Guest Editorial
The Turbo Principle: From Theory to Practice II

INTRODUCTION

IN 1997, Hagenauer coined the phrase "the turbo principle" to describe the fundamental strategy underlying the success of turbo decoding, namely the iterated exchange of soft information between different blocks in a communications receiver in order to improve overall system performance.

This principle, embodied in the iterative decoding of parallel concatenated "turbo codes" (Berrou, Glavieux, and Thitimajshima, 1993), as well as in the message-passing decoding of low-density parity-check codes (Gallager, 1963), is now widely recognized as a very general and powerful concept in communication theory, with applications that go beyond the practical decoding of these near capacity achieving codes.[1]

In this issue, the second of two parts, the reader will find a collection of 15 papers representative of three important areas in which the turbo principle is finding use: joint source-channel decoding, joint channel estimation and decoding, and multiuser communications. The following is a brief summary of the contents of Part II.

THE TURBO PRINCIPLE IN JOINT SOURCE-CHANNEL DECODING

The papers in this group show how elegantly the turbo principle can be applied to joint source-channel decoding (JSCD). The underlying motivation for the use of JSCD hearkens back to Shannon himself, who stated: "... any redundancy in the source will usually help if it is utilized at the receiving point. In particular, if the source already has a certain redundancy and no attempt is made to eliminate it in matching to the channel, this redundancy will help combat noise." The source redundancy may reflect properties of the actual source or of the residual correlations in the output from a source encoder. Both scenarios are considered in the three papers included in this issue.

The first paper (Görtz) considers a serial concatenation of a source encoder, modeled as a Markov source, and a binary channel encoder for transmission over a discrete-time, memoryless, additive white Gaussian noise (AWGN) channel. To achieve statistical independence the source and channel decoder are separated by a random interleaver. JSCD is formulated as a parameter estimation problem, and an optimal, but computationally intractable, solution is reviewed. An iterative JSCD procedure, modeled after turbo decoding, is then proposed, and comparisons to the optimal algorithm suggest the potential merits of the approximate scheme.

The second paper (Garcia-Frias and Villasenor) considers joint source-channel coding for hidden Markov sources. The source is serially concatenated through a random interleaver with a parallel-concatenated turbo code for transmission over an AWGN channel. The authors present an iterative decoding algorithm that can estimate the parameters of the hidden Markov source and, if necessary, the channel signal-to-noise ratio during the decoding process. Simulation results confirm that this JSCD approach offers substantial improvement over decoding techniques that ignore the source characteristics.

In the final paper of this group (Guyader, Fabre, Guillemot, and Robert), the authors investigate iterative JSCD techniques for a system comprising a concatenation of a Markov source, a source encoder, and a convolutional code. Using a Bayesian network representation of the system variables, the authors first derive an effective iterative turbo-like JSCD technique that can be used for a constant-length source code (CLC). A random interleaver is used to separate the source encoder and the channel encoder, but the authors show that no such interleaver is needed between the Markov source and source encoder. One might imagine that the performance of such JSCD techniques when applied to a variable-length source code (VLC) would suffer dramatically, given the potential for catastrophic error propagation that could arise from incorrect parsing of the source codewords. Remarkably, the decoding approach yields impressive performance, even in this case.

THE TURBO PRINCIPLE IN JOINT CHANNEL ESTIMATION AND DECODING

Wireless communication systems are playing an increasing role in data transmission, and mobile communication networks, in particular, are proliferating at an astounding pace. In these systems, the transmission channel may be statistically time varying, even unknown. The effects of multipath fading and intersymbol interference, in addition to additive noise, must be mitigated, and channel estimation and equalization may be required. The next six papers address the use of iterative algorithms to jointly perform channel estimation and decoding, and they demonstrate that the turbo principle can be used to substantially improve channel estimates as well as coding gain.

