Guest Editorial The Turbo Principle: From Theory to Practice

THE INTRODUCTION of turbo codes by Berrou, Glavieux, and Thitimajshima in the mid-90s, and the widespread recognition of their significance that quickly followed, triggered a tidal wave of research addressing their performance analysis, design, implementation, and application in digital communications and data storage systems. The novel encoding architecture—which combined parallel concatenation of recursive systematic convolutional codes, large block length, and random permutation ("interleaving")—and the ingenious, and surprisingly effective, iterative decoding approach—which relied upon the exchange of information between soft-input, soft-output (SISO) component decoders—opened many new avenues of investigation for communication theorists and practitioners alike.

The February 1998 J-SAC issue, entitled "Concatenated Coding Techniques and Iterative Decoding: Sailing Toward Channel Capacity," was devoted entirely to the exciting early developments in this new branch of coding theory. Structural properties of these near-capacity achieving codes were beginning to be understood but the success of the associated iterative decoding algorithms remained largely a mystery. In the editorial preface to that issue, the Guest Editors (Benedetto, Divsalar, and Hagenauer) adopted the expression "the turbo principle" to describe the key idea underlying the turbo-decoding algorithm, namely "(the) strategy exploiting the iterated exchange of soft information between different blocks in a communication receiver," similar to the exchange between the turbine and the compressor in a turbo-engine (Hagenauer, 1997). They identified several major open questions pertaining to fundamental properties and practical applications of iterative decoding techniques that exploited this concept. The need for analytical methods to study the dynamics and convergence of the iterative process was cited, along with the importance of understanding the impact of block length on performance. There also remained the issue of iterative decoding latency in applications where delay constraints were imposed. Finally, they noted the potential importance and applicability of this general principle to a wide range of problems in communications, extending well beyond channel coding.

This J-SAC double-issue, which may be regarded as a sequel to that seminal February 1998 J-SAC issue, brings together 32 papers that reflect, and contribute to, the extraordinary progress that has been made in the broad program of research suggested by those earlier editorial observations. In the slightly more than three years that have elapsed, a substantially better understanding of the properties of turbo-like codes, as well as of the behavior of iterative decoding algorithms employing the turbo principle, has emerged. Powerful coding schemes amenable to iterative decoding have been developed for virtually every communication channel model, and, for certain memoryless channels, the Shannon capacity has now effectively been achieved (although block length and decoding complexity may remain concerns). Also, as anticipated, the turbo principle has grown to be a powerful tool in attacking a diverse set of problems in communications: the papers in this double-issue represent applications to decoding of higher order coded-modulation schemes, including space–time codes; joint source-channel decoding; joint channel estimation/equalization and decoding; and, detection and decoding of multiuser and spread-spectrum communication systems. Moreover, the intensive study of the turbo principle has further elucidated important connections among the disciplines of communication theory, information theory, dynamical systems, graph theory, and artificial intelligence.

In order to set the stage for the contributions presented in this double-issue, we will briefly review some recent milestones achieved in the design, analysis, and application of coding schemes that, by exploiting the turbo principle, approach information-theoretic performance limits.

In the area of turbo-code design, properties of several "turbo-like" encoding schemes based upon serial and hybrid serial/parallel concatenation architectures have been examined. The astonishing coding theorems for "Repeat-Accumulate" codes (Divsalar, Jin, and McEliece, 1998) and their extensions to other turbo-like codes have confirmed that concatenations of simple outer codes with recursive inner codes (even rate-1 inner codes!) through random interleavers can provide asymptotically good performance. Here, asymptotic goodness refers to the existence of a threshold signal-to-noise ratio, above which a specified decoder (e.g., maximum-likelihood) yields vanishing word-error-rate (or bit-error-rate) as the code block length approaches infinity. Improvements in performance bounds based upon distance spectrum analysis—the key to proving these coding theorems—have provided ever-tighter thresholds that, in some cases, have been shown to approach the Shannon capacity. Empirical results of computer simulation show that, for large enough block lengths, iterative turbo-decoding can achieve excellent performance at signal-to-noise ratios close to the maximum-likelihood decoding threshold.

