Guest Editorial
Large-Scale Multiple Antenna Wireless Systems

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THE DATA rate demands of wireless systems will continue to grow for the foreseeable future. Since current technologies are not capable of supporting these demands, new and more efficient antenna configurations need to be devised. One of the most viable solutions is the deployment of Large-scale multiple antenna (LSMA) wireless systems. LSMA wireless systems with hundreds of low-power antennas, that may be colocated at a base station (BS) site, spread out on the face of a building, or distributed geographically, provide a plethora of advantages over conventional multiple-input multiple-output (MIMO) and cooperative networks. In particular, these large-scale systems offer higher data rates, increased link reliability, and potential power savings, since the transmitted RF energy can be more sharply focused in space, while many random impairments (e.g., thermal noise and intercell interference) can be averaged out. We note that these gains can be achieved by coherent, but simple, processing (e.g., linear reception techniques in an uplink scenario). LSMA also entails a revolution in hardware. Expensive ultra-linear forty-Watt amplifiers are replaced by many cheap low-power devices whose combined action, only, has to meet stipulated tolerances. Likewise it is expected that lower resolution A/D and D/A converters can be used. Equally importantly, the analysis of large-scale systems can be carried out using tools from random matrix theory, which has attracted considerable research interest. For all these reasons, the area of LSMA systems has recently emerged at the forefront of wireless communication research.

With the above vision, a Call for Papers for a special issue in the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, was published in July 2011. The invited topics included information theoretic issues of LSMA systems, efficient feedback reduction and power allocation strategies, channel estimation, propagation measurements, and channel modeling of LSMA systems as well as antenna design and experimental demonstrations. By the deadline in February 2012, we received 44 manuscripts, out of which 18 were finally accepted after a thorough and rigorous review process.[1] Unfortunately, due to space constraints, several high-quality manuscripts could not be accommodated in this JSAC issue.

The papers appearing in this special issue can be classified into three broad thematic categories: capacity/sum rate analysis of LSMA systems, design of efficient signal processing algorithms suitable for LSMA systems (e.g., beamforming (BF) design, precoding, channel estimation, power allocation), and antenna theoretic issues of LSMA systems. A brief description of each of the accepted papers is provided in the following for the convenience of the readers.

The paper by Yang, Durisi, and Riegler, entitled, "On the Capacity of Large-MIMO Block-Fading Channels," characterizes the capacity of Rayleigh block-fading MIMO channels in the noncoherent setting. The authors prove that unitary space-time modulation (USTM) is not capacity-achieving at high signal-to-noise ratio (SNR) when the total number of antennas exceeds the coherence time of the fading channel (measured in symbols)—a situation that is relevant for LSMA systems. Moreover, the authors show that the high-SNR capacity-achieving input distribution, which they refer to as beta-variate space-time modulation, yields substantial rate gains over USTM at SNR values of practical relevance.

The paper by Zhang, Wen, Jin, Gao, and Wong, entitled, "On Capacity of Large Scale MIMO Multiple Access Channels with Distributed Sets of Correlated Antennas," investigates a large-scale MIMO system consisting of multiple users and one BS with several distributed antenna sets. Each link between a user and an antenna set forms a two-sided spatially correlated MIMO channel with line-of-sight components. A deterministic equivalent of the ergodic sum rate and an algorithm for evaluating the capacity-achieving input covariance matrices for the uplink large-MIMO antenna channels are proposed. The presented derivations are based on novel techniques from large dimensional random matrix theory, under the assumption that the numbers of antennas at the terminals grow large with a fixed ratio.

The paper by Guthy, Utschick, and Honig, entitled, "Large System Analysis of Sum Capacity in the Gaussian MIMO Broadcast Channel," examines the large system sum capacity in the MIMO broadcast channel with infinitely many transmit and receive antennas. First, the case of non-cooperating re-

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[1]Papers coauthored by Guest Editors were handled independently by Senior Editors.

ceivers, i.e., multiple-input single-output, is considered and an exact analytical expression for the asymptotic sum capacity is derived. Then, a lower bound is presented for the general case of cooperating antennas at each receiver. Finally, the losses in sum rate of two sub-optimum schemes based on spatial ZF are analyzed asymptotically.

