GUEST EDITORIAL

ADVANCES IN SMART ANTENNAS


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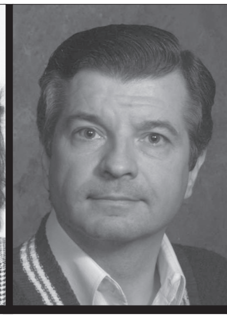
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Over the last decade, few themes have captured the imagination of wireless researchers as much as smart antennas and multiple-input multiple-output (MIMO) communications. Although phased arrays had been widely used to synthesize directive beams in radar and satellite communications, it was only in the 1990s that antenna arrays drew the attention of terrestrial wireless system designers. This attention was due, largely, to the enormous success of cellular systems and the need for higher capacities resulting from that success. Since the challenging channel conditions encountered in cellular systems (e.g., fast multipath fading and non-line-of-sight propagation) can preclude formation of a coherent beam, smart antenna techniques relying on accurate tracking of the channel state had to be devised in order to reap the benefits of signal enhancement, interference mitigation, and diversity. Furthermore, a number of seminal information-theoretic works surfaced in the mid-90s predicting hefty capacity gains for MIMO systems. These papers ignited tremendous research activity in the analysis of MIMO channel capacity and also motivated the development of practical techniques to achieve these gains, such as the layered space-time architecture and its many refinements.

After a decade of relentless research efforts, the physical layer implications of using transmit and/or receive antenna arrays appear to be, by and large, well understood. Moreover, smart antennas and MIMO techniques are already integral ingredients of the latest releases of the UMTS and CDMA third-generation standards as well as of their evolutionary roadmaps. Similar techniques are featured in various other infrastructure-based systems such as IEEE 802.11n, IEEE 802.16, and the developing IEEE 802.20.

Despite much progress at the physical layer, the impact that smart antennas and MIMO may have on the higher layers of the communication protocol stack and on systems at large is only beginning to be explored. This impact resonates directly with research areas of growing interest such as cross-layer design, ad hoc systems, relaying, and meshed networking. Furthermore, it gives rise to cross-layer design questions such as whether the physical layer should be made aware of the nature of the traffic for the full potential of MIMO to be unleashed, or whether the structure of networks should be tailored to the available MIMO transceivers or vice versa. Established physical layer notions such as the diversity-multiplexing trade-off take on new meaning when viewed from the stance of the application, which must decide the optimal operational point on this trade-off curve in order to optimize its specific performance criterion.

The goal of this special issue is to tackle these and other related matters from perspectives that transcend the physical layer. In that spirit, we have solicited nine invited articles that address and emphasize several aspects of these interactions for both infrastructure-based and ad hoc wireless networks.

The issue opens with a timely overview of the recent progress toward the inclusion of MIMO concepts in wireless standards. This article, penned by Hottinen *et al.*, evidences that almost every emerging wireless standard includes multiple antennas at the link layer. Thus, there is a pressing need to understand how to exploit this link layer technology to improve network capacity and end-to-end performance of the many diverse applications these systems aim to support. This article therefore sets the stage to motivate the subsequent articles addressing this very issue.

The next two articles discuss the state of the art in code design for MIMO systems. Although channel coding resides at the physical layer, both these articles present the trade-offs associated with such codes as well as the coding techniques required in distributed MIMO for cellular systems and ad hoc wireless networks. Specifically, the article by ten Brink presents an account of how coding has evolved to leverage the spatial dimension provided by MIMO. In addition, it surveys the various families of space-time codes that have been developed to date and discusses the advantages and disadvantages of each, in terms of performance as well as implementation, complexity, and potential industrial adoption.

In the article by Helmut Bölcskei attention is focused on the extra degrees of freedom provided in the spectral domain by the use of OFDM. A core problem therein lies in the efficient exploitation of synergies between the diversity associated with the spatial and frequency dimensions, in particular through the design of high-performance space-time-frequency codes.

The next three articles explore the subject of cross-layer design in cellular systems with multiple antennas at the physical layer. Many wireless systems currently exploit dynamic resource allocation to address the time-varying nature of radio channels, network conditions, and user requirements. The article by Letaief and Zhang provides a comprehensive overview of cross-layer dynamic resource allocation techniques for cellular systems with MIMO and OFDM at the physical layer. They discuss practical considerations in such systems, including imperfect channel estimates, overhead, and complexity. The article concludes with recent work and open issues on cross-layer resource allocation and adaptation across all layers of the protocol stack.