Another important class of codes, extending Gallager's low-density parity-check (LDPC) codes, has received considerable attention (MacKay, 1999). With iterative message-passing decoding algorithms, these coding techniques have been shown to exhibit performance comparable to, and sometimes better

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than, the original turbo codes. The extension of Gallager's technique of "density evolution" has provided a breakthrough in the analysis of such iterative message-passing decoders, as well as the basis for a practical design method for powerful LDPC codes on a large class of channels. Beginning with a specified class of bipartite graphs and the corresponding ensemble of LDPC codes, the technique determines a threshold value that can be translated into a minimum signal-to-noise-ratio (Richardson and Urbanke, 2001), above which the message-passing decoder will yield asymptotically good performance for most codes in the associated LDPC code family. For optimized graph structures, the resulting thresholds have been shown, in some cases, to be extremely close to those corresponding to the Shannon capacity, and simulations with large block lengths have confirmed good code performance essentially at the threshold (Richardson, Shokrollahi, and Urbanke, 2001). We encourage the reader interested in these and other recent advances to consult the February 2001 Special Issue on Codes on Graphs and Iterative Algorithms of the IEEE TRANSACTIONS ON INFORMATION THEORY.

There have also been significant strides in the translation of the turbo principle from theory to practice, a central theme of this double-issue. One of the application areas that has benefited the most from the development of powerful turbo codes is deep space communications. The benefit has been twofold: an improvement in performance over the most complex concatenated codes used for the Cassini and Pathfinder missions, and, even more important, a significant reduction in decoding complexity. This has led to the selection of a family of parallel-concatenated turbo codes, using a pair of 16-state component codes, as a new Consultative Committee for Space Data Standards (CCSDS) standard, based on code designs by NASA/JPL and the European Space Agency (ESA). These codes will be supported by the Deep Space Network (DSN) for NASA and interagency missions with launch dates in 2003 and beyond. In order to overcome the stress that these turbo codes impose upon the receiver synchronization loops by operating at extremely low symbol signal-to-noise ratios, new iterative joint receiver/decoder schemes are being developed. Through application of the turbo principle, these schemes can virtually eliminate synchronization losses.

In the arena of wireless terrestrial communications, new so-called third generation (3G) cellular standards now make use of turbo codes for data services. The cdma2000 (IMT-2000: 1xMC, 3xMC) standard provides mixed voice and data services. For data services, a parent rate-1/5 turbo code consisting of two identical, eight-state, parallel, rate-1/3 constituent recursive systematic convolutional (RSC) encoders is employed. In the 1x mode, this code is punctured to rates between 1/2 and 1/4 and supports data rates from 19.2 kb/s to 307.2 kb/s per code channel (a maximum of 2 per user) with turbo interleaver lengths in the range of 378 to 12,282. In the 3xMC mode, data rates up to 1.0368 Mb/s per code channel are supported with interleaver sizes up to 20,730. cdma2000 1x is already commercially deployed and has been providing voice and data services to customers since October 2000.

The cdma2000 High Rate Packet Data Air Interface Specification (IS-856: 1xEV) provides data services and employs the exact same parent turbo encoder as that used for cdma2000 1x/3x. This standard provides data rates between 38.4 kb/s and 2.4578 Mb/s (on the forward link) using turbo interleaver lengths between 1018 and 4090, and coding rates of 1/3 and 1/5. cdma2000 1xEV has conducted successful trials and is planned for commercial deployment in the latter half of 2001.

In the WCDMA (Wideband CDMA) standard (IMT-2000: DS), a turbo code is provided which is identical to the cdma2000 turbo encoder when punctured to rate 1/3, with the one notable exception that the two turbo encoders use different pseudorandom interleavers. Both interleavers are deterministic in nature and reasonably low in required chip area and circuit complexity. Symbol repetition and puncturing on the parent rate-1/3 code may be applied to match rates specific to a given data service. The WCDMA turbo code supports data rates up to 2 Mb/s with interleaver sizes from 40 to 5114. It will most likely be used for data services only, although it does support very small packet sizes.

With respect to voice transmission, conventional vocoded data frames still make use of convolutional coding in the cdma2000 and WCDMA standards. This is because the required voice data frame sizes are so small that the gain of turbo codes over convolutional codes is insufficient to justify the increased decoder latency. Voice-Over-IP (VOIP) could be implemented through a turbo-coded data service, however. Nevertheless, at higher packet sizes, there is no question that turbo codes provide significant gains, as much as 1 to 2 dB, even in multipath Rayleigh fading scenarios, over standard convolutional codes. This performance advantage translates into a significant increase in data link capacity.

Another application area in which the use of turbo and LDPC codes is under consideration is wired transmission, specifically in Digital Subscriber Line (DSL) technologies. Various coding schemes for multilevel transmission have been proposed to the ITU-Telecommunication Standardization Sector, and to the Standards Committee T1-Telecommunications, for enhancing the performance of the existing Asymmetric DSL (ADSL) standard as well as of the evolving Very-high-rate DSL (VDSL) standard. It has been demonstrated that introduction of advanced coding and iterative decoding techniques offers the promise of operating DSL links much closer to their capacity. Application of turbo and LDPC codes for multilevel DSL transmission is currently a topic of intense debate in the standards bodies.

