Final Report for Period: 08/2007 - 07/2008
Submitted on: 11/11/2008
Principal Investigator: Barry, John R.
Award ID: 0431031
Organization: GA Tech Res Corp - GIT
Submitted By:
Barry, John - Principal Investigator
Title:
Coding and Detection for Next-Generation Recording

Project Participants

Senior Personnel

Name: Barry, John
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: McLaughlin, Steven
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Milliner, David
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Sankarasubramaniam, Yogesh
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Srinivasa, Shayan
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Waters, Deric
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Kannan, Arumugam
Worked for more than 160 Hours: Yes
Contribution to Project:

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

Activities and Findings

Research and Education Activities:

This project investigates four advances in the areas of communications, signal processing, and security:

1. Signal processing and equalization: beyond partial response
2. Constrained coding: flipping and sliding, stuffing and interleaving
3. Iterative timing recovery: synchronization that exploits coding
4. New security paradigms for security in recording systems

The highlights of our results are summarized below.

Findings:

As an alternative to partial response, we devised a new channel detection strategy for the recording channel based on lattice reduction. Our approach exploits the fact that a sector of readback samples can be viewed as a noisy observation of an element of a large-dimensional lattice, where the lattice is spanned by the columns of the convolution matrix. The idea is to find a 'better' basis for the lattice, one that is as orthogonal as possible, and to detect the symbols that pass through the corresponding fictional channel using linear (or otherwise low-complexity) processing. Because this new channel is nearly orthogonal, a linear zero-forcing or minimum mean-squared error filter results in only a small amount of noise enhancement. Overall the detector consists of a linear filter, a simple nonlinear quantization step, and another linear filter. Similar structures have been proposed for multiple-input multiple-output wireless communications channels, but their practicality has been limited by the high computational complexity required to find a good basis, a step that must be performed each time the channel changes. There is no such disadvantage for the essentially static recording channel. We devised zero-forcing and minimum-mean-squared error variations, as well as linear and decision-feedback variations.

At the heart of this topic is a desire to find the sweet spot in the performance versus complexity trade-off that characterizes the detection problem. Our focus began with the recording channel but naturally evolved to encompass other channels as well, including the wireless MIMO channel.

The proposed lattice-aided channel detector outperforms a batch ordered MMSE-DFE (the generalized DFE of Cioffi and Forney) by 0.7 dB when applied to the Lorzentzian channel that models longitudinal recording. It would outperform a conventional MMSE-DFE by even more. However, it falls almost 2 dB short of the performance of the ML detector.

The viability of lattice-aided detection is limited in practice by the high complexity of lattice-reduction algorithms such as the LLL algorithm. Particularly on wireless channels that vary rapidly with time, the high overhead of lattice reduction can negate much of the computational savings. The lattice-aided BODF detector of Wubben et all (ICC2004) achieves near-ML performance by combining LLL lattice reduction with MMSE BODF detection. However, we believe that LLL lattice reduction is overkill when accompanied by BODF detection. The presence of the BODF detector relaxes considerably the lattice reduction constraints. We have proposed a new stripped-down lattice-reduction technique called the DOLLAR algorithm, that is an alternative to the full-blown LLL algorithm. Roughly speaking, while the LLL algorithm is matched to a linear detector, the DOLLAR reduction is matched to the MMSE BODF detector. The DOLLAR reduction consists of a weak-Gram-Schmidt process sandwiched between two ordering procedures. Combining this lattice reduction with a MMSE-BODF leads to near-ML performance with complexity comparable to that of the BODF detector. For example, over a 4-input 4-output Rayleigh-fading channel with 16-QAM inputs, the DOLLAR detector outperformed the BODF detector by 6 dB while requiring 16% more complexity. In the same setting, the LLL-BODF detector needed as much as 7.6 times the complexity the DOLLAR detector to perform only 0.3 dB better. In another experiment, the DOLLAR detector achieved within a fraction of a dB of ML performance over a 2-input 2-output Rayleigh-fading channel with 4-QAM inputs, while requiring only 10% more complexity than the BODF detector.