The first paper (Valenti and Woerner) presents a method for coherently detecting and decoding turbo-coded BPSK signals transmitted over flat fading channels. Estimates of the complex channel gain and the AWGN noise variance are derived first from received (known) pilot symbols and an estimation filter. After each iteration of turbo decoding, the channel estimates are refined using information fed back from the decoder. The authors then use simulation to gain insight into the performance

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[1] See "The Turbo Principle: From Theory to Practice I," *J. Select. Areas Commun.*, vol. 19, no. 5, May 2001, for papers pertaining to applications of the turbo principle in channel decoding.

of the proposed technique. Both hard- and soft-decision feedback are considered and are compared with systems using perfect and conventional channel estimation. Optimum values of the pilot symbol spacing and filter size are also found for the specific code scheme and normalized fade rates.

The second paper (Komninakis and Wesel) addresses the design and performance evaluation of M-PSK turbo-coded systems operating in flat fading channels. The receiver jointly performs channel estimation and turbo decoding, allowing the two processes to benefit from each other. A Markov model is introduced to approximate the values and the statistical properties of the correlated flat fading channel phase (which is more relevant than amplitude fading in an M-PSK system). The BCJR algorithm is applied to determine both the MAP value for each symbol in the data sequence and the MAP channel phase. The soft output phase estimates can be used to adjust channel inputs in an iterative loop. Simulation results show good performance in correlated Rayleigh fading channels. Several progressively tighter upper bounds to the capacity of a simplified Markov-phase channel are derived and the performance of the proposed system is shown to approach these capacity bounds.

For reliable communication in high-speed mobile units (trains or airplanes) or at very high radio frequencies, an accurate estimation technique for fast fading channels is required. Furthermore, to retain high spectral efficiency, any redundancy introduced by the use of training sequences must be kept to a minimum. The next contribution (Kammeyer, Kühn, and Petermann) deals with nonblind and blind channel estimation approaches for a full-rate GSM data Traffic Channel (TCH/F9.6). The authors show that blind channel estimation based on higher order statistics can be as efficient as nonblind methods. A new bandwidth-efficient, iterative "turbo estimation" scheme, applicable to both nonblind and blind channel estimation, is shown to be capable of accurately estimating fading channels with Doppler frequencies up to 500 Hz.

Turbo equalization has been shown to be a valuable technique for combined detection and decoding on coded channels with intersymbol interference (ISI) induced by multipath signal fading. The next three papers consider this topic.

When the channel has large memory, or when spectrally efficient higher order modulation is used, the implementation of the optimal constituent soft-input, soft-output (SISO) (e.g., BCJR) channel decoding algorithms becomes extremely complex. In the first of these papers (Berthet, Ünal, and Visoz), the authors show that reduced-complexity trellis-search algorithms based upon decision-feedback techniques represent a viable alternative for a certain class of channels. In addition, they propose iterative channel parameter re-estimation techniques for use in turbo-equalization applications.

The next paper (Laot, Glavieux, and Labat) considers an iterative approach to joint adaptive equalization and channel decoding. As in the preceding paper, the intended application is to spectrally efficient modulation on frequency-selective fading channels with large delay spread. The authors present a turbo-equalization technique incorporating a new low-complexity SISO channel decoder, and they demonstrate its potential value when using higher order modulation on both time-invariant and time-varying Rayleigh fading channels.

In the last paper (Yang and Wang), the authors address the problem of signal restoration in Gaussian minimum shift keying (GMSK) systems impaired by multipath fading. They introduce a nonlinear signal model for GMSK, and they derive a Bayesian equalizer whose implementation is based upon the Gibbs sampler, a Markov chain Monte Carlo (MCMC) procedure for estimating the posterior symbol probabilities. A turbo equalizer incorporating the nonlinear Bayesian equalizer is then proposed, and simulation results show that it is competitive with schemes that assume a linearized system with perfect channel estimation.

The Turbo Principle in Multiuser Communications

The final group of six papers illustrates the application of the turbo principle in the context of multiuser wireless communication systems.

