Editorial
Signal Processing for High Density Storage Channels

ALTHOUGH Moore's law is generally associated with progress in integrated circuit technologies, it has been equally applicable to the magnetic hard disk drive area with respect to the annual rate of areal density growth. Since the early 1990s, areal density has grown at the rate of 60% annually, thus, doubling the data storage density every 18 months. Over the past two years, the annual growth rate in areal density is a whopping 100%, thus, actually exceeding Moore's law. The trend for increased storage capacity is likely to continue in the foreseeable future as the insatiable demand for storage grows amidst the emerging applications stemming from the convergence of voice, data, video, and mobile services. The growth of the Internet extends the need to store massive amounts of data, including graphics and images, on central servers as well as on personal computers. The pervasion of the e-commerce industry will only stimulate the appetite for more storage space. Hard disk storage devices are increasingly used in the consumer electronics area as well. The size of a quarter, miniature hard disk drives are now available that can store up to one Gigabyte of data. These small drives are competing with flash memory for applications in portable electronics, such as digital cameras as well as wireless handheld devices. High-capacity magnetic storage devices are also needed to implement the emerging personal TV concept that requires smart viewing of a huge volume of entertainment content. The primary technological drivers behind the progress in storage capacity are advances in key component technologies, including heads, media, and signal processing and coding techniques, as well as the scaling of mechanical components, leading to improved mechanical design and accurate servo positioning. Indeed, the physical bit dimensions in this inherently mechanical system are comparable to those of the solid-state DRAM cells. Commercial disk drives now store up to 18 Gbits of data per square inch of disk surface. Internal media transfer rates go up to 700 Mbits/s. The reliability requirement is stringent: after rereads and full error correction, the unrecoverable bit error rate is kept below 10^{-14} while the probability of miscorrection is typically less than 10^{-21}.

Signal processing and coding have played a key role in the progress in storage systems, both in the read/write process of data and in the positioning and control of mechanical components. Unlike in most other communication systems, there are no coding and signal processing standards in hard disk storage, as it is a tightly encapsulated system with no interoperability or removability requirements on the recording media. This lack of standards at the physical layer has resulted in an unimpeded and steady pace of new technology introduction. The partial response maximum likelihood (PRML) technology became ubiquitous by the mid-1990s. The first-generation PRML read channel was soon made obsolete by advanced methods based on higher order partial response equalization [extended PRML (EPRML) and generalized PRML] and combined coding and equalization techniques, akin to trellis-coded modulation for intersymbol inference (ISI)-free channels. Powerful constrained codes that enhance Euclidean distance properties at the channel output also have been developed. Overall, significant improvements in signal-to-noise ratio (SNR) utilization have been achieved during the past five years. This trend is likely to continue, if not accelerate, in the foreseeable future as novel coding techniques combining turbo and error control codes are deployed in conjunction with sophisticated equalization and noise whitening approaches. Advances in semiconductor process scaling are on the horizon to support the next generation of signal processing and coding techniques for magnetic hard disk drives, which remains the technology driver and the benchmark for all mechanical storage systems.

Unlike their hard disk storage counterparts, recording media in optical and tape storage devices must be removable as well as interoperable across different readers/writers. This means that the coding and signal processing methods employed must be able to cope with not only the usual problems such as noise, ISI, and nonlinearities, but also a host of additional impairments like fingerprints and scratches on the disk, tilt, and so on. The interoperability requirement is not only concerned with different manufacturers of the recorders and media, but also with a variety of different standards, such as CD, CD-R, CD-RW, and DVD. These considerations have driven optical data storage systems to rely much more heavily on modulation coding and error control coding to maintain the data integrity. On the other hand, use of powerful coding has enabled optical recording systems to employ simple timing recovery and detection schemes; only recently have PRML-type methods been considered in optical data storage systems. However, with current emphasis on even higher capacity optical storage systems (e.g., capable of recording and playing back HDTV programming), increasing attention is being paid to advanced equalizers and detection schemes. Other important directions for achieving high-density optical data storage are the use of shorter wavelength (e.g., blue lasers) illumination and near-field recording. Both of these advances are expected to significantly affect the role of coding and signal processing in optical data storage systems. Magnetic tape storage systems

Publisher Item Identifier S 0733-8716(01)01751-6.

have traditionally used read channels adapted from the hard disk drive industry. There are, however, several important ways in which these magnetic recording systems differ. One distinguishing characteristic of the tape channel is the dropout effects. Dropouts arise as tape particle asperity or mechanical fluctuation of head-tape spacing causes deep and prolonged signal fades. To maintain data integrity, dropouts must be taken into account in any read channel design and evaluation.