The value of lattice-aided detection depends strong on the channel. On a Rayleigh-fading MIMO channel, the lattice-aided detector offers spectacular performance. But the performance is less than spectacular on the longitudinal recording channel. At issue may be the difficulty of reducing large-dimensional lattices; for the recording channel, the lattice of interest has dimension equal to the number of bits in a sector, typically about 4300 bits. With some effort we implemented a more powerful lattice reduction algorithm called the block-KZ reduction algorithm, which is significantly more complex than the LLL but is able to find a more orthogonal lattice basis. It did not lead to an appreciable improvement in performance.

We have demonstrated how lattice reduction can be used to facilitate soft-output (as opposed to hard-output) detection. Our lattice-aided soft-output detector compare favorably to previously reported soft-output MIMO detectors, including the list-sphere detector and the max-log-MAP sphere detector. Our approach is to tentatively ignore the boundary control problem, and to gradually increase the radius of a sphere about the hard decision for the effective symbol vector, adding effective symbol vectors to the list, until the list is sufficiently long.

Because of the incompatibility between lattice-aided detection and fast-fading channels, we are also exploring tree-search detection strategies that do not have the high up-front complexity requirements of a lattice reduction. Of particular interest is the classical M algorithm for searching the tree, which is a breadth-first search that retains only M nodes at any level of the tree. We have recently improved the M algorithm by varying on a stage-by-stage basis the number of children extended from retained nodes in the detection tree, according to the receiver's knowledge of the channel matrix. We call the resulting algorithm the CLAM algorithm. The CLAM algorithm is on average less complex than the M algorithm while achieving significantly improved performance. For example, on a 4-input 4-output Rayleigh-fading channel with 64-QAM inputs, the CLAM algorithm outperforms the M algorithm by 2 dB at a BER of 0.001, falling only 0.6 dB short of the joint maximum-likelihood detector, while simultaneously reducing the average search complexity by 12%.

We have recently discovered a new architecture for vertically layered MIMO communications that signficantly outperforms the conventional V-BLAST strategy with comparable complexity. The new architecture is called V-STAR and it is surprisingly simple. In the STAR architecture, the duration of the frame over which the channel response is constant, is divided into t blocks, one for each transmit antenna. During the k-th block, the k-th antenna is silent. The receiver uses a sucessive cancellation decoder suitably modified to account for the time-varying nature of the interference imposed by the V-STAR transmitter. V-STAR with SC decoding outperforms existing spatial multiplexing systems, while maintaining low complexity. For example, on a 4 Î 4 MIMO system, STAR with SC decoding outperforms transmitter-optimized V-BLAST by many dB, falling just 1.4 dB away from the optimum outage probability of spatial multiplexing systems.

The success of the proposed MIMO architecture led us to explore the possibility of extending the concept to a network of users. Our first finding in this area was applied to the Rayleigh-fading multiple-access channel. In this context we proposed the space-time active rotation (STAR) transmission strategy for multiple-access systems. STAR is an enhanced space-division multiple-access (SDMA) strategy that enables a successive-cancellation (SC) decoder to approach the outage performance of an unconstrained decoder. Roughly speaking, the STAR protocol can be viewed as 'complementary TDMA', in the sense that the different users take turns being silent, rather than being active. This occasional inactivity may seem inconsequential, but it has a big impact on the performance of a SC decoder. Specifically, an optimized SC decoder can begin by decoding the stream with the highest capacity, when time-averaged over the entire frame. The averaging of the resulting time-varying interference provides a form of time diversity. On the Rayleigh-fading multiple-access channel, the STAR strategy enables near-optimal outage performance with a low-complexity successive-cancellation decoder. We derived the outage probability and proposed an ordering algorithm for SC decoding that minimizes the outage
probability of STAR. We derived an upper bound on the diversity-multiplexing tradeoff of the proposed architecture. We showed that the proposed system outperforms naive SDMA with SC decoding by 8.2 dB for a 4-user multiple-access system with 2 transmit antennas each and 8 receive antennas. We also show that STAR with SC decoding gets to within 1.6 dB of the optimum outage probability for this case. Thus, the STAR transmission strategy with SC decoding is an effective solution to achieve near-optimum outage probability of multiple-access systems at low computational complexity.