The first paper (Kim, Milstein, and Song) examines a multicarrier direct-sequence CDMA (DS/CDMA) system where the parity outputs of a turbo code are repetition-coded using different rates and are transmitted in parallel over different fading carriers. A bound is developed to characterize the error floor for a fading channel. The key result is that nonuniform repetition coding (i.e., different repetition code rates) applied to the respective turbo parity streams yields an improved error floor. This result is confirmed by theoretical analysis and performance simulations.

The following paper (Hsu and Wang) proposes a low-complexity suboptimal iterative scheme for joint multiuser detection and decoding in a turbo-coded DS/CDMA system. A modified decorrelating decision-feedback detector (DDFD) and single-user turbo decoders exchange appropriately derived soft outputs in an iterative manner. Performance analysis and computer simulations confirm that the iterative procedure improves the multiuser detection capability of both the conventional and modified DDFD, approaching single-user performance when the spreading sequences have low cross correlation.

The next paper (Qin, Teh, and Gunawan) also addresses iterative methods for multiuser detection in a coded CDMA system, but with a focus on asynchronous CDMA systems. Both parallel and serially concatenated code architectures are considered for the users, and simulation results show performance approaching that of a single-user detector in heavily loaded systems. Two approaches to reducing the detector complexity are proposed, namely reduced-state multiuser detection and iterative interference cancellation using noise-whitening techniques. Simulation results show that these techniques offer significant complexity savings with little performance degradation.

The fourth paper (Tang, Milstein, and Siegel) presents an analysis of the performance of a turbo-coded CDMA system using a minimum mean-square-error (MMSE) receiver for interference suppression on a Rayleigh fading channel. Two enhancements of the conventional union bound on bit error probability are used. First, the minimum distance of a turbo code with a particular interleaver is used to modify the average weight spectrum that assumes a uniform random interleaver, yielding better performance estimates in the error-floor region. Second, an extension of the tangential bound to the uncorrelated Rayleigh fading channel is shown to improve upon the union bound in the region below the channel cutoff rate. The modified bound and simulation results indicate that the MMSE receiver can increase system capacity, particularly in a severe near–far scenario. Other practical issues such as code rate, constituent code selection, block size, finite interleaving, and RLS adaptation are also considered.

In the next paper (Cusani and Crea), the authors propose iterative multiuser detection techniques to improve the performance of turbo-coded CDMA systems such as the standardized third-generation UTRA-TDD system. The receiver combines a SISO multistage interference canceller with a turbo decoder in an iterative detection process. Simulation results show that, by using the low-complexity soft-output Viterbi algorithm (SOVA) in the turbo decoder, this modified detection technique can enhance system performance while remaining compatible with the existing standard.

The final paper in this group (Liang and Stark) applies the turbo principle in a multiuser detection scheme intended to improve performance in frequency-hop multiple-access (FHMA) systems. The proposed receiver uses iterative cancellation of adjacent channel interference (ACI)—the dominant component of multiple-access interference under the specified system conditions—on a turbo-coded FH/CDMA signal. The authors use computer simulation to compare the performance of this receiver to that of the traditional noniterative receiver under various system conditions, identifying several practical scenarios in which the new detector provides substantial improvement.

CONCLUSION

In conclusion, the 32 papers in Parts I and II of this double-issue underscore the elegance and richness of the turbo principle as a communication-theoretic concept, as well as its power and practicality as a tool in the design of state-of-the-art communication systems. Its application has enabled the conquest of previously unattainable summits in communications while revealing vistas of new areas that we can share the excitement of exploring.

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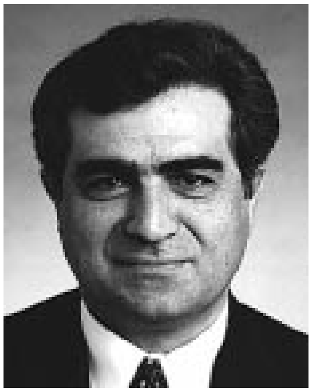

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