The first IEEE Journal on Selected Areas in Communication special issue dedicated to the storage channel appeared in January 1992, featuring some 20 quality technical papers on various coding- and signal processing-related issues for recording channels. Nearly 10 years have passed, and the recording industry has witnessed developments of many new coding and signal processing technologies. The advent of digital LSI technologies also has accelerated the pace at which sophisticated algorithms are implemented and deployed in commercial storage products. This issue is aimed at providing a focused perspective on recent coding and signal processing activities related to storage as well as at introducing new approaches that may potentially be at the core of the future generation read channel technology. We have loosely grouped 20 selected papers into five categories: coding, timing and data recovery, iterative algorithms, recording channel characterization and detection, and nonmagnetic storage.

We start the issue with articles on constrained coding. Constrained codes go back to the very early days of magnetic storage devices. They were designed to minimize pulse overlap to aid the simple-minded but robust peak detector as well as to ensure smooth operation of timing and gain control loops. They were also designed to control the spectral content for other purposes such as to aid detection of embedded servo signals, in the case of optical recorders, or to enable writing through an AC-coupled transducer as in helical-scan tape recorders. More recently, constrained codes have been developed that enhance distance properties at the channel output. Two examples of this type of coding are the maximum transition run (MTR) code and the forbidden list code. First, the paper entitled “A combinatorial technique for constructing high rate MTR-RLL codes,” co-authored by A. J. van Wijngaarden and E. Soljanin, presents a detailed description of a high-rate code that satisfies both a maximum runlength constraint and an MTR constraint. This code has actually been implemented in Lucent read-channel chips and has shown excellent performance. The second paper in this category is by D. S. Modha and B. Marcus, entitled “Art of constructing low-complexity encoders/decoders for constrained block codes,” where heuristic algorithms are proposed that can design constrained block encoder/decoders that reduce the complexity and eliminate excess extra codewords. The algorithm complexity is comparable to human-generated encoders/decoders and is much simpler than lexicographical versions. The paper “Maximum runlength-limited codes with error control capabilities,” by A. J. van Wijngaarden and K. A. S. Immink, describes new constrained-coding methods that protect maximum runlength-limited sequences against random and burst errors. The idea enables the application of high-rate constrained codes, and error control can be provided with the same capabilities as for unconstrained sequences. The proposed schemes also allows a low-complexity implementation. On a related issue, L. Reggiani and G. Tartara in their article, “On reverse concatenation and soft decoding algorithms for PRML magnetic recording channels,” show new results on reverse concatenation, where the traditional order of the ECC and constrained code is reversed. Reverse coding, first appeared in the literature in the early 1980s, is a promising technique for achieving a very high efficiency of the recording code. In line with what other researchers have suggested, Reggiani and Tartara show that reverse coding may also provide the possibility of a simpler use of soft decoding information, which may result in a significant coding gain. R. Cideciyan *et al.*, in their paper, “Maximum transition run codes for generalized partial-response channels,” introduce a new twins constraint for MTR codes to eliminate potential quasi-catastrophic error propagation for certain generalized partial-response channels. They also establish the connection between (G, I) constraints and MTR (j) constraints. Several constructions of high-rate MTR codes are provided based on look-ahead coding in combination with violation detection/substitution as well as the state-splitting technique.

A critical component of data storage channels that has been discussed relatively sparsely in open literature is the timing recovery module. For advanced sampled detectors to perform well, the sampling instants must be optimally chosen. P. M. Aziz and S. Surendran’s paper, “Symbol rate timing recovery for higher order partial response channels,” considers timing recovery schemes for higher order partial response channels of relevance to high-density magnetic recording. In particular, timing recovery loops employing different timing gradients or phase detectors are compared. This paper also discusses a timing recovery scheme in the context of a slope lookup table, which allows an efficient implementation. In the paper, “Reduced-complexity sequence detection for high-order partial response channel,” M. Leung *et al.* show how the employed distance-enhancing code can be used to reduce states from the original and two-step extended Viterbi trellis. The reduced set of ACS units is dynamically assigned to the states. The result is a significant reduction in complexity without compromising performance. The paper by V. Dorfman and J. K. Wolf, “A method for reducing the effects of thermal asperities,” deals with thermal asperity issues. The basic idea is to introduce an additional equalizer/detector path that is less sensitive to thermal asperity, although it performs not as well as the conventional equalization strategy. The selection as to which detected bits are more reliable is based on the detection of the presence of thermal asperity. The last paper on timing and data recovery is “Accelerated error propagation prediction techniques for decision feedback–based detectors,” by M. Jin *et al.*, where error propagation (EP) of decision feedback detectors such as the decision feedback equalizer and the fixed delay tree search is considered. The authors introduce a new method to measure EP statistics that can save up to 99% of the simulation time.