What if the user is able to listen to others while it is silent? This question led us to consider the cooperative multiple-access channel, where each user has the capability to relay signals or information received from one or more other users. We have recently proposed the space-division-relay protocol, a cooperation strategy for the cooperative multiple access channel that scales nicely with the number of users. The rate of typical existing cooperation strategies (like the LTW protocol) is 1/n^2, where n is the number of users. In contrast, the rate of the proposed SDR strategy is (n - 1)/(n + 1). Despite the high rate, SDR is able to achieve the full diversity of the multiple-access channel. Currently we are exploring various relay strategies (such as amplify and forward, decode and forward, nonothogonal amplify and forward, and decode and decide-to-forward), the last showing promise in our preliminary work.

No previously reported space-time codes achieve the diversity-multiplexing tradeoff for an arbitrary number of antennas and an arbitrary rate while maintaining low decoding complexity. In our research we have partially filled this gap by proposing a framework for the construction and decoding of high rate space-time block codes. In particular,have recently proposed the embedded Alamouti space-time (EAST) codes, which is a family of codes with a nonvanishing determinant for any number of antennas up to eight, and for any rate up to half the number of antennas. When compared to previously reported codes with the same number of antennas and the same rate larger than one, the EAST codes are simultaneously lower in complexity and lower in error probability on quasistatic Rayleigh-fading channels.

In related work, we have proven that the golden code (a full-rate full-diversity space-time code for two transmit antennas that is a part of the WiMAX standard) is 'fast decodable,' a result that had been overlooked in prior work. Because each codeword conveys four information symbols from an M-ary quadrature-amplitude modulation alphabet, the complexity of an exhaustive search decoder is proportional to M^4. We have presented a new fast algorithm for maximum-likelihood decoding of the golden code that has a worst-case complexity of only O(M^2.5). Further, we have shown that the golden code is fast decodable on both quasistatic and rapid time-varying channels. This work has been used to argue for support of the golden code in mobile WiMAX standards.

Training and Development:

Five graduate students were exposed to next-generation recording technologies and research methodologies.

Outreach Activities:

Journal Publications

D. Waters and J. R. Barry, "A Reduced-Complexity Lattice-Aided Decision-Feedback Detector", IEEE International Conference on Wireless Networks, Communications, and Mobile Computing (WirelessComm2005), Maui, Hawaii, June 13-16, 2005, p. 122, vol. 1, (2005). Published,

D. Milliner and J. R. Barry, "An Adaptive M-Algorithm for Detection of Multiple-Input Multiple-Output Channels", Signal Processing Advances in Wireless Communications (SPAWC), Helsinki, Finland, June 17-20, 2007., p. , vol. , (2007). Published,

A. Kannan and J. R. Barry, "Space-Division Relay: A High-Rate Cooperation Scheme for Fading Multiple-Acces Channels", Global Communications Conference (Globecom 2007), Washington, D.C., November 26-30, 2007, p. , vol. , (2007). Submitted,

D. Milliner and J. R. Barry, "A Lattice-Reduction-Aided Soft Detector for Multiple-Input Multiple-Output Channels", IEEE 2006 Global Communications Conference, (Globecom 2006), San Francisco, November 27 - December 1, 2006, p. 1, vol. CTH09-4, (2006). Published,

A. Kannan and J. R. Barry, "Space-Time Active Rotation (STAR): A New Layered Space-Time Architecture", IEEE Global Communications Conference (Globecom 2005), St. Louis, November 28 - December 2, 2005, p. 2575-2579, vol. , (2005). Published,

A. Kannan and J. R. Barry, "An Improved Space-Division Multiple-Access Strategy for Rayleigh-Fading Channels", IEEE 2006 Zurich Seminar on Communications (IZS 2006), Zurich, Switzerland, February 22-24, 2006., p. 1, vol. , (2006). Published,

D. Waters and J. R. Barry, "The Chase Family of Detection Algorithms for MIMO Channels", IEEE Transactions on Signal Processing, May 2006, p. 739, vol. 2, (2008). Published,

John Barry, F. Ling, K. Narayanan, J. Proakis, and D. SLock, "Equalization Techniques for Wireless Communications: Theory and Applications (Guest Editorial)", IEEE Journal on Selected Areas in Communication, p. 241, vol. 26, (2008). Published,