Finally, turbo and LDPC codes hold the promise to push the areal density of magnetic recording systems to the limit for given magnetic components. It has been shown that—despite the existing sector-size constraints of hard-disk drives that limit the block length of a code and the high code-rate requirement—rather simple iterative decoding schemes can bring performance to within approximately 1.5 dB of the theoretical limit, which represents a significant gain compared to existing systems. However, despite progress in the area of reduced-complexity detection and decoding algorithms, turbo equalization structures with iterative, SISO detectors/decoders have not yet found their way into digital recording systems owing to the still unfavorable tradeoff between performance, implementation complexity, and latency. The design of high-rate, short-block length turbo-like codes as well as low-latency iterative decoding algorithms remains an area of active research. Additional results pertaining to the application of turbo and LDPC codes in digital recording systems may be found in the April J-SAC issue on Signal Processing for High Density Storage Channels.

With regard to circuit implementation, several researchers have observed that turbo decoding lends itself naturally to an analog approach (eg., Hagenauer, 1997, and Loeliger *et al.*, 1998). Recently, analog VLSI implementations of the *a posteriori* probability (APP) algorithm and full iterative decoders have been reported, and the potential advantages in speed and power consumption inherent in analog circuits certainly warrant further investigation.

Despite the impressive progress of the past few years, it is clear that a great deal remains to learned regarding the theory and practical application of the turbo principle. We close the general introduction to this double-issue by highlighting a critical, and very challenging, problem for future research. Although the enormous potential of turbo, LDPC, and related codes has been convincingly demonstrated, the adoption of these coding methods in many practical applications requires a thorough study of their system-level performance. For example, high data-rate transmission applications that require extremely low overall error-rates, such as digital recording and optical communications, make use of an outer algebraic code, often an interleaved Reed-Solomon (RS) code, to achieve their error-rate targets. In these settings, a mismatch between the error-correcting capabilities of these algebraic codes and the statistics of the residual errors from an inner turbo or LDPC code can significantly reduce, or eliminate completely, the potential benefit offered by these powerful inner codes. Therefore, it is of interest to pose the question: can a suitably designed turbo, LDPC, or other code of appropriate rate and length replace the outer hard-decision RS code in these applications? More generally, what is the proper way - if in fact a way exists - to exploit the power of the turbo principle to improve the overall performance of such systems? We invite the readers of this issue to tackle this important problem.

The general theme of the papers in Part I of this double-issue is the use of the turbo principle in the context of coding for various channel models. The papers in Part II address the use of the turbo principle in joint source-channel decoding, joint channel estimation/equalization and decoding, and multiuser/spread-spectrum communications.

Following is a brief summary of the contents of Part I.

Concatenated Codes: Distance Properties and Performance Bounds

The first group of three papers examine distance properties and performance bounds for several classes of concatenated codes.

The first paper (Garello, Pierleoni, and Benedetto) presents an efficient algorithm for computing the free distance of parallel and serially concatenated codes with interleavers. The free distance determines code performance at high signal-to-noise ratios, and knowledge of it can be used to estimate error floors. The algorithm allows the computation of large distances for large interleaver lengths without the need to restrict the search to input sequences of small weight. The authors use this new algorithm to compute, for the first time, the free distance of practical codes for deep-space-telemetry applications as well as for third-generation cellular systems.

The next paper (Bossert, Freudenberger, Zyablov, and Shavgulidze) examines encoding schemes for woven codes with outer wrap. Serially and parallel concatenated (turbo) codes are considered as special cases of woven constructions. The authors derive lower bounds on the minimum (free) distances of various woven constructions, based upon the active distances of the component codes. They introduce specially designed interleavers that improve the bounds, and demonstrate that woven code constructions can achieve lower error floors than typical turbo codes with random interleavers do. A particular design, woven turbo codes, is shown to exhibit good waterfall region performance, as well.

The final paper is this group (Zangl and Herzog) improves upon the tangential sphere bound (TSB) on bit error probability given by Sason and Shamai as an extension of the work of Poltyrev. Simulation results confirm that the new method provides tighter bounds for certain concatenated codes at signal-to-noise ratios below the computational cutoff rate.

Turbo Codes: Practical Design, Implementation, and Applications

The next set of seven papers address a number of issues pertaining to the practical design, implementation, performance, and application of turbo-like concatenated codes and iterative turbo decoders.