In order for the data storage industry to sustain the growth rate trend in density, it is important that the read channel provides substantial SNR gains in future storage systems. One of the techniques that will potentially yield large SNR gains is iterative coding (e.g., turbo codes and LDPC codes). We have listed four papers in the category of iterative algorithms. An important issue that must be addressed in applying iterative codes to data storage is the interplay between turbo codes and runlength-limited (RLL) codes needed in magnetic recording channels for timing recovery. K. Anim-Appiah and S. McLaughlin's paper, "Turbo codes cascaded with high-rate block codes for $(0, k)$-constrained channels," discusses several issues related to this process of combining turbo codes and $(0, k)$ RLL codes. A. Ghrayeb and W. E. Ryan's paper, "Concatenated code system design for storage channels," concerns optimal precoder design for generalized PR channels serially concatenated with a convolutional code via interleaver, based on a partial conditional distance spectrum. Joint optimization of interleaver and precoder is addressed for a fixed outer convolutional code and a PR target, and effects of thermal asperity are also examined. In his paper, "Effect of precoding on convergence for turbo-equalized partial response channels," K. Narayanan considers the effect of the precoder on the convergence of turbo equalization by viewing turbo equalization as a dynamical system that iterates on the reliabilities of the equivalent channel. The impact of precoding on the design of the outer code is also studied. Finally, Z.-N. Wu and J. Cioffi's paper, "Low-complexity iterative decoding with decision-aided equalization for magnetic recording channels," proposes a new soft *a posteriori* probability (APP) detector based on decision-aided equalization to reduce complexity in iterative coding systems. The reduction of channel APP detection complexity is substantial.

New head and media technologies have made channel noise characteristics different from those of the past. For example, now channel noise is becoming predominantly the medium noise, which is highly correlated with data. A. Kavcic and M. Srinivasan, in their paper, "The minimum description length principle for modeling recording channels," are concerned with signal-dependent autoregressive modeling of the medium noise in the magnetic recording channel. A formal criterion is established based on the minimum description length to choose a model order that compromises between complexity and accuracy. J. Moon and J. Park's paper, "Pattern-dependent noise prediction in signal-dependent noise," derives noise prediction that is locally optimized to combat pattern-dependent noise. They also establish links among previous related works on noise predictive ML and detectors optimized against signal-dependent noise. The paper entitled, "Dropout-tolerant read channels," by Sarigoz *et al.*, addresses modeling and detection of the fading tape channel. They establish a model for dropouts in tapes that properly explains excessive peak shifts observed in the real tape systems as well as the amplitude fades. A dropout compensation technique is then described, and turbo coding is shown to provide immunity to dropouts if minimal information about the dropout characteristics is passed onto the turbo decoder.

