Signal Transformation and Information Representation

Academic and Research Staff
Professor Vivek K Goyal

Visiting Scientists and Research Affiliates
Dr. Alyson Fletcher[1], Dr. Byeungwoo Jeon[2], Dr. José M.F. Moura[3]

Graduate Students
Lav Varshney, Daniel Weller, Adam Zelinski

Undergraduate Student
Vinith Misra

Technical and Support Staff
Eric Strattman

Introduction

Tools for Practical Source Coding

The primary focus of our work is the analysis and design of building blocks for practical compression systems. We tend to work at a level of abstraction where our parts fit in many applications, but we also sometimes follow through to final applications. Being practical means that we emphasize structured signal transformations and scalar and lattice quantization. Beyond just compression, we are interested in whole communication systems, including channel coding, networking, and congestion control.

Oversampling

Though it is not obvious on the surface, the power of oversampled representations is central to the digitization that surrounds us in this digital age. For scientific processing but also for most communication and storage, acquired signals are quantized to discrete values in the process of analog-to-digital conversion (ADC). ADC is made orders of magnitude cheaper by having very coarse (e.g., one bit) discretization of a highly oversampled version of a signal; it is much cheaper to run fast than to be accurate in analog electronics. The ubiquity of these techniques in audio processing is evidenced by the obscure "1-bit DAC" imprint on CD players, yet the full power of oversampled representations for higher-dimensional signals remains to be exploited.

Nonlinearities

For reasons of both computational complexity and mathematical elegance, linear transformations are central to the theory and practice of signal processing. But there are many nonlinear operations that are not too difficult to analyze or implement that provide very valuable properties. Examples include sorting, as in the Burrows-Wheeler Transform or permutation coding; thresholding, which is prominent in denoising; and pseudolinear integer-to-integer transforms, which are promising for conventional lossy source coding and multiple description coding. We are interested in developing tools based on tractable nonlinearities.

Technology and Pedagogy

The goal in any engineering research should be to aid good engineering, specifically the design of objects and processes for the betterment of the human condition. While we strive to advance technology, at the same time we embrace the additional opportunities that come from being at an

---

[1] Department of Electrical Engineering and Computer Science, University of California, Berkeley.
[2] Associate Professor, School of Information and Communication Engineering, Sungkyunkwan University, Suwon, Korea.
[3] Professor, Electrical and Computer Engineering, Carnegie Mellon University.

educational institution. We make some of our contribution by illuminating topics we find important to non-specialists. And we take the time to work beyond the point of having mathematical proof to also have clear, intuitive, and visual demonstrations.

1. Functional Quantization

Sponsors
NSF 05-579, Faculty Early Career Development (CAREER) Program
Texas Instruments Leadership University Program

Project Staff
Vinith Misra, Professor Vivek K. Goyal

Traditional lossy compression is performed with the goal of recreating source random variables. Functional compression, on the other hand, concentrates on recreating a function of the compressed variables. Our work approaches functional source coding from the perspective of high-rate quantization, with the goal of obtaining asymptotically optimal quantizer distortion.

With an eye towards data processing systems, we consider the scenario of separately quantizing N variables x1...xN to minimize distortion of a function f(x1...xN). We find that this separates into N 1 dimensional quantization problems, each of which can be easily solved. From this, it is shown that functional quantization always performs or outperforms naive quantization by a factor independent of the rate. For certain classes of functions, this factor grows with the number of samples. In the case of the median of N samples, naive quantization achieves a distortion constant with N, whereas the distortion from functional quantization falls with 1/N.

2. Performance of LDPC Codes Under Noisy Message-Passing Decoding

Sponsors
National Science Foundation Graduate Research Fellowship Program (NSF GRFP)

Project Staff
Lav R. Varshney, Professor Rüdiger L. Urbanke, Professor İ. Emre Telatar

In traditional communication theory, it is assumed that error correcting codes may be decoded with algorithms that perform perfectly. Noise, however, provides a fundamental limit to computation systems just as it does to communication systems. In this work, we investigate the effect of noise in message-passing decoders for low-density parity-check codes. We observe that the concentration of the performance of the decoder around its average performance continues to hold when noise is introduced into message-passing. Given the concentration result, density evolution equations for a simple noisy message-passing decoder are derived. Analytic computation of thresholds shows that performance degrades smoothly as decoder noise increases. Decoding is robust to noise in the decoder.

3. Universal Coding of Unordered Data

Sponsors
National Science Foundation Graduate Research Fellowship Program (NSF GRFP)
Texas Instruments Leadership University Program.