M. Sinnokrot and J. R. Barry, "A Single-Symbol-Decodable Space-Time Block Code with Full Rate and Low Peak-to-Average Power Ratio", IEEE Transactions on Wireless Communications, p. , vol. , (2008). Accepted,

J.-H. Sung and John R. Barry, "Approaching the Zero-Outage Capacity of MIMO-OFDM without Water Filling", IEEE Transactions on Information Theory, p. 1423, vol. 54, (2008). Published,

Deric Waters and John R. Barry, "A Low-Complexity Upgrade of the Linear Detector for MIMO Channels via Partial Decision Feedback", IEEE Transactions on Wireless Communications, p. 1587, vol. 6, (2007). Published,

J. Vasseur, M. Hanna, J. Dudley, J.-P. Goedgebuer, J. Yu, G.-K. Chang and J. R. Barry, "Alternate multiwavelength picosecond pulse generation by use of an unbalanced Mach-Zehnder interferometer in a modelocked fiber ring laser", Journal of Quantum Electronics, p. 85, vol. 43, (2007). Published,

A. R. Nayak, J. R. Barry, G. Feyh, and S. W. McLaughlin, "Timing Recovery with Frequency Offset and a Random Walk: The Cramer-Rao Bound and a Phase-Locked Loop Post-Processor", IEEE Transactions on Communications, p. 2004, vol. 54, (2006). Published,

D. Boivin, J. Yu, G. K. Chang, M. Haris, and J. R. Barry, "Experimental measurement of optical phase Variance in RZ-DPSK systems using direct detection after demodulation by a MZDI", Photonics Technology Letters, p. 1990, vol. 18, (2006). Published,

D. Boivin, G.K. Chang, J. Yu, J. R. Barry, "Reduction of Gordon-Mollenauer phase noise in dispersion-managed systems using midlink spectral inversion", J. Optical Society of America B, p. 2019, vol. 23, (2006). Published,

A. R. Nayak, J. R. Barry, and S. W. McLaughlin, "Optimal Placement of Training Symbols for Frequency Acquisition: A CramÉr-Rao Bound Approach", IEEE Transactions on Magnetics, p. 1730, vol. 42, (2006). Published,

R. R. Lopes and J. R. Barry, "The Soft-Feedback Equalization for Turbo Equalization of Highly Dispersive Channels", IEEE Transactions on Communications, p. 783, vol. 54, (2006). Published,

J. Vasseur, M. Hanna, J. M. Dudley, and J. R. Barry, "Numerical and Theoretical Analysis of an Alternate Multiwavelength Mode-Locked Fiber Laser", EEE J. Photonics Technology Letters, p. 2295, vol. 17, (2005). Published,

B. Varadarajan and J. R. Barry, "The Outage Capacity of Linear Space-Time Codes", IEEE Transactions on Wireless Communications, p. 2642, vol. 4, (2005). Published,

D. Boivin, M. Hanna, and J. R. Barry, "Reduced-Bandwidth Duobinary Differential Continuous-Phase Modulation Format for Optical Communications", IEEE Photonics Technology Letters, p. 1331, vol. 17, (2005). Published,

D. W. Waters and J. R. Barry, "Noise-Predictive Decision-Feedback Detection for Multiple-Input Multiple-Output Channels", IEEE Transactions on Signal Processing, p. 1852, vol. 53, (2005). Published,

J. Yu, G. K. Chang, J. R. Barry and Y. Su, "40-Gbit/s signal format conversion from NRZ to RZ using a Mach-Zehnder delay interferometer", Optics Communications, p. 419, vol. 248, (2005). Published,

R. R. Lopes and J. R. Barry, "The Extended-Window Channel Estimator for Iterative Channel-and-Symbol Estimation", EURASIP Journal on Wireless Communications and Networking, p. 92, vol. 2005, (2005). Published,

W. Xiang, D. Waters, T. Pratt, and J. R. Barry, "Implementation and Experimental Results of a Three-Transmitter Three-Receiver OFDM/BLAST Testbed", IEEE Wireless Communications Magazine, p. 88, vol. 42, (2004). Published,

J. Yu, G. K. Chang, M. Haris and J. R. Barry, "10 Gbit/s repeaterless transmission over 265km SMF-28 using a modified duo-binary RZ signal generated by one dual-drive LiNb03 modulator", Optics Communications, p. 99, vol. 239, (2004). Published,

