from the guest editors

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Iterative, Soft Signal Processing for Digital Communications

This editorial covers the emerging iterative signal processing methods in digital communications. Iterative methods are not new to the field of signal processing and communications. Indeed, many such methods were known for a number of years, e.g., expectation-maximization [1] and low-density parity-check (LDPC) codes, [2]. It has generally been considered impractical, however, to perform iterative signal processing tasks in a receiver at the end of a communications channel. Receivers needed to operate in real time, so it was perceived that iterative processing methods would introduce unnecessary delays. In addition, iterative processing typically meant increased complexity, so it was to be avoided.

Turbo and LDPC Codes

A shift in the line of thinking occurred in the mid 1990s with the advent of turbo codes [3]. Turbo codes belong to a class of iteratively decodable error-correction codes. Even though other iteratively decodable codes, such as LDPC codes, were known in the past, the unprecedented decoding performance of such codes was first demonstrated with turbo codes. The first turbo codes were shown to achieve very low bit error rates at signal-to-noise ratios that were only a fraction of a decibel above the Shannon capacity limit. Prior to that, no code was ever shown to perform closer than 3–4 dB away from the Shannon limit.

Naturally, the extraordinary performance of turbo codes sparked an enormous interest in iteratively decodable codes. Soon, many other iteratively decodable codes (re)emerged, including LDPC codes, repeat-accumulate codes, and turbo product codes. Along with the new codes, the research community pursued tools that enabled the construction and optimization of iteratively decodable codes, such as extrinsic information transfer (EXIT) charts [4] and density evolution [5], [6]. Today, iteratively decodable codes are known to approach the capacity of Gaussian channels to within less than 0.01 dB of the Shannon capacity.

A significant development following the introduction of turbo codes is the iterative equalization and decoding of ISI channels, also referred to as turbo equalization. The basic idea in turbo equalization is to treat the ISI channel as an inner code in a serial concatenated system and to apply an iterative soft decoding procedure to equalize the channel and decode the outer code. LDPC codes fit into the turbo equalization framework naturally, and have been investigated as potential candidates for many applications including orthogonal frequency division multiplexing systems, digital subscriber lines, long-haul optical communication systems, magnetic recording, and optical recording systems. Consequently, these codes have become serious competitors to turbo codes for error control in communication and data storage systems where high reliability is required.

The enormous potential of iteratively decodable codes revolutionized the thinking about the structure of a communications receiver. While in the past it was considered that the signal processing tasks of the receiver (timing recovery, phase recovery, interference suppression, detection, equalization, decoding) should be performed sequentially and unidirectionally, it is now perceived that the receiver can execute these tasks iteratively. This special section of *IEEE Signal Processing Magazine* presents some emerging iterative signal processing methods in communications. Naturally, iteratively decodable codes are a big part of these methods, but they are not limited to codes alone. Apart from iteratively decodable codes, this special section covers the general notion of factor graphs (which have proved to be extremely useful for constructing and analyzing iterative methods in signal processing), iterative (turbo) equalization, iterative multiuser detection, and iterative timing recovery. The articles in this issue will demonstrate that iterative scheduling of the processing tasks achieves enormous performance gains over the unidirectional scheduling. Given this enormous gain, it is extremely likely that future communications receivers will be iterative receivers.

In This Special Section

The issue contains the following six articles:

▲ 1) "An Introduction to Factor Graphs" by Loeliger

▲ 2) "Structured Low-Density Parity-Check Codes" by Moura, Lu, and Zhang

▲ 3) "Low-Density Parity-Check Codes for Partial Response Channels" by Song and Kumar

▲ 4) "Turbo Equalization" by Koetter, Singer, and Tüchler

▲ 5) "Iterative Multiuser Detection" by Poor

▲ 6) "Iterative Timing Recovery" by Barry, Kavčić, McLaughlin, Nayak, and Zeng.