The paper by Hoydis, ten Brink, and Debbah entitled, "Massive MIMO in the UL/DL of Cellular Networks: How Many Antennas Do We Need?," studies the achievable rates with linear precoders and detectors which are proven to be asymptotically tight. The analysis accounts for channel estimation, pilot contamination, and an arbitrary path loss and antenna correlation for each link, in the uplink and downlink of non-cooperative multi-cellular time-division duplexing systems. The authors derive how many antennas per user-terminal are needed to achieve $\eta\%$ of the ultimate performance limit, that would be obtained with infinitely many antennas, and how many more antennas are needed with matched filter and eigenbeamforming to achieve the performance of minimum mean-square error detection and regularized ZF, respectively.

The paper by Yang and Marzetta, entitled, "Performance of Conjugate and Zero-forcing Beamforming in Large-Scale Antenna Systems," compares the performance of two prominent linear precoders. The authors derive explicit capacity lower bounds, which account for channel-state information acquisition overhead and errors, as well as the suboptimality of the precoders. Optimized trade-off curves are generated to show that for high spectral-efficiency and low energy-efficiency zero-forcing (ZF) outperforms conjugate BF, while at low spectral-efficiency and high energy-efficiency the opposite holds. A comparison of computational burdens yields a surprise that in an optimized system, conjugate BF may require more computations than ZF.

The paper by Matthaiou, Zhong, McKay, and Ratnarajah entitled, "Sum Rate Analysis of ZF Receivers in Distributed MIMO Systems," presents upper and lower bounds on the uplink achievable sum rate of distributed MIMO systems assuming ZF reception. By taking the effects of the large-scale fading and path-loss into account, the authors also pursue a detailed large-system analysis and provide asymptotic expressions when the number of antennas at the BS grows large, and when the number of antennas at both ends grows large with a fixed and finite ratio.

The paper by Fernandes, Ashikhmin, and Marzetta, entitled, "Inter-Cell Interference in Noncooperative TDD Large Scale Antenna Systems," derives new expressions for the signal-to-interference-plus-noise ratio (SINR) of both downlink and uplink channels, in the scenario of an infinite number of antennas. The authors demonstrate that the contamination of the channel estimates happens whenever a pilot sequence is received at a BS simultaneously with non-orthogonal signals coming from other users. Moreover, a method to avoid such simultaneous transmissions from adjacent cells, thus significantly decreasing interference, is proposed.

The paper by Özgür, Lévêque, and Tse, entitled, "Spatial Degrees of Freedom of Large Distributed MIMO Systems and Wireless Ad hoc Networks," pursues an asymptotic capacity analysis of distributed MIMO systems, where wireless users with single transmit and receive antennas cooperate in clusters to form distributed transmit and receive antenna arrays. In particular, the authors investigate how the capacity scales with the number of cooperating users, the area of the clusters and the separation between them. They also use this result to investigate whether distributed MIMO provides capacity gains over traditional multi-hop in large ad-hoc networks, with n source-destination pairs randomly distributed over an area A. The results contradict the available results in the literature and include scaling optimal architectures for a new intermediate regime, that had not been previously considered.

The paper by Aggarwal, Koksal, and Schniter, entitled, "On the Design of Large Scale Wireless Systems," considers the downlink of large Orthogonal Frequency-Division Multiple Access (OFDMA)-based networks and studies their performance as a function of the number of transmitters, users, and resource-blocks. The authors analyze the expected achievable sum rate as a function of the above variables and derive novel upper and lower bounds for a general spatial geometry of transmitters, a truncated path-gain model, and a variety of fading models. They also establish the associated scaling laws for dense and extended networks, and develop a distributed resource allocation scheme that achieves the same sum rate scaling as that of the proposed upper bound.

The paper by Hong, Sun, Baligh, Luo, entitled, "Joint Base Station Clustering and Beamformer Design for Partial Coordinated Transmission in Heterogeneous Networks," looks at a heterogeneous multicell multiuser MIMO network, and devises BS clustering and linear BF algorithms using optimization with sparsity constraints. A novel feature of the proposed algorithm is that it performs BS clustering and beamformer design jointly rather than separately, while the cluster size can be controlled by adjusting a single parameter.

The paper by Zhang, Yuan, and Ping, entitled, "Hermitian Precoding for Distributed MIMO Systems with Individual Channel State Information," studies a distributed multiuser MIMO system with each transmitter only having partial channel state information (CSI), and proposes a novel Hermitian precoding technique for this scenario. The optimality of the proposed precoder is analytically investigated.