Project Staff
Lav R. Varshney, Professor Vivek K. Goyal

There are several applications in information transfer and storage where the order of source letters is irrelevant at the destination. For these source-destination pairs, *multiset communication* rather than the more difficult task of *sequence communication* may be performed. In this work, we study universal multiset communication. For classes of countable-alphabet sources that meet Kieffer's condition for sequence communication, we present a scheme that universally achieves a rate of $n + o(n)$ bits per multiset letter for multiset communication. We also define redundancy measures that are normalized by the logarithm of the multiset size rather than per multiset letter and show that these redundancy measures cannot be driven to zero for the class of finite-alphabet memoryless multisets. This further implies that finite-alphabet memoryless multisets cannot be encoded universally with vanishing fractional redundancy. For continuous alphabet sources, we find lossy universal schemes that can drive redundancy to zero.

4. Bandlimited Signal Estimation in the Presence of Timing Noise for Analog-to-Digital Converters.

Sponsors
Analog Devices, Inc.
NEC Corporation

Project Staff
Daniel Weller, Professor Vivek K. Goyal

The impact of timing noise, or "jitter", on limiting the throughput and design of analog-to-digital converters (ADCs) was studied, and the benefits of compensating for the jitter through digital post-processing were examined. Current methods to correct sampling errors due to jitter in the clock signal of ADCs, including correlation and linear estimation, were investigated. Non-linear iterative algorithms, including one based on the EM algorithm, were developed to approximate maximum-likelihood (ML) estimators of the signal parameters (i.e. the non-oversampled discrete values of the signal) and Bayes least-squares (BLS) estimators of the timing noise. Both block post-processing and iterative post-processing methods were examined. MATLAB was utilized to simulate and analyze the speed and performance of these algorithms for arbitrary bandlimited signals, with different levels of oversampling and varying quantities of additive noise and jitter. In addition, Cramer-Rao lower bounds on the covariance matrix of the estimators of the signal parameters were derived; these bounds were computed and evaluated for the two-parameter case with various levels of oversampling and different relative magnitudes of jitter and additive noise.

5. Sparsity-Enforced RF Pulse Design for Single-Channel and Multi-Channel Excitation Systems

Sponsor
National Defense Science and Engineering Graduate Fellowship (NDSEG)

Project Staff
Adam Zelinski, Kawin Setsompop, Professor Vivek K. Goyal, Professor Elfar Adalsteinsson, Lawrence L. Wald (MGH, Harvard Medical School Radiology Department), Vijay Alagappan (MGH), and Borjan Gagoski.

A sparsity-enforcement algorithm that optimized the number, placement and weighting of spokes in k-space was designed. The framework extended from single- to multi-channel excitation systems and permitted the design of arbitrary slice-selective excitations, trading off target profile fidelity with pulse duration in a near-optimal manner. The utility and capabilities of this algorithm were demonstrated in the following experiments:

In Vivo B1 Mitigation in the Human Brain at 7 Tesla. At high field strengths such as 7T, the presence of B1 inhomogeneity causes significant center brightening, contrast variation, and SNR uniformity throughout images. Standard slice-selective pulses fail to mitigate the inhomogeneity, making several large regions of collected images unacceptable for clinical analysis. Here, the sparsity-enforced algorithm was employed to produce a slice-selective, B1-mitigating excitation. In vivo experiments in the brain were performed, demonstrating that pulses designed with the proposed algorithm were capable of significant B1 mitigation, while at the same time having short pulse durations and essentially the same peak voltage and SAR of standard slice-selective pulses. Figure 1 below illustrates the benefits of applying the sparsity-enforced pulses: from left to right, various amounts of non-uniformity are removed, and the right-most image shows nearly complete mitigation of B1-effects. Figure 2 is representative of the typical design flow for generating such pulses.

