Guest Editorial for the Special Issue on Multiple-Input Multiple-Output (MIMO)

WE are pleased to present this special issue on multiple-input multiple-output (MIMO), which represents a breakthrough in the use of antenna arrays in wireless transmission. Unlike traditional phased array or diversity techniques that enhance one signal of interest, MIMO systems employ antenna arrays jointly at the transmitter and receiver to spatially multiplex signals, providing tremendous capacity gains.

Although there has already been intense research in MIMO wireless communications, and many obstacles in signal processing, modulation, and coding for MIMO systems have been overcome, outstanding questions in the areas of antennas and propagation remain, making MIMO a timely topic for our community. The need for research in this area becomes even more apparent as new standards such as IEEE 802.11n, LTE Advanced, and WiMAX that include MIMO operation are implemented, revealing that physical devices, antennas, and channels can no longer be oversimplified or neglected.

This special issue is organized into three main sections: 1) antenna design, modeling, and analysis, 2) channel sounding and modeling, and 3) system performance evaluation.

A. Antenna Design, Modeling, and Analysis

Although signal processing treatments of MIMO may treat antennas as isotropic elements that are not affected by nearby antennas or scatterers, real antennas exhibit non-isotropic patterns and inter-element coupling. This section contains papers that consider the challenges of designing compact MIMO antennas with good performance, as well as novel and rigorous ways to model and analyze such antenna systems.

Exploiting multiple polarizations is a possible method of achieving a compact MIMO design with low coupling. Yan and Bernhard present a clever design allowing two orthogonal resonant modes of a compact dielectric resonator antenna (DRA) for LTE700 femtocell applications, achieving polarization and angle diversities and 30 dB isolation. A low profile tri-polarized antenna consisting of a dual-polarized ring patch and a disk-loaded monopole is explored in Zheng *et al.* to build an 18-port antenna cube, exhibiting lower mutual coupling and simpler feeding than a dipole MIMO cube.

Several papers address the challenge of MIMO antenna design for compact user terminals exhibiting higher mutual coupling and correlation. Su *et al.* implement a printed neutralization line along one ground plane edge to decouple a two-monopole array for a USB dongle application at 2.4 GHz, requiring little modification of the ground plane. The use of parasitic structures for coupling mitigation is explored in several contributions. Lau and Bach Andersen introduce the theory of parasitic decoupling, whereby two arbitrary antennas of a given antenna spacing can be perfectly decoupled with a reactively loaded parasitic element acting as a reflector. Experiments reveal that decoupling is achieved with only a small penalty in total efficiency. Z. Li *et al.* introduce a complementary perspective that the parasitic elements create a second path for coupling cancellation, demonstrating the principle by decoupling two closely-coupled slot antennas using two monopoles as parasitic elements. J. Li *et al.* design an efficient wideband MIMO antenna by combining a parasitic decoupling strip with right-angled slits in the ground plane to obtain 2.4 GHz–6.55 GHz operation and 18 dB isolation.

The ground plane of compact user terminals can play a major role in the radiation of MIMO antennas at low frequency where the chassis is excited. The theory of characteristic mode is explored by H. Li *et al.* in the context of designing efficient MIMO antennas by placing the elements to avoid simultaneous excitation of the chassis by more than one antenna element. A tradeoff analysis shows that MIMO performance is significantly improved by the increased isolation. Pelosi *et al.* carry out a comprehensive study on the performance of small narrowband antennas with and without a user in either MIMO mode or transceiver separation mode (TSM). This approach can relax the duplex filter requirement in TSM, although user effects may largely influence the antenna performance.

In order to further improve MIMO antenna performance in a time-varying propagation channel, reconfigurable antenna elements may be employed to optimize the antenna-channel interaction. Qin *et al.* show that two pattern reconfigurable U-slot antenna elements can provide capacity gain in measured line-of-sight (LOS) and non-LOS channels, relative to two omnidirectional reference antennas.

Metrics and models for MIMO antennas are considered by two contributions. Yun and Vaughan isolate the role of antenna efficiencies from correlation in the diversity and capacity performance of a given MIMO antenna. Thereafter, the MIMO antenna can be represented with an equivalent number of ideal antenna branches that are called diversity order and capacity order, respectively. The question of the validity and accuracy of equivalent circuit models for MIMO arrays is addressed by Wallace and Mehmood, where a method-of-moments analysis based on first principles reveals that such models are exact under normal circumstances, and that transmit and receive modes can be analyzed with a single unified model.

B. Channel Sounding and Modeling

This section focuses on accurate channel characterization through sounding and modeling, which is vital to correctly assess the benefits of MIMO transmission, allowing critical tradeoffs and design decisions to be made.

Two papers in this section directly consider the topic of channel sounding. Pinchera and Migliore present an interesting measurement approach using a parasitic array instead of a switched array. Using low cost switched parasitic elements instead of a large multiport microwave switch dramatically reduces the cost of MIMO channel sounding with only modest reduction in accuracy. The impact of an imperfect underlying model on the accuracy of high-resolution double-directional MIMO channel estimation is studied by Landmann *et al.* It is shown that modeling this uncertainty allows multipath to be correctly classified as discrete or diffuse, and that imperfect calibration can lead to large error in multipath estimates.

