# Introduction to the Special Issue on Coding for Storage Devices

IT has become widely recognized that retrieving data stored over time is much the same as decoding data transmitted across space. Accordingly, there has been a growing effort to use information theory to explore theoretical and practical problems related to the design of digital data storage devices. This special issue is the first in the IT Transactions—in fact, in any IEEE Transactions—to be devoted entirely to this theme.

We begin with a paper and two correspondences that bound the capacity of certain storage channels, including the magnetic recording channel with peak detection (Duel-Hallen, Heegard, and Krishnamoorthy; Shamai and Zehavi), and write-unidirectional optical memories (van Overveld). The remaining papers and correspondences fall naturally into six categories: Compression, Error Correction (EC), Modulation, Combined EC/Modulation, Trellis-Coded Modulation, and Write Equalization. The ordering reflects the path taken by a datum through the block diagram of a recording channel shown in Fig. 1.

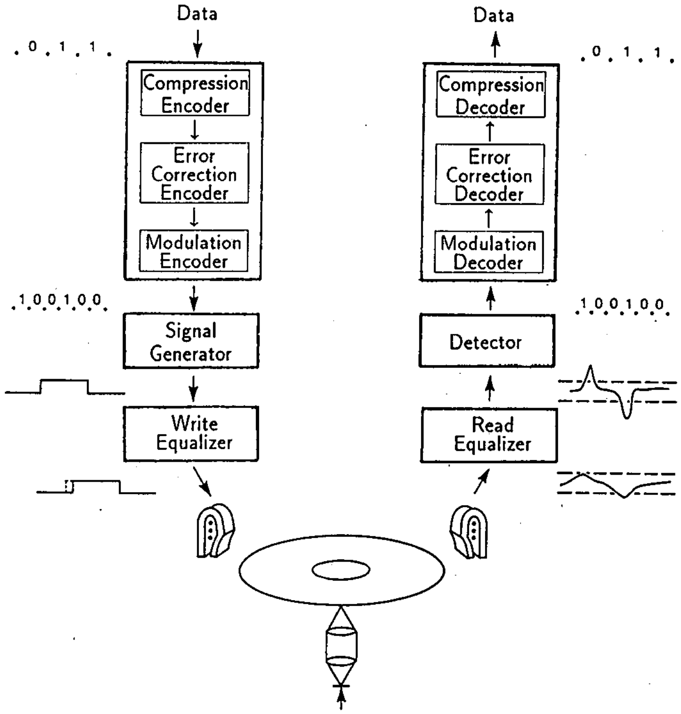


Fig. 1. Digital data recording channel.

As demand for storage capacity grows, the application of data compression algorithms is becoming more widespread. The Lempel–Ziv algorithm is the most widely used compression scheme, having found its way into many general-purpose file compression programs. The paper and correspondence in the Compression category (Bender and Wolf; Wyner and Ziv) describe new performance bounds, extensions, and improvements to this celebrated algorithm.

The papers listed under Error Correction are primarily algebraic in nature, and cover several quite different applications. One paper (Zémor and Cohen) develops a new class of error-control codes for write-once memories, a special case of write-unidirectional memories. A second (Abdel-Ghaffar and Hassner) describes and analyzes multilevel codes, designed to be compatible with the magnetic disk architecture that is a standard in large capacity drives. Finally, there is a cluster of articles related to coding for semi-conductor memories and VLSI circuits. These correspondences cover a new channel model suggestive of random-access memories (Bassalygo, Gelfand, and Pinsker), reliability analysis of on-chip coding (Goodman and Sayano), as well as new coding techniques (Davydov and Tombak; Saitoh and Imai).