The first of these (Sadjadpour, Sloane, Salehi, and Nebe) addresses interleaver design for turbo codes having short block lengths. The design takes into account both the code distance spectrum and the correlation properties of the decoder inputs (or iterative decoding suitability (IDS) criterion). The proposed algorithm produces good interleavers whose performance is shown to be superior to that achieved by S-random and random interleavers. Methods to reduce implementation complexity of the interleavers are also presented.

It is well known that the performance of a turbo code can be severely degraded if no trellis termination is employed. The next paper (Hokfelt, Edfors, and Maseng) investigates the origin of this problem and studies the performance differences of various commonly used termination methods. This paper is the first to show that the performance of the trellis termination method depends on the choice of interleaver used in the turbo-encoder. Furthermore, the authors observe that this dependency is the result of the so-called “interleaver edge effects.” They present interleaver design rules that are tailored to the chosen trellis termination technique, and demonstrate that, by following these design guidelines, it is possible to avoid performance degradation completely, even without any trellis termination.

The Bahl, Cocke, Jelinek, and Raviv (BCJR) algorithm, also known as the forward-backward or the *a posteriori* probability (APP) algorithm, is the core component in many iterative detection and decoding schemes. For systems with large memory the complexity of the BCJR algorithm may be prohibitively high. The next paper (Colavolpe, Ferrari, and Raheli) presents an extension of reduced-state sequence detection techniques to a general soft-input/soft-output BCJR algorithm. The resulting reduced-state BCJR-type algorithms are highly suited for iterative detection and decoding applications. Using concrete examples, the authors demonstrate with concrete examples that the new BCJR-type algorithms are very effective in substantially limiting the complexity of the iterative detection and decoding process, without incurring significant performance degradation.

A fundamental operation in iterative detection is the soft inversion of a finite-state machine which is typically executed using the forward-backward SISO algorithm. The next paper (Beerel and Chugg) shows that exactly the same operation can be executed using a tree-structured algorithm. The resulting tree-SISO algorithm may be implemented in an architecture that has latency logarithmic in the observation record length. This represents an exponential speed increase over the architectures for the forward-backward algorithm whose latency grows linearly with the block length. The authors develop the tree-SISO by showing that the soft-inversion problem can be formulated as a combination of prefix and suffix operations and then draw upon well-known tree-structures for fast parallel prefix computations in the VLSI (e.g., tree adders). The paper also considers how one may use the tree-SISO technique to implement a high-speed turbo decoder in practice.

The next, implementation-oriented paper (Montorsi and Benedetto) deals with the analysis of turbo decoding implemented by fixed point processors. The authors show that the number of bits for the log-likelihood ratio (LLR) and the extrinsic information must be carefully chosen to avoid the occurrence of error floors. A very useful conclusion of the paper is a rule of thumb for a satisfactory implementation of the approximate BCJR algorithm: Quantize to five bits, with three bits for the dynamic and two bits for the precision. This quantization rule was shown to provide near-ideal performance when applied to the turbo code used in the UMTS system.

The authors of the next paper (Bajcsy, Chong, Garr, Hunziker, and Kobayashi) address a problem often encountered in engineering real systems, namely that of achieving improved performance while retaining backward compatibility. They present an iterative decoder based upon ambiguity zone detection (AZD) for concatenated systems that do not allow the use of turbo decoding. Applications of this decoding technique to wireless communications and digital recording are described.

The final paper in this group (Divsalar, Dolinar and Pollara) applies density evolution techniques to explain the behavior of the iterative decoding process, as well as to gain new insights into the design of turbo and turbo-like codes. The authors use the input-output signal-to-noise ratio characteristics of individual component decoders on the same plot to explain the conditions of decoder convergence. In their analysis, they consider parallel and serially concatenated codes, as well as LDPC codes. The paper includes a wealth of examples illustrating the technique, including concatenations of mixed outer and inner codes that approach their capacity limits within 0.1 to 0.6 dB.

Low-Density Parity-Check Codes

The next three papers present recent advances in decoding algorithms for LDPC codes, as well as applications of this class of codes to magnetic recording channels and Rayleigh fading channels.

The first paper (Fossorier) proposes a new iterative decoding algorithm for LDPC codes and combines ordered statistic decoding with belief-propagation (BP) decoding. For short- to medium-length LDPC codes, the algorithm is shown to close the performance gap between BP decoding and maximum-likelihood decoding. Performance-complexity trade-offs are also addressed.

The next paper (Song, Todd, and Cruz) proposes the use of high-rate LDPC codes as outer codes for magnetic recording systems. The maximum-transition-run (MTR) code—a constrained code used in recent commercial magnetic recording systems—is serially concatenated in reverse order with a LDPC code to avoid the need for soft decoding of the MTR code. Iterative detection/decoding is then performed between the partial response channel and the LDPC code. The authors present simulation results that show significant gains over uncoded systems. This suggests that LDPC codes are a candidate to increase the areal density of future magnetic recording systems.

