Introduction to the Issue on Managing Complexity in Multiuser MIMO Systems

A DECADE has passed since the pioneering works in which multiple-input multiple-output (MIMO) wireless systems have been introduced. By using multiple antennas at both link ends, MIMO in theory offers tremendous rate and reliability gains. These promises have spurred an extraordinary amount of research activities. By now, MIMO has become a well-established research topic, with thousands of papers published on the topic each year (a search for "MIMO" on IEEEXplore reports 264 hits for the year 2000 and 2880 hits for 2008), addressing signal processing topics like data detection, space-time code design, precoding, beamforming, channel estimation, and synchronization (list not complete). So far, the largest part of MIMO research has been devoted to point-to-point (single-user) channels. It is only fairly recently that MIMO started to be considered in the context of multiuser (multipoint) systems, where additional opportunities like spatial multiple access, interference suppression, and improved resource allocation exist. In this context, the recent survey "Shifting the MIMO paradigm" by Gesbert *et al.* in the Sept. 2007 issue of the *IEEE Signal Processing Magazine* is recommended reading.

Soon after its introduction, MIMO technology also started to attract the attention of standardization bodies. By now, MIMO techniques have been incorporated into the mainstream of wireless standards like IEEE 802.11n (high-throughput WiFi), IEEE 802.16x (802.16e, a.k.a. mobile WiMAX, and upcoming 802.16m), and 3GPP's Long Term Evolution (LTE). While WiFi and 802.16e build on single-user MIMO techniques like spatial multiplexing and space-time coding, LTE Advanced and 802.16m also add multiuser MIMO features.

In spite of the plethora of MIMO research and the fact that MIMO is now part of several standards, industry still faces problems with integrating MIMO into their products. The principal barrier to widespread industry adoption is implementation complexity and the sensitivity of receiver signal processing to departures from the standard propagation assumption of Rayleigh scattering. Management of signal processing complexity is thus essential to realizing the theoretical promise of MIMO technology. Here, the goal is to cleverly design tunable algorithms for the terminal and infrastructure side that entail a graceful trade-off between performance and implementation complexity. Substantial advances in this area would certainly have a big practical impact, e.g., with chip manufacturers and terminal and infrastructure vendors.

There are 17 papers in this special issue that deal with various aspects of this challenging new thread in MIMO research. We have grouped these papers according to the following three major research themes: efficiently decodable space–time codes, MIMO detection and demodulation, and multi-user precoding and beamforming.

The first five papers discuss the design of space-time codes. Previous work in this area was mainly concerned with maximizing diversity and coding gain and with achieving the optimal diversity-multiplexing trade-off. In contrast, these five papers aim at designing space-time codes that can be efficiently decoded while maintaining (close to) optimal performance. The paper by Chen and Cioffi develops quasi-orthogonal space-time block codes that permit symbol-by-symbol maximum-likelihood detection in a system with four transmit antennas, losing only a fraction of a dB against optimal designs. In a similar vein, Srinath and Rajan design space-time codes for 2×2 and 4×2 MIMO systems that perform as well as the Golden Code and the DjABBA code while featuring lower maximum-likelihood decoding complexity. In the paper by Wu and Calderbank, the main innovation is allowing the transmitter to switch between a small number of codes. Interestingly, using simple ZF detection with such code diversity systems results only in small performance loss. Based on cyclic division algebras, Lu *et al.* construct multi-user MIMO codes for two users that achieve the optimal diversity-multiplexing trade-off and outperform previously proposed codes. Finally, the paper by Mohammed *et al.* proposes a multistage likelihood ascent method to decode non-orthogonal space-time codes in large MIMO systems in conjunction with an iterative detection-channel estimation scheme.

The second group, consisting of seven papers, is concerned with efficient ways to detect or soft-demodulate the data transmitted over a MIMO channel. The first two of those papers share the idea of trading-off diversity order against reduced detection complexity. Ling, Mow, and Gan start out with a dual-lattice view of layer ordering in V-BLAST and then propose to perform lattice reduction only for a subset of layers, thereby achieving different integer diversity orders. The approach of Maurer *et al.* consists of partial channel equalization followed by a suitably adapted sphere decoder; this allows to achieve arbitrary diversity orders (below maximum diversity) via a corresponding complexity reduction. The paper by Radji and Leib proposes an optimal channel partitioning to obtain a modified version of generalized parallel interference cancellation with lower complexity and improved performance. Milliner *et al.* consider soft-output MIMO demodulation and introduce a tree-search algorithm with improved layer ordering and candidate adding. Dai and Yan discuss tree-search algorithms for MIMO detection but with a focus on memory efficiency. The paper by Ma *et al.* demonstrates that three different semidefinite relaxation schemes that have been proposed independently for detection in MIMO systems using higher-order QAM alphabets are in fact equivalent. Finally, Coluccia *et al.* study optimum pilot-aided detection in MIMO-OFDM systems and subject the

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detection metric to an iterative reformulation and a spectral approximation in order to minimize complexity.

The last five papers address the problem of exploiting channel state information at the transmitter to design precoding and beamforming schemes in multiuser MIMO systems. Li and Jafarkhani propose a precoder design for a two-user MIMO channel that allows the users to transmit interference-free over two orthogonal signal spaces while maintaining full diversity and low decoding complexity. Hardjawana, Vucetic, and Li present a scheme in which multiple base stations cooperate to perform Tomlinson–Harashima precoding and downlink beamforming to serve multiple users; an iterative optimization of the beamforming weights and a new user precoding ordering keep the complexity of the method low. A similar scenario with multiple base stations is considered by Chae, Kim, and Heath who develop linear and nonlinear network-coordinated beamforming schemes for cell-boundary users. The paper by Guthy, Utschick, and Dietl presents a practical way of user allocation and transmit and receive filter optimization in a MIMO broadcast scenario under the constraint of zero multiuser interference. Last but not least, Yuan *et al.* develop precoding schemes for MIMO multiple access systems that employ a single channel code, maximum eigen-beamforming, and turbo-equalization in the frequency domain.

Two major aims of this special issue were to bring complexity issues in MIMO wireless to the attention of a broader audience and to provide readers with an idea about the current state of the art in complexity-aware designs of multiuser MIMO systems. Our hope is that this issue also stimulates further research that extends and complements the many innovative ideas that have been proposed in this area, thereby helping to make MIMO an even bigger (scientific and commercial) success than it has been to date.

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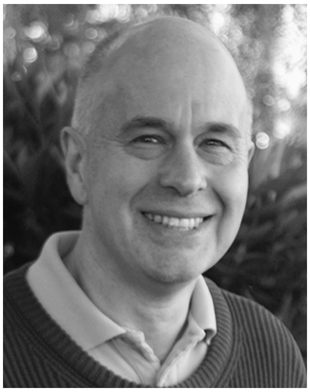

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Dr. Calderbank served as Editor-in-Chief of the IEEE TRANSACTIONS ON INFORMATION THEORY from 1995 to 1998, and as Associate Editor for *Coding Techniques* from 1986 to 1989. He was a member of the Board of Governors of the IEEE Information Theory Society from 1991 to 1996 and began a second term in 2006. He was honored by the IEEE Information Theory Prize Paper Award in 1995 for his work on the Z4 linearity of Kerdock and Preparata Codes (joint with A. R. Hammons, Jr., P. V. Kumar, N. J. A. Sloane, and P. Sole), and again in 1999 for the invention of space–time codes (joint with V. Tarokh and N. Seshadri). He received the 2006 IEEE Donald G. Fink Prize Paper Award and the IEEE Millennium Medal, and was elected to the US National Academy of Engineering in 2005.

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