In the first article, Loeliger introduces factor graphs, with particular emphasis on a new class of graphs, and iterative methods in signal processing. It has been noticed that, generally, the signal processing task is to solve a rather complex optimization problem. The optimization problem can typically be described by a very large system of equations. A factor graph is an alternative representation of this system of equations. It has the advantage of topologically organizing the equations, which then leads to an intuitive understanding of how the signal processing tasks can be completed on the given topology of the factor graph. The generic sum-product algorithm is presented as a signal processing tool for performing the tasks on a factor graph. The article goes on to demonstrate that many well-known signal processing tasks such as turbo decoding and Kalman filtering can be viewed as instances of the sum-product algorithm over a suitably constructed factor graph.

The second article, by Moura et al., designs LDPC codes with certain desirable properties. The problem is cast as the design of the graph that represents the LDPC decoder. To facilitate its implementation, it is desired that the graph exhibit a regular structure and, for performance and computational reasons, it is advantageous that the graph has large girth. The girth of a graph is the length of the minimum length closed path, cycle, in the graph. This article briefly reviews the literature on the subject of designing structured LDPC codes with large girth, considers two particular constructions that can design codes with very large girth, and demonstrates the impact of girth on the bit error performance of the resulting codes.

Song and Kumar describe LDPC codes for partial response (PR) channels. PR channels arise in many applications where intersymbol interference (ISI) is present. The article briefly introduces LDPC codes, the iterative decoding algorithm sum-product algorithm, and how LDPC codes can be used to improve the bit error rates in PR channels by turbo equalization. For simplicity, the article assumes that the channel is perfectly equalized to a family of PR polynomials. This family of PR targets offers a reasonably good match to the natural channel response in magnetic and optical recording channels and thus is popular in digital storage systems. The authors discuss two general constructions of LDPC codes based on disjoint difference sets (DDSs) and permutation matrices (PMs) and then illustrates their performance with PR channels.

The fourth article in this issue, by Koetter et al., covers the topic of turbo equalization. Even the simplest receiver typically has to perform at least two tasks 1) detection of the transmitted symbols and 2) error-correction decoding. If there is ISI in the transmitted symbols, the detector is often coupled with a device that removes the interference. The joint operation is often referred to as equalization. If the equalization and decoder iteratively exchange information, we have an iterative or turbo equalizer. The authors explain the basics needed to understand turbo equalization. It concentrates on two examples of turbo equalization, namely turbo equalization based on the maximum a posteriori symbol detection algorithm and turbo equalization based on linear filtering.

The fifth article, by Poor, is on iterative multiuser detection. It addresses turbo multiuser detection algorithms for optimal detection and decoding in channels that involve both error-control coding and multiple-access signaling. Such channels arise in numerous applications including cellular telephony, wireless computer networks, and broadband local access. These algorithms iterate among the constituent decision algorithms, with intermediate exchanges of soft information about tentative decisions. The article outlines the basic principles and the reasons for low-complexity of the resulting algorithms.

The final article in this issue, by Barry et al., covers iterative timing recovery. The proper detection of digitally transmitted information relies on sampling the received waveform. The process of estimating where to sample the waveform is known as timing recovery. It is by now accepted that iteratively decodable codes have the ability to correct errors incurred by the transmission process at very low SNRs. At these low SNRs, however, traditional timing recovery methods fail. This failure is typically characterized by skipping (either forward skipping or backward skipping) a sample, known as a cycle-slip. Iterative timing recovery relies on utilizing the iterative structure of the decoder (and turbo equalizer) to perform the timing recovery task in an iterative manner.

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sharing what you do on a daily basis, as well as the challenges and rewards you receive from your work, is the key to attracting students. Students begin to see engineering as a vital service profession, dramatically influencing the quality of life in our country and the world at large. After Michael Navin from the Army Corp of Engineers left our class, one student immediately commented, “Who knew that locks and dams on the Mississippi River could be so interesting?” Students will never know unless YOU tell them!

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The article covers two such methods and demonstrates its superior performance over the traditional timing recovery methods in its ability to avoid (or correct) cycle slips.

We thank all the authors who worked hard to write their articles in a somewhat unusual style and under strict deadlines.

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