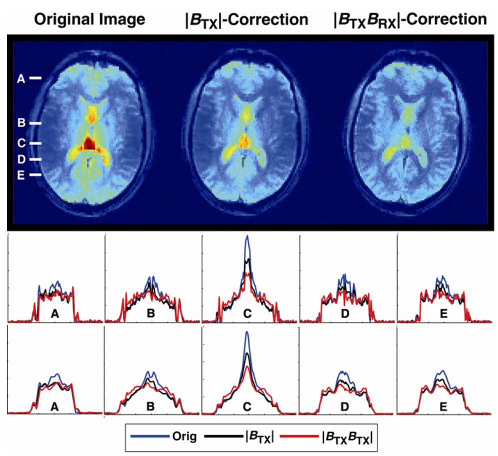

Figure 1

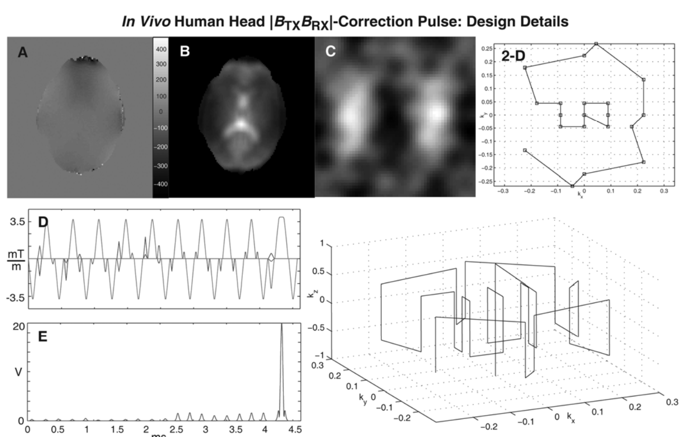

Figure 2

Parallel RF Excitation Pulse Design. The sparsity-enforcement algorithm was used to generate spatially-selective, phase-encoded excitations in an oil phantom placed within an 8-channel excitation system on a 3T human scanner. These experiments showed that for approximately the same pulse duration, the sparsity-enforcing spoke placement algorithm led to higher-fidelity excitations than the conventional Fourier-based spoke-placement technique.

6. Analysis of 3 Algorithms for Solving Linearized Systems of Parallel RF Excitation Equations

Sponsor
National Defense Science and Engineering Graduate Fellowship (NDSEG).

Project Staff
Adam Zelinski, Kawin Setsompop, Professor Vivek K. Goyal, Professor Elfar Adalsteinsson, Lawrence L. Wald (MGH, Harvard Medical School Radiology Department), Vijay Alagappan (MGH), and Borjan Gagoski.

Three RF waveform design algorithms for calculating accelerated spatially-tailored excitations for parallel excitation systems were studied in detail. The traditional singular value decomposition (SVD) method was compared to Least Squares QR (LSQR) and Conjugate Gradient Least Squares (CGLS), two large system solvers with desirable numerical properties and fast runtimes. For k-space trajectory acceleration factors greater than one, experiments conducted on an 8-channel parallel TX array on a 3T Siemens Magnetom TRIO scanner showed that waveforms designed by LSQR and CGLS resulted in excitations with lower artifact levels and had lower peak and root-mean-square (RMS) voltages than those of the SVD-based method, which means that for the less energy deposition in a subject, a higher quality excitation may be conducted, with the performance increase coming solely from the pulse generation algorithm.

Publications

Journal Articles, Published

L. R. Varshney, P. J. Sjöström, and D. B. Chklovskii, “Optimal Information Storage in Noisy Synapses under Resource Constraints,” *Neuron*, vol. 52, no. 3, pp. 409-423, Nov. 2006.

Journal Articles, Accepted

A. C. Zelinski, L. L. Wald, K. Setsompop, V. Alagappan, B. A. Gagoski, F. Hebrank, U. Fontius, F. Schmitt, and E. Adalsteinsson, “Comparison of 3 Algorithms for Solving Linearized Systems of Parallel Excitation RF Waveform Design Equations: Experiments on an 8-Channel System at 3T,” *Concepts in Magnetic Resonance, Part B: Magnetic Resonance Engineering* forthcoming.

V. Alagappan, J. Nistler, E. Adalsteinsson, K. Setsompop, U. Fontius, A. C. Zelinski, M. Vester, G. C. Wiggins, F. Hebrank, F. Schmitt, and L. L. Wald, “A Degenerate Mode Band-Pass Birdcage for Accelerated Parallel Excitation,” *Magnetic Resonance in Medicine* forthcoming.

Journal Articles, Submitted

A. C. Zelinski, K. Setsompop, V. Alagappan, V. K Goyal, L. L. Wald, and E. Adalsteinsson, “Fast Slice-Selective RF Excitation Pulse for Mitigating in Vivo B1 Inhomogeneity in the Brain at 7T,” submitted to *Magnetic Resonance in Medicine*.

K. Setsompop, A. C. Zelinski, V. Alagappan, J. Fontius, F. Hebrank, F. Schmitt, L. L. Wald, and E. Adalsteinsson, “High-flip Angle Slice-Selective Parallel RF Excitation with 8 Channels at 3 Tesla,” submitted to *Magnetic Resonance in Medicine*.

Conference Papers, Published

L. R. Varshney and V. K Goyal, “On Universal Coding of Unordered Data,” *Proc. 2007 Workshop Inform. Theory & Its Applications*, La Jolla, California, January 29 – February 2, 2007.

A. C. Zelinski, L. L. Wald, K. Setsompop, V. Alagappan, B. A. Gagoski, F. Hebrank, U. Fontius, F. Schmitt, and E. Adalsteinsson, “RF Pulse Design Methods for Reduction of Image Artifacts in Parallel Excitation: Comparison of 3 Techniques on a 3T Parallel Excitation System with 8 Channels,” *Proc. International Society for Magnetic Resonance in Medicine (ISMRM)*, Berlin, Germany, May 19 – 25, 2007.