The final category is nonmagnetic storage. In addition to their highly visible place in consumer electronics, optical devices are also emerging as an important data storage means. Advanced optical storage systems like DVD and innovative optical recording technologies, such as near-field recording and optically assisted Winchester (OAW) recording, are good examples. A first paper in this category is a survey article by K. A. S. Immink entitled, "A survey of codes for optical disk recording." Immink reports on 20 years of development of codes for optical disk recording systems. A description of the state-of-the-art and feasible options for future extensions and improvements are given. The next article by B. Vasic *et al.*, "Loose composite constraint codes and their applications in DVD," also deals with constrained coding for the classic optical recording channel. In such channels, sequences with a minimum runlength constraint are used to circumvent difficulties with mastering and mass-replication of disks. Typical examples of such codes are EFM and EFMPlus, which are used in the compact disk (CD) and DVD, respectively. Vasic *et al.* introduce a modification of EFMPlus that gives a better suppression of the low-frequency content than is possible with EFMPlus. The article "Iterative decoding for partial response (PR) equalized magneto-optical (MO) data storage channels," by Song *et al.*, discusses iterative decoding techniques for the magneto-optical recording channel subject to mark edge jitter. Their results show that both turbo codes and low-density parity check (LDPC) codes are robust to mark edge jitter. The last paper in the nonmagnetic storage category is about volume holographic data storage, which offers the potential for very high volumetric storage densities (one bit in a few microns) as well as very high data rates (data pages with more than a million bits being read out at submillisecond rates). Two-dimensional modulation codes can improve the capabilities of volume holographic memories by ensuring that local regions in a data page exhibit similar intensity levels. B. M. King and M. A. Neifeld discusses in their paper, "Low-complexity maximum-likelihood decoding of shortened enumerative permutation codes for holographic storage," how one type of nonbinary, constant-weight modulation code can be used to achieve higher storage capacities in volume holographic memories employing gray level.

Bringing forth this special issue was not an easy task; it would not have been possible without the help of all the reviewers who volunteered their time and expertise. We also thank Sue McDonald, Aubrey Bush, and Larry Milstein of the J-SAC Editorial Board for their help and support.

Finally, we also mention some additional materials that may benefit the interested reader. For a comprehensive treatment on constrained codes used for data storage channels, see K. A. S. Immink, *Codes for Mass Data Storage Systems* (Shannon Foundation Publishers, 1999). For equalization and detection related issues as well as timing recovery, J. W. M. Bergmans's book, *Digital Baseband Transmission and Recording* (Kluwer Academic, 1996), may be helpful. Also, each year, the IEEE Global Telecommunications Conference and the IEEE International Conference on Communications run sessions dedicated to data storage. In addition, either the September or the November issue of the IEEE TRANSACTIONS ON MAGNETICS includes papers presented in the annual International Conference on Magnetics, and contains a significant number of papers on communication methods of data storage technology. Finally, every third year, The Magnetic Recording Conference (TMRC) is devoted to systems and signal processing issues for storage. The last TMRC dedicated to signal processing was in the year 2000, and some of the papers presented there appeared in the January 2001 issue of the IEEE TRANSACTIONS ON MAGNETICS.

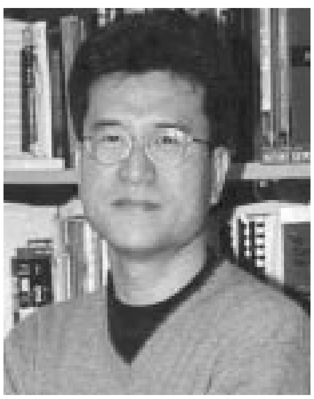
JAEKYUN MOON, *Guest Editor*
University of Minnesota
Minneapolis, MN 55455 USA

HEMANT THAPAR, *Guest Editor*
LSI Logic Corporation
San Jose, CA 95138 USA

B. V. K. VIJAYA KUMAR, *Guest Editor*
Carnegie Mellon University
Pittsburgh, PA 15213 USA

KEES A. SCHOUHAMER IMMINK, *Guest Editor*
University of Essen
Essen, Germany

A. M. BUSH, *J-SAC Board Representative*



Jaekyun Moon (S'89–M'90–SM'97) received the B.S.E.E. degree from the State University of New York at Stony Brook and the M.S. and Ph.D. degrees in electrical and computer engineering department from Carnegie Mellon University, Pittsburgh, PA, in 1987 and 1990, respectively.

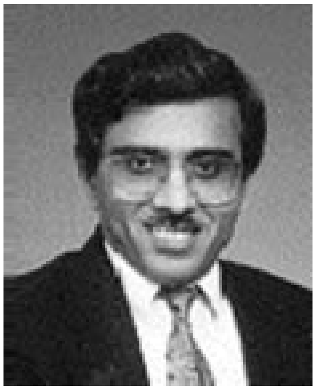
He held a short-term position at IBM Research in 1987. Since 1990, he has been with the faculty of the Department of Electrical and Computer Engineering at the University of Minnesota, Twin Cities, where he is now a Professor. His research interests include channel characterization and signal processing for data storage and digital communication. He has served as a Consultant for the disk drive and tape drive industry since 1990.

