Guest Editorial
Concatenated Coding Techniques and Iterative Decoding: Sailing Toward Channel Capacity

From Shannon theory, we know that increasing the codeword length n of block codes (or the constraint length of convolutional codes) leads to better performance. It is also well known that the complexity of maximum likelihood decoding algorithms increases with n, up to a point where decoding becomes physically unrealizable.

Thus, research in coding theory has seen many proposals aimed at the construction of powerful codes with large equivalent block lengths structured so as to permit breaking the ML decoding into simpler partial decoding steps, thus obtaining a suboptimum yet powerful decoding strategy. Iterated codes [1], product codes and their extension [2], concatenated codes [3], and large constrained-length convolutional codes with suboptimal decoding strategies, like sequential decoding, are nonexhaustive examples of these attempts.

Furthermore, Shannon theory has proved that "random" codes are good; their decoding complexity, however, increases exponentially with the block length. On the other hand, the structure imposed on the codes in order to decrease their decoding complexity often results in relatively poor performance. As a result, approaching the channel capacity or even, more modestly, going significantly beyond the channel cutoff rate had been an unreachable dream of coding theorists for many years.

In decreasing the bit-error probability of a system through channel coding, we can use two approaches. The more traditional one has attempted to increase the minimum Hamming distance of the code, thus reducing at the same time the *word*- and *bit*-error probabilities. The goal of the second approach is rather to reduce the multiplicity of codewords with low Hamming weights. This was the approach applied to the design of "turbo" codes [4], a new coding strategy that, to quote Dave Forney [3]: "Rather than attacking error exponents, they attack multiplicities, turning conventional wisdom on its head."

Turbo codes, in the consideration of many experts of the field, are one of the most exciting and potentially important developments in coding theory in many years. They cleverly integrate code concatenation in a "pseudorandom" approach where the randomness and long block size are provided by an interleaver, a building block that does not add to the decoding complexity. This is due to an iterative strategy based on alternately decoding two simple constituent codes and passing the so-called *extrinsic information* (a part of the soft output provided by an *a posteriori* probability algorithm) to the next decoding stage. Strictly speaking, the name "turbo" has nothing to do with the encoder; rather, it is justified because the decoder uses its processed output values as *a priori* input for the next iteration, similar to a turbo engine.

Since the first appearance of turbo codes and a related structure in 1993 [4], [5], many of the structural properties of turbo codes have now been put on a firm theoretical footing [6]–[8], and other forms of concatenations with interleavers have been studied and shown to offer similar, in some cases even better, performance [10]–[12]. They form a class of codes that, under iterative decoding, permit us to approach the Shannon capacity at a bit-error probability on the order of 10^{-6}–10^{-7}, still quite far from the unlimited reliability promised by the Shannon capacity theorem, yet more than enough for several applications.

Successively applied to the iterative decoding of concatenated codes [9], what we would call the "turbo principle," i.e., a strategy exploiting the iterated exchange of soft information between different blocks in a communication receiver, could (and in part has already been) successfully applied to many detection/decoding problems such as channel equalization, coded modulation, multiuser detection, joint source and channel decoding, and others.

At the time this issue was completed, there was still a lack of a satisfactory analysis of the iterative process and of a theoretical explanation of why the turbo decoding algorithm performs as well as it does. Also, some performance bounds seem to point to the fact that, theoretically, the same performance should be obtainable with significantly shorter block lengths. These seem, at the moment, to be two of the major open problems in the field. On a more practical ground, convincing results are still to come in those applications where decoding latency is an issue, like for voice transmission and others.

The first paper in this issue, by McEliece *et al.*, describes the close connections between the iterative "turbo" decoding algorithm with Pearl's *belief propagation* algorithm, which is well known in the artificial intelligence scientific community. Once this connection is established, the belief propagation algorithm becomes a general framework to devise iterative decoding algorithms for other codes. Closely related to the first paper is the paper by Kschischang and Frey, which presents a unified framework, based on a Bayesian network description of codes, for describing compound codes and deriving iterative decoding algorithms.

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Iterative decoding algorithms for decoding concatenated codes are also the subject of several other papers. The paper by Frey and Kschischang introduces a technique, called *early detection*, to reduce the computational complexity of iterative decoders. The paper by Riedel presents a variation of the MAP symbol-by-symbol algorithm that operates on the dual code, thus reducing the decoding complexity for high-rate codes. The paper by Viterbi offers an intuitive justification of the MAP symbol-by-symbol decoder for convolutional codes together with some simplifications in its implementation. The paper by Anderson and Hladik extends the MAP decoding algorithm to the case of tailbiting trellis codes, and the one by Franz and Anderson shows the performance of concatenated decoding employing reduced-search algorithms. Lucas *et al.* introduce an iterative algorithm to decode block codes, and they apply it to several code classes.

The paper by Benedetto *et al.* analyzes a new form of concatenation in which three convolutional encoders are serially concatenated through a pair of interleavers. Multilevel turbo codes employing short interleavers are the subject of the paper by Herzberg, whereas Robertson and Wörz show an interesting way of designing and iteratively decoding bandwidth-efficient trellis codes based on the parallel concatenation of convolutional codes and multilevel modulations. Battail describes a conceptual framework to understand the behavior of turbo codes, seen as random-like codes.

The paper by Hall and Wilson extends the performance bounding technique and design methodology of turbo codes to the case of Rayleigh fading. Correlated Rayleigh fading is also the system environment envisaged by Marsland and Mathiopoulos: they show the performance of turbo codes in connection with multiple differential detection. Superorthogonal turbo codes and their performance in Gaussian and Rayleigh fading channels are the subject of the paper by Komulainen and Pehkonen. Finally, the paper by Balachandran and Anderson shows the effect of mismatched decoding for channels with intersymbol interference using a turbo-type scheme employing parallel concatenation and iterative decoding.

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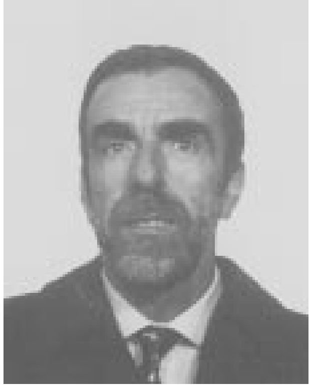

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