, G.W. "The duality between information embedding and source coding with side information and its implications and applications," submitted to *IEEE Trans. Inform. Theory*.

Eldar, Y. C. and Oppenheim, A. V. ``Orthogonal multiuser detection," submitted to *IEEE Comm. Letters*.

### Meeting Papers, Published

Laneman, J. N. and Wornell, G. W. "Exploiting Distributed Spatial Diversity in Wireless Networks," *Proc. Allerton Conf. on Communications, Controls and Computing*, Illinois, October 2000.

Chan, A. M. and Wornell, G. W. "A New Class of Efficient Block-Iterative Interference Cancellation Techniques for Digital Communication Receivers," *Proc. Allerton Conf. on Communications, Controls and Computing*, Illinois, October 2000.

Laneman, J. N. and Wornell, G. W. "Energy-Efficient Antenna Sharing and Relaying for Wireless Networks," *IEEE Wireless Communications and Networking Conference (WCNC-2000)*, Chicago, IL, September 2000.

Chen, B. and Wornell, G. W. "Quantization Index Modulation: A Class of Provably Good Methods for Digital Watermarking and Information Embedding," *Proc. Int. Symp. Inform. Theory* (ISIT-2000), Sorrento, Italy, June 2000.

Chan, A. M. and Wornell, G. W. "A Class of Block-Iterative Equalizers for Intersymbol Interference Channels," *Proc. Int. Conf. Commun.* (ICC-99), New Orleans, Los Angeles, June 2000.

Eldar, Y.C. and Oppenheim, A. V. "Filter Bank Interpolation and Reconstruction from Generalized and Recurrent Nonuniform Samples," *Proc. ICASSP 2000*, Istanbul, Turkey, June 2000.

Eldar, Y.C. and Oppenheim, A. V. "Filter Bank Interpolation and Reconstruction from Generalized and Recurrent Nonuniform Samples," *Proc. Fed Lab Symposium*,College Park, Maryland, February 2000.

Chen, B. and Wornell, G. W. "Preprocessed and Postprocessed Quantization Index Modulation Methods for Digital Watermarking," *Proc. SPIE: Security and Watermarking of Multimedia Contents* (EI'00), San Jose, California, January 2000.

**Theses**

Barron, R. J., "*Systematic Hybrid Analog/Digital Signal Coding*," Ph.D. diss., Department of Electrical Engineering and Computer Science, M.I.T., June 2000.

Chen, B., "*Design and Analysis of Digital Watermarking, Information Embedding, and Data Hiding Systems* " Ph.D. diss., Department of Electrical Engineering and Computer Science, M.I.T., June 2000.

Lee, L., "*Distributed Signal Processing,*" Ph.D. diss., Department of Electrical Engineering and Computer Science, M.I.T., June 2000.