A. C. Zelinski, K. Setsompop, V. Alagappan, B. A. Gagoski, L. M. Angelone, G. Bonmassar, U. Fontius, F. Schmitt, E. Adalsteinsson, and L. L. Wald, “Pulse Design Methods for Reduction of Specific Absorption Rate in Parallel Excitation,” *Proc. International Society for Magnetic Resonance in Medicine (ISMRM)*, Berlin, Germany, May 19 – 25, 2007. 2007

A. C. Zelinski, K. Setsompop, V. K Goyal, V. Alagappan, U. Fontius, F. Schmitt, L. L. Wald, and E. Adalsteinsson, “Designing Fast 3-D RF Excitations by Optimizing the Number, Placement and Weighting of Spokes in k-Space via a Sparsity-Enforcement Algorithm,” *Proc. International Society for Magnetic Resonance in Medicine (ISMRM)*, Berlin, Germany, May 19 – 25, 2007.

A. C. Zelinski, V. K Goyal, L. Angelone, G. Bonmassar, L. L. Wald, and E. Adalsteinsson, “Designing RF Pulses with Optimal Specific Absorption Rate (SAR) Characteristics and Exploring Excitation Fidelity, SAR and Pulse Duration Tradeoffs,” *Proc. International Society for Magnetic Resonance in Medicine (ISMRM)*, Berlin, Germany, May 19 – 25, 2007.

K. Setsompop, A. C. Zelinski, V. Alagappan, J. Nistler, U. Fontius, F. Hebrank, F. Schmitt, L. L. Wald, and E. Adalsteinsson, “In Vivo Parallel RF Excitation with B_0 Correction,” *Proc. International Society for Magnetic Resonance in Medicine (ISMRM)*, Berlin, Germany, May 19 – 25, 2007.

K. Setsompop, A. C. Zelinski, V. K Goyal, L. L. Wald, and E. Adalsteinsson, “Sparse Spokes Slice-Selective Design for B_1 Inhomogeneity Correction at 7T,” *Proc. International Society for Magnetic Resonance in Medicine (ISMRM)*, Berlin, Germany, May 19 – 25, 2007.

K. Setsompop, A. C. Zelinski, V. Alagappan, U. Fontius, F. Hebrank, F. Schmitt, L. L. Wald, and E. Adalsteinsson, “High Flip Angle Slice Selective Parallel RF Excitation on an 8-Channel System at 3T,” *Proc. International Society for Magnetic Resonance in Medicine (ISMRM)*, Berlin, Germany, May 19 – 25, 2007. 2007

V. Alagappan, E. Adalsteinsson, K. Setsompop, U. Fontius, A. C. Zelinski, G. C. Wiggins, F. Hebrank, F. Schmitt, and L. L. Wald, “Comparison of Three Transmit Arrays for Parallel Transmit,” *Proc. International Society for Magnetic Resonance in Medicine (ISMRM)*, Berlin, Germany, May 19 – 25, 2007.

V. Alagappan, J. Nistler, E. Adalsteinsson, K. Setsompop, U. Fontius, A. C. Zelinski, M. Vester, G. C. Wiggins, F. Hebrank, W. Renz, F. Schmitt, and L. L. Wald, “A Degenerate Birdcage Coil for Parallel Excitation,” *Proc. International Society for Magnetic Resonance in Medicine (ISMRM)*, Berlin, Germany, May 19 – 25, 2007.

Conference Papers, to be Published

L. R. Varshney and D. B. Chklovskii, “On Optimal Information Storage in Synapses,” *Proc. 2007 IEEE Inform. Theory Workshop*, Lake Tahoe, California, September 2-6, 2007.

L. R. Varshney, “Performance of LDPC Codes Under Noisy Message-Passing Decoding,” *Proc. 2007 IEEE Inform. Theory Workshop*, Lake Tahoe, California, September 2-6, 2007.

Talks Presented

V.K. Goyal and A.C. Zelinski, "Exploiting Sparsity-Based Modeling in Hyperspectral Data Processing," 2006 SIAM Conference on Imaging Science, Minneapolis, Minnesota, May 15-17, 2006. (Invited Talk)

Patents

V.K. Goyal, “Method and Apparatus for Adaptive Signal Processing Involving a Karhunen-Loeve Basis,” U.S. Patent no. 6 993 477, issued January 31, 2006.

V.K. Goyal, J. Kovacevic, and F. Masson, “Method of Multiple Description Coding of Signals for Wireless Transmission,” U.S. Patent no. 6 983 243, issued January 3, 2006.