In the final paper of this set (Hou, Siegel and Milstein), the authors apply the previously mentioned "density evolution" technique in the context of LDPC code design and optimization for Rayleigh fading channels. The nonlinear optimization technique of differential evolution is used to identify good degree distributions for irregular LDPC codes. The authors show that the thresholds of the optimized LDPC codes are generally very close to the channel capacity, and provide a concrete example of an optimized irregular LDPC code having a threshold that is only 0.07 dB away from capacity. Simulation results indicate that optimized LDPC codes can outperform turbo codes on the correlated Rayleigh fading channel.

The Turbo in Higher Order Coded Modulation

The final group of papers in Part I investigate the application of code concatenation, interleaving, and iterative decoding to systems using higher order modulation alphabets.

The first paper (Isaka and Imai) addresses the application of the turbo principle to multistage decoding of multilevel codes. Classical multistage decoding of multilevel codes, as introduced by Imai and Hirakawa, suffers from error propagation from the lower to the higher stages. Here, the authors propose a remedy for this problem based upon the iterative updating of the metrics used in the successive decoding stages. This technique effectively reduces the error multiplicity and often achieves a performance comparable to maximum-likelihood decoding. Applying this method to multilevel codes over 8-PSK, the authors demonstrate good performance within 0.8dB of the Shannon limit.

The next paper in this group (Chindapol and Ritcey) applies iterative decoding (ID) to bit-interleaved coded modulation (BICM) for Rayleigh fading channels. Using a proposed design criterion for the component code, as well as a new constellation labeling for QAM constellations, the BICM-ID system achieves performance that surpasses that of BICM and is comparable to that of other, more complex, turbo coded modulation schemes. The codes designed for Rayleigh fading channels are also shown to perform well in additive-white-Gaussian-noise (AWGN) channels.

Part I concludes with two papers that apply principles of turbo coding and iterative demodulation/decoding to systems having multiple transmit and receive antennas in a Rayleigh fading environment. The first of these (Stefanov and Duman) presents a new method of applying turbo coded modulation to such a system and compares the performance of the proposed scheme to that of recently proposed space–time trellis codes. Practical issues such as imperfect channel state information and spatial correlation are also considered.

The second of these (Liu, Fitz, and Takeshita) proposes a class of space–time turbo codes that achieve full rate as well as full spatial diversity. Both parallel and serial concatenation architectures are considered. Theoretical analysis and simulation are used to confirm the spatial and temporal diversity. Finally, robustness in correlated fading channels is addressed.

In summary, the papers in Part I of this double-issue reflect the substantial progress that has been made in building a better theoretical foundation for the study of codes and decoders that exploit the power of the turbo principle. They also address key issues involved in the practical design and implementation of these coding schemes in applications ranging from wireless communications to magnetic recording. Although many interesting and important problems in fully realizing the potential of these codes remain to be solved, it is evident that major forward steps have been achieved in extending the turbo principle from coding theory to coding practice.

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We have enjoyed working with all those involved in preparing this double-issue, and we hope that you, the readers, will benefit from all of their efforts.

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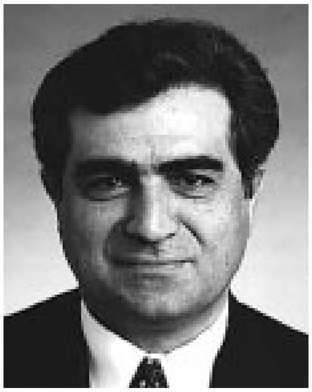

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Dr. Eleftheriou holds over 30 patents (granted and pending applications) in the areas of coding and detection for transmission and digital recording systems, and was named a Master Inventor at IBM Research in 1999. He was Editor of the IEEE TRANSACTIONS ON COMMUNICATIONS from 1994 to 1999 in the area of Equalization and Coding.

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Initially, his research considered a comparison of wideband single and multicarrier CDMA systems using convolutional coding. Subsequent research investigated rate compatible punctured turbo codes based on the rate compatible punctured convolutional codes of Hagenauer. He has over 19 years experience in industry as a systems engineer and is currently with Qualcomm Incorporated, San Diego, CA, where he is a Senior Staff Engineer/Manager. While at Qualcomm, he codeveloped a turbo interleaver, based on two-dimensional linear congruential sequences which was eventually accepted into the cdma2000 (IS-2000) third-generation wireless standard. In addition, he participated in the design, simulation and implementation of the cdma2000 turbo decoder for numerous ASIC developments.