M. Sinnokrot, J. R. Barry, and V. Madisetti, "Embedded Alamouti Space-Time Codes for High Rate and Low Decoding Complexity", Asilomar Conference on Signals, Systems, and Computers, p. , vol. , (2008). Accepted,

M. Sinnokrot and J. R. Barry, "The Golden Code is Fast Decodable", IEEE Global Telecommunications Conference, p. , vol. , (2008). Accepted,

E. Zimmermann, D. L. Milliner, J. R. Barry, and G. Fettweis, "Optimal LLR Clipping Levels for Mixed Hard/Soft Output Detection", IEEE Global Telecommunications Conference, p. , vol. , (2008). Accepted,

M. Sinnokrot and J. R. Barry, "A Single-Symbol Decodable Space-Time Block Code with Full Rate and Low Peak-to-Average-Power Ratio", EEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), p. , vol. , (2008). Published,

D. L. Milliner, E. Zimmermann, J. R. Barry, and G. Fettweis, "Channel-State-Information-Based LLR Clipping in List MIMO Detection", IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), p. , vol. , (2008). Published,

M. Sinnokrot and J. R. Barry, "Modified Golden Codes for Fast Decoding on Time-Varying Channels", The 11th International Symposium on Wireless Personal Multimedia Communications (WPMC), p. , vol. , (2008). Published,

D. L. Milliner, E. Zimmermann, J. R. Barry, and G. Fettweis, "Computational Complexity Bounds for List MIMO Detection", he 11th International Symposium on Wireless Personal Multimedia Communications (WPMC), p. , vol. , (2008). Published,

D. L. Milliner, E. Zimmermann, J. R. Barry, and G. Fettweis, "A Framework for Fixed Complexity Breadth-First MIMO Detection", 10th International Symposium on Spread Spectrum Techniques and Applications (ISSSTA), p. , vol. , (2008). Published,

E. Zimmermann, G. Fettweis, D. L. Milliner, and J. R. Barry, "A Parallel Smart-Candidate-Adding Algorithm for Soft-Output MIMO Detection", 7th International ITG Conference on Source and Channel Coding," (SCC08), p. , vol. , (2008). Published,

A. Kannan and J. R. Barry, "Space-Division Relay: A High-Rate Cooperation Scheme for Fading Multiple-Access Channels", IEEE Global Communications Conference (Globecom 2007), p. 1673, vol. , (2007). Published,

D. Milliner and J. R. Barry, "A Layer Adaptive M-Algorithm for Detection of Multiple-Input Multiple-Output Channels", IEEE Signal Processing Advances in Wireless Communications, (SPAWC 2007), p. 1, vol. , (2007). Published,

D. Milliner and J. R. Barry, "A Lattice-Reduction-Aided Soft Detector for Multiple-Input Multiple-Output Channels", IEEE 2006 Global Communications Conference, (Globecom 2006), p. 1, vol. CTH09, (2006). Published,

A. Kannan and J. R. Barry, "An Improved Space-Division Multiple-Access Strategy for Rayleigh-Fading Channels", IEEE 2006 Zurich Seminar on Communications (IZS 2006), p. , vol. , (2006). Published,

A. Kannan and J. R. Barry, "Space-Time Active Rotation (STAR): A New Layered Space-Time Architecture", EEE Global Communications Conference (Globecom 2005), p. 2574, vol. , (2005). Published,

E. Chesnutt, R. Lopes, and J. R. Barry, "Beyond PRML: Linear-Complexity Turbo Equalization Using the Soft-Feedback Equalizer", International Magnetics Conference (Intermag 2005), p. , vol. , (2005). Published,

A. R. Nayak, J. R. Barry and S. W. McLaughlin, "Optimal Training Symbol Placement for Frequency Acquisition on Magnetic Recording Channels", International Magnetics Conference (Intermag 2005), p. , vol. , (2005). Published,

P. Kovintavewat, J. R. Barry, M. Erden, and E. Kurtas, "Robustness of Per-Survivor Iterative Timing Recovery in Perpendicular Recording Channels", International Magnetics Conference (Intermag 2005), p. , vol. , (2005). Published,