The paper by Dai, Wang, and Yang, entitled, "Spectrally Efficient Time-Frequency Training OFDM for Mobile Large-Scale MIMO Systems," proposes a time-frequency training orthogonal frequency-division multiplexing (TFT-OFDM) transmission scheme suitable for large-scale MIMO systems. In this algorithm each TFT-OFDM symbol, without cyclic prefix, adopts the time-domain training sequence and the frequency-domain orthogonal grouped pilots as the time-frequency training information. At the receiver, a corresponding time-frequency joint channel estimation method is proposed, where the received time-domain training sequence is used for path delay estimation without interference cancellation. The authors also demonstrate that the new TFT-OFDM MIMO scheme achieves higher spectral efficiency and lower low-density parity-check coded bit error rate, compared with conventional large-scale OFDM MIMO systems.

The paper by Yin, Gesbert, Filippou, and Liu, entitled, "A Coordinated Approach to Channel Estimation in Large-scale Multiple-antenna Systems," develops a scheme for coordination between cells in order to limit pilot contamination in large-scale multiuser MIMO systems. The coordination makes use of additional second-order statistical information about the user channels, which is shown to offer a powerful way of discriminating across interfering users.

The paper by Zhou and Ma, entitled, "Element-Based Lattice Reduction Algorithms for Large MIMO Detection," develops and analyzes new element-based lattice reduction (ELR) algorithms for MIMO detection problems of large dimensions. The proposed ELR-aided detectors yield better error performance than the existing low-complexity detectors for large MIMO systems while maintaining lower complexity.

The paper by Zakhour and Hanly, entitled, "Min-Max Power Allocation in Cellular Networks with Coordinated Beamforming," considers BS cooperation in the form of coordinated BF, focusing on min-max fairness in the power usage. The authors show that the optimal BF strategies have an interesting nested ZF structure, while the optimal solution is characterized in general, and an algorithm is proposed that converges to the optimal transmit parameters, for feasible SINR targets. Interestingly, the asymptotically optimal beamformers only require the BSs to have local instantaneous CSI, thereby reducing the signaling overhead.

The paper by Studer and Larsson, entitled, "PAR-Aware Large-Scale Multi-User MIMO-OFDM Downlink," investigates an OFDM-based downlink transmission scheme for large-scale multi-user MIMO wireless systems. A novel downlink transmission scheme, which achieves a low peak-to-average (power) ratio (PAR), is devised. The proposed scheme jointly performs multi-user precoding, OFDM modulation, and PAR reduction by solving a convex optimization problem. Moreover, the authors develop a corresponding fast iterative truncation algorithm and demonstrate significant PAR-reduction capabilities.

The paper by Alrabadi, Tsakalaki, Huang, and Pedersen, entitled, "Beamforming via Large and Dense Antenna Arrays above a Clutter," studies the BF performance of large and dense antenna arrays with arbitrarily many elements. Two modes are investigated: Single-layer BF and multi-layer BF. In the first mode, a practical BF criterion is revisited and employed in order to assess the far-field and the near-field effects on the BF performance of large-scale antennas above a clutter. In the multi-layer BF mode, the RF coverage is divided into a number of directive non-overlapping sector-beams in a deterministic manner within the MIMO system. The authors also present the optimal number of layers that maximizes the users' sum-rate given a constrained antenna array.

The paper by Taluja and Hughes, entitled, "Diversity Limits of Compact Broadband Multi-Antenna Systems," investigates the impact of coupling on bandwidth, in the context of circular arrays. It is shown that mutual coupling creates eigen-modes with diverse frequency responses, using the standard matching techniques. Furthermore, the authors present an optimization methodology of well-known communication techniques, such as Diversity-OFDM, regarding the above effects.

The guest editorial team would like to express their appreciation to all the authors of the papers submitted to this special issue. Moreover, we are grateful to all the reviewers involved in the review process, for delivering high-quality review reports. We would also like to express our gratitude to the JSAC team: the Editor-in-Chief Dr. Martha Steenstrup, the Senior Editor Prof. Laurence B. Milstein, the Executive Editor Laurel Greenidge and the IEEE publications staff (Sue Lange in particular) for their fantastic support and input, which made this issue successful.

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