The papers and correspondences listed under Modulation address the analysis and construction of recording codes satisfying runlength limitations and frequency-domain constraints in the form of spectral nulls and discrete spectral lines. There are two papers and one correspondence that continue the theoretical investigation and application of sliding-block codes in the context of storage devices. The first paper (Marcus and Roth) derives several lower bounds on encoder complexity. It finds immediate use in proving the optimality of a new (1,7) runlength-limited (RLL) code presented in the correspondence (Weathers and Wolf). In the second paper (Heegard, Marcus, and Siegel), a statistical variation on the usual runlength limitations is introduced and analyzed. These average-runlength constraints provide a vehicle for the demonstration of improved methods for constructing fixed-rate, variable-length codes. A series of four correspondences deals with the evaluation and characterization of sequences with spectral nulls and discrete spectral lines. The first (Hollmann and Immink) evaluates the effectiveness of low-frequency suppression for two classes of codes with spectral nulls at zero frequency (dc). The second (Fredrickson) provides a new description of constrained sequences with simultaneous spectral nulls at dc and the Nyquist frequency, along with a tabulation of Shannon capacity as a function of the two parameters defining the constraint. The third and fourth focus on codes with discrete spectral lines. These codes have been proposed and used in magnetic/optical disk systems to provide the equivalent of a pilot tone, suitable for timing and position recovery. The third (Janssen and Immink)

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determines the eigenstructure of a certain class of matrices, and applies this result to the computation of the Shannon capacity and power spectrum of maxentropic binary systems with spectral line at dc. The fourth (Kamabe) gives a complete characterization of the more general class of constrained sequences with discrete spectral lines at a rational submultiple of the symbol frequency.

The next two categories, Combined EC/Modulation and Trellis-Coded Modulation, reflect the explosion of interest in coding schemes that combine the functions of error control and modulation. The first collection of papers and correspondences addresses the derivation of theoretical bounds on the achievable rates of certain constrained codes satisfying specified minimum Hamming distance criteria, as well as the construction of efficient error-correcting modulation codes. The first paper (Kolesnik and Krachkovsky) develops a lower bound on achievable rates for error-correcting sequences satisfying a runlength constraint or with a spectral null at dc. This bound, similar in spirit to the Gilbert–Varshamov bound for unconstrained sequences, is proved using a generating function approach. The first correspondence (Ytrehus) derives upper bounds on the rate of block codes satisfying runlength limitations and capable of correcting a single error. These upper bounds are extended and improved in (Abdel-Ghaffar and Weber), which also describes several new, efficient block-code constructions. The next correspondence (Blaum) proposes an alternative method for constructing block codes that combine substantial error-correcting capability with commonly-used runlength constraints. The performance of these codes is compared to the performance of a concatenated coding scheme similar to that currently used in many commercial systems. Turning to codes with spectral null constraints, the next correspondence (Cohen and Litsyn) derives upper and lower bounds on the possible rates of dc-free subcodes of Hamming codes, where the running-digital-sum (RDS) is restricted to a small range of values. In a related paper (Barg and Litsyn), a new class of error-correcting codes with RDS constraints is proposed. The construction of these codes is based upon properties of Hadamard matrices.

Trellis-coded modulation has had an enormous impact on data transmission during the latter part of the past decade. In the setting of digital magnetic recording, the recent introduction of digital signal processing techniques, such as partial-response signaling with maximum-likelihood sequence estimation, has opened the door to the application of trellis-based coding and detection methods in this very different channel environment. The correspondence in this category (Vannucci and Foschini) presents an efficient algorithm for computing the minimum (Euclidean) distance of multilevel partial-response models that are well-suited to recording channels, thereby providing a baseline for evaluating coding gains. The two papers present different approaches to the design of trellis codes for some relevant partial-response channels. The first paper (Hole), employing a channel inversion approach, defines and analyzes a new class of punctured convolutional codes for the precoded dicode partial-response channel. The method described in the second paper (Karabed and Siegel) exploits, rather than eliminates, the memory of the partial-response channel by matching the spectral nulls in the code power spectrum to those in the channel frequency response.

In the last category, Write Equalization, the sole paper (Hollmann) is an unusual hybrid of coding and equalization. It characterizes the transfer functions of digital recursive filters that transform two-level, runlength-constrained input sequences to two-level output signals, generalizing a family of write-equalization codes recently developed for use in digital magnetic tape recording.

In summary, the articles in this special issue represent some of the latest, innovative thinking about coding problems relevant to digital data storage applications. They confirm that data storage, by virtue of its conceptual kinship to data transmission, offers new and interesting opportunities to apply a wide range of information–theoretic tools. Moreover, they serve to emphasize that the unique characteristics of storage channels can, in turn, suggest new problems of a fundamental nature that stimulate progress in information and coding theory.

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