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Sounder-based channel modeling is considered in two papers. Zhang *et al.* extend tensor-based MIMO modeling approaches to the case of wide bandwidth, which is required for today's wireless standards. The model is assessed using measured indoor channels, indicating a tradeoff between complexity and accuracy when generating synthetic MIMO channel data. Poutanen *et al.* propose a method for extending geometry-based stochastic channel models to the case of multiple links, which is important to analyze MIMO systems using coordinated transmission or relays. This model is accomplished by having certain clusters that are shared by the links, creating dependence in the statistics of the MIMO channels.

Finally, this section includes two papers that present measurement of land mobile satellite (LMS) channels. Cheffena *et al.* consider the effect of signal shadowing by trees in MIMO-LMS links, proposing a multipath model for trees based on multiple scattering theory. The model is compared with direct FDTD simulation, indicating that good accuracy can be obtained with modest complexity. King *et al.* investigate the use of multiple antennas to increase the capacity of LMS networks, where a Markov chain is employed to characterize the time-variant nature of shadowing and depolarization effects. The utility of the proposed technique is illustrated through direct measurements with an artificial LMS platform.

C. System Performance Evaluation

The final section deals principally with system-level aspects, indicating how detailed characteristics of the propagation channel, antennas, and devices affect the performance of the overall MIMO system or network.

Two papers consider the emerging topic of relays and coordinated MIMO transmission. Nishimori *et al.* evaluate the capacity of relay-enhanced multi-antenna transmission in a cellular environment through direct propagation measurements taken in Yokkaichi City, Japan. This study shows that characterizing path-loss differences is critical and that relay-enhanced MIMO can provide a 50% improvement in capacity. Lau *et al.* analyze urban propagation measurements involving three coherent base stations and a mobile unit equipped with four antennas. Capacity for cooperative transmission from the base stations is analyzed, revealing dramatic sum-rate capacity gains compared to non-cooperative methods.

User influence and exposure limits are considered in two contributed papers. Nielsen *et al.* provide a detailed study of user influence on the outage capacity for mobile devices in the data mode operation. Six different handsets at two bands are characterized for twelve different users, showing that handset design and hand position critically impact body loss, mean effective gain, and outage capacity. Perentos *et al.* consider compliance and exposure testing of MIMO devices, which is important as multi-antenna technology is increasingly incorporated into advanced devices. The developed methodologies allow such testing to be performed with scalar field probes, avoiding expensive upgrades of existing test equipment.

The use of parasitic arrays for MIMO transmission are considered in two papers, providing reduced complexity or capacity enhancement compared to classical MIMO systems. Alrabadi *et al.* develop the methodology of using a switched parasitic array (SPA) with only a single active RF source to replace a full MIMO transmitter with reduced cost and complexity. The generalized method for forming the required orthogonal bases is demonstrated through simulation and direct measurement with a prototype SPA. Mehmood and Wallace propose flexible reconfigurable aperture (RECAP) antennas to increase MIMO capacity in interference-limited scenarios. Multi-user simulations with a detailed noise model suggest that high reconfigurability can lead to many-fold capacity increase.

Finally, four papers are included that extend or verify assumptions made in existing modeling approaches for MIMO systems. Webb *et al.* consider the coherence time and bandwidth of channel state information in measured time-varying urban channels, indicating how sensitive feedback methods are to time and frequency offsets. The study shows that controlling the feedback rate can lead to significant improvements in mobile MIMO systems. Hallbjörner *et al.* explore the impact of sparse multipath on antenna correlation and diversity, in contrast to classical treatments where infinite and uniform arrivals are assumed. Multipath channels are simulated using antenna arrays in an anechoic chamber, showing that sparse multipath can lead to high variability or spread of channel statistics like correlation. Yanakiev *et al.* study the use of correlation as a metric in the design stage to predict handset performance in terms of MIMO capacity in real scenarios. The surprising result is that correlation may have little bearing on capacity, indicating correlation may be a misleading figure of merit. Finally, Banani and Vaughan investigate the effect of non-linear amplifiers in practical MIMO systems and how to compensate the resulting degradations to channel capacity. A model for non-linear MIMO systems is introduced, and a blind channel-estimation technique is developed to estimate and track the channel in the presence of non-linearities.

To conclude this guest editorial, we would like to thank the former Editor-in-Chief Dr. Trevor S. Bird and his successor Prof. Michael A. Jensen, for providing us with the opportunity to coordinate and organize this special issue and for their continued support throughout the process. We are also grateful to the many anonymous reviewers who helped make the special issue possible. We believe that the issue provides a true snapshot of the state-of-the-art in antennas and propagation research in MIMO systems, serving as interesting reading as well as a useful reference for years to come.

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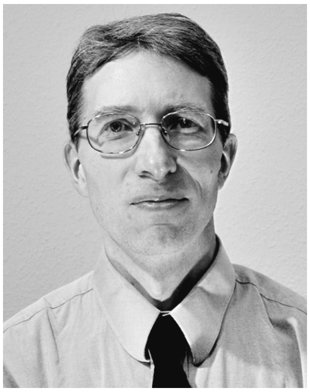

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Prof. Daneshrad is the recipient of the 2005 Okawa Foundation award, a coauthor of the best paper award at PADS 2004, and was awarded first prize in the DAC 2003 design contest. He is the beneficiary of the endowment for "UCLA-Industry Partnership for Wireless Communications and Integrated Systems."

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