Dr. Moon was selected to receive the IEEE-Engineering Foundation Research Initiation Award in 1991. He received the 1994–1996 McKnight Land-Grant Professorship from the University of Minnesota. He also received the IBM Faculty Development Awards as well as the IBM Partnership Awards. He is a recipient of the 1997 National Storage Industry Consortium (NSIC) Technical Achievement Award. He served as Program Chair for the 1997 The Magnetic Recording Conference. He is also a past Chair of the Signal Processing for Storage Technical Committee of the IEEE Commuincations Society. He served as a Guest Editor for the 2001 IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS issue on signal processing for high-density recording.

Hemant Thapar (S'78–M'79–SM'97–F'98) received the Ph.D. degree in electrical engineering from Purdue University, in 1979.

He has held various technical and management positions in advanced technology development at Bell Telephone Laboratories, Holmdel, NJ, (1979–1984) and at IBM, San Jose, CA, (1984–1994). He co-founded DataPath Systems Inc. in 1994 and was its CEO until July 2000 when it merged with LSI Logic Corporation. He is presently a Vice-President in the Broadband Communications Group at LSI Logic and also an Adjunct Lecturer at Santa Clara University, Santa Clara, CA. His interests inlcude communication signal processing, system architecture, and VLSI development. He has authored many publications and patents in the areas of data communications, networking, and data storage.

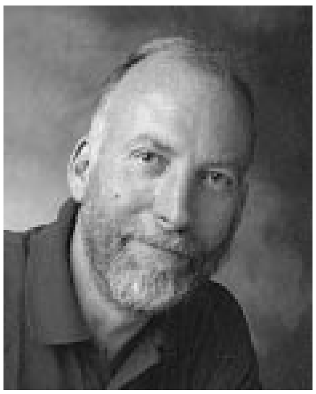
Dr. Thapar is co-recipient of three best paper awards for his work on high-speed data transmission and high-density data storage. He has served as the Chairperson of the Signal Processing for Storage Committee of the IEEE Communications Society and the Guest Editor for the first IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS issue on signal processing and coding for data storage.



B. V. K. Vijaya Kumar (S'78–M'80–SM'90) received the B.Tech. and M.Tech. degrees in electrical engineering from the Indian Institute of Technology, Kanpur, and the Ph.D. degree in electrical engineering from Carnegie Mellon University (CMU), Pittsburgh, PA.

Since 1982, he has been a faculty member in the Department of Electrical and Computer Engineering, CMU, where he is now a Professor. His research interests include image processing, pattern recognition, coding, and signal processing for data storage systems. He has authored or co-authored more than 250 technical papers in these areas in various conference proceedings and journals.

Dr. Kumar served as a Topical Editor for the Information Processing Division of Applied Optics. He is a member of Sigma Xi, a Fellow of SPIE, and a Fellow of Optical Society of America. He is listed in *Marquis's Who's Who in the World* and in the *American Men and Women of Sciences.*



Kees A. Schouhamer Immink (M'81–SM'86–F'90) was born in Rotterdam, The Netherlands. He received the M.Sc. (EE) and Ph.D. degrees from the Eindhoven University of Technology.

He is President and Founder of Turing Machines Inc. and serves as a Guest Professor at the Institute of Experimental Mathematics, Essen University, Germany, and the National University of Singapore. He has contributed to the design and development of a variety of digital recorders such as the compact disk, compact disk video, DAT, DCC, and recently, the DVD. Immink was granted 35 U.S. patents, is (co)author of three books and has written numerous papers in the field of digital recorders.

Dr. Immink is Vice-President of the Audio Engineering Society (AES), a Governor of the IEEE Consumer Electronics Society, and Trustee of the Shannon Foundation. He served as Program Chairman and Conference Chairman of various international conferences over the years. He holds fellowships of the AES, IEE, and SMPTE, and is an elected member of the Royal Netherlands Academy of Arts and Sciences. For his part in the digital audio and video revolution, he was honored with the AES Gold and Silver Medal, IEE Thomson Medal, SMPTE Ponyatoff Gold Medal, IEEE Information Theory Society Golden Jubliee Award for Technical Innovation, IEEE Masaru Ibuka consumer electronics award, a Knighthood in the Order of Orange-Nassau, and the IEEE Edison Medal "For a career of creative contributions to the technologies of video, audio, and data recording."