D. Waters and J. R. Barry, "The Sorted-QL Chase Detector For Multiple-Input Multiple-Output Channels", IEEE Wireless Communications and Networking Conference (WCNC 2005), p. 538, vol. 1, (2005). Published,

A. Kannan, B. Varadarajan, and J. R. Barry, "Joint Optimization of Rate Allocation and BLAST Ordering to Minimize Outage Probability", IEEE Wireless Communications and Networking Conference (WCNC 2005), p. 550, vol. 1, (2005). Published,

P. Kovintavewat, F. Erden, E. Kurtas, and J. R. Barry, "Per-Survivor Iterative Timing Recovery for Coded Partial Response Channels", International Global Communications Conference (Globecom 2004), p. 2604, vol. 4, (2004). Published,

P. Kovintavewat and J. R. Barry, "EXIT Chart Analysis for Iterative Timing Recovery", International Global Communications Conference, p. 2435, vol. 5, (2004). Published,

Books or Other One-time Publications

P. Kovintavewat, J. R. Barry, M. Erden, E. Kurtas, "Interpolated Timing Recovery", (2004). Book, Published

Editor(s): Bane Vasic and Erozan Kurtas
Collection: Coding and Signal Processing for Magnetic Recording Systems
Bibliography: CRC Press

A. R. Nayak, J. R. Barry, and S.W. McLaughlin, "Cramer-Rao Bound for Timing Recovery on Channels with Inter-symbol Interference", (2008). Book, Published
Editor(s): P. Siegel, E. Soljanin, A. van Wijngaarden, B. Vasic
Collection: Advances in Information Recording
Bibliography: American Mathematical Society Press, ISBN 0-8218-3752-4

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

Contributions to Other Disciplines:

Contributions to Human Resource Development:

Contributions to Resources for Research and Education:

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Organizational Partners
Activities and Findings: Any Outreach Activities
Any Web/Internet Site
Any Product
Contributions: To Any within Discipline
Contributions: To Any Other Disciplines
Contributions: To Any Human Resource Development
Contributions: To Any Resources for Research and Education
Contributions: To Any Beyond Science and Engineering

Compiler Design - Code Generation - Code generation can be considered as the final phase of compilation. Through post code generation, optimization process can be applied on the code, but that can.Â A code generator is expected to have an understanding of the target machineâ€™s runtime environment and its instruction set. The code generator should take the following things into consideration to generate the code: Target language : The code generator has to be aware of the nature of the target language for which the code is to be transformed. That language may facilitate some machine-specific instructions to help the compiler generate the code in a more convenient way. The target machine can have either CISC or RISC processor architecture. 256 chapter 8. detection, coding, and decoding. Note that these formulas involve only the ratio Eb/N0 rather than Eb or N0 separately. If the signal, observation, and noise had been measured on a dierent scale, then both Eb and N0 would change by the same factor, helping explain why only the ratio is relevant.Â 8.3.2 Detection for binary non-antipodal signals. Next consider the slightly more complex case illustrated in Figure 8.3. Instead of mapping 0 to. +a and 1 to âˆ'a, 0 is mapped to an arbitrary number b0 and 1 to an arbitrary number b1. And probably never will be, because no one else really adopted VP9 and it's already last-generation tech. permalink. embed.Â It's a complex process, I worked on prediction and I still can't figure out all the different cases for how the entropy coding works and the changing probabilities. But the short version is the block segmentation is very correlated between channels and the entropy coding considers this, so if your channels don't correlate as well (which could be the case with RGB over YUV), it could have some adverse effects. Signal Processing and Detection for Array Reader Magnetic Recording System. Article. Jul 2015. IEEE T MAGN. Haitao Xia.Â These simple codes achieve coding gains in the order of 3-4 dB. It is then shown that the codes can be interpreted as binary convolutional codes with a mapping of coded bits into channel signals, which we call "mapping by set partitioning." Based on a new distance measure between binary code sequences which efficiently lower-bounds the Euclidean distance between the corresponding channel signal sequences, a search procedure for more powerful codes is developed. Codes with coding gains up to 6 dB are obtained for a variety of multilevel/phase modulation schemes. Simulation results are