In the subsequent article by Boche and Wiczanowski, MIMO systems are also looked on from a cross-layer perspective. Specifically, the article proposes the stability region (defined by the traffic load that can be sustained for each user by the network) as an end-to-end performance metric for cross-layer design. This stability region under various classes of data traffic as well as the delay statistics are studied under the presence of a MIMO-enabled physical layer.

One of the hurdles posed by current cellular systems with aggressive spectral reuse is the low operational signal-to-interference ratio, which is not the regime where MIMO techniques shine the most. The ambitious idea put forth by Karakayali, Foschini, and Valenzuela is to circumvent this obstacle by coordinating base stations so they effectively behave as a single distributed base. This idea, whose background is the quest for the ultimate capacity of multicell systems, has challenging implications for the system architecture as a whole.

The remaining contributions address cross-layer MIMO issues in ad hoc wireless networks. In particular, the problem of designing ad hoc networks using MIMO-capable nodes is engaged by Zorzi *et al.* in their article. Trade-offs concerning the achievement of the conflicting goals of rate and reliability increases, power savings, and latency reduction are brought up and thoroughly discussed. Particular emphasis is placed on the role of channel state information, in its various forms, at both transmitter and receiver.

The article by Winters discusses the use of smart antennas in mobile ad hoc and mesh networks. It investigates multiple smart antenna techniques, including directional antennas, beamforming/adaptive antennas, and/or MIMO space-time techniques. Interestingly, the article indicates that while smart antennas can greatly increase the performance of wireless networks, the MAC and routing algorithms must be modified to realize these performance gains.

The final article, by Liu *et al.*, returns to the theme of cooperation, but for nodes cooperating in an ad hoc wireless network rather than base station cooperation in a cellular system. In particular, this article investigates cooperative techniques whereby multiple nodes in a wireless network work together to form a virtual antenna array. The article shows that these virtual arrays exhibit similar diversity benefits as co-located antennas. It also investigates how cooperative communication at the physical layer can be integrated into the MAC design for dramatic improvements in throughput and interference mitigation. The impact of cooperative communication on network design is also discussed.

We would like to thank all of the invited authors for their contributions and the numerous reviewers for their time and dedication. Our gratitude extends also to the previous Editor-in-Chief, Michele Zorzi, for launching the idea of this special issue, and to the new Editor-in-Chief, Abbas Jamalipour, for embracing it.

BIOGRAPHIES

ANGEL LOZANO [SM] (aloz@lucent.com) received an Engineer degree in telecommunications from the Polytechnical University of Catalonia, Barcelona, Spain, in 1992, and Master of Science and Ph.D. degrees in electrical engineering from Stanford University, California, in 1994 and 1998, respectively. Between 1996 and 1998 he worked for Pacific Communication Sciences Inc. and Conexant Systems in San Diego, California. Since January 1999 he has been with Bell Laboratories (Lucent Technologies), Holmdel, New Jersey. He has published about 70 papers and three book chapters, and holds nine patents in the areas of communications and information theory. Since October 1999 he has served as Associate Editor for *IEEE Transactions on Communications*. He is actively involved in committees, conference organization, and editorial boards for the IEEE Communications Society. He is also an adjunct associate professor of electrical engineering at Columbia University, New York, New York.

ANDREA GOLDSMITH [F] is an associate professor of electrical engineering at Stanford University, and was previously an assistant professor of electrical engineering at Caltech. She has also held industry positions at Maxim Technologies and AT&T Bell Laboratories. Her research includes work on capacity of wireless channels and networks, energy-constrained wireless communications, wireless communications for distributed control, and cross-layer design of wireless networks. She received B.S., M.S. and Ph.D. degrees in electrical engineering from the University of California at Berkeley. She is a Fellow of Stanford, and currently holds Stanford's Bredt Faculty Development Scholar Chair. She has received several awards for her research, including the National Academy of Engineering Gilbreth Lectureship, the Alfred P. Sloan Fellowship, the Stanford Terman Fellowship, the National Science Foundation CAREER Development Award, and the Office of Naval Research Young Investigator Award. She was also a co-recipient of the 2005 IEEEE Communications Society and Information Theory Society joint paper award. She currently serves as editor for the *Journal on Foundations and Trends in Communications and Information Theory and in Networks*, and was previously an editor for *IEEE Transactions on Communications* and *IEEE Wireless Communications*. She is active in committees, conference organization, and editorial boards for the IEEE Information Theory and Communications Societies, and is an elected member of the Board of Governers for both societies.

REINALDO A. VALENZUELA [F] obtained his Bachelor of Science from the University of Chile and his Ph.D. from the Imperial College of Science and Technology of the University of London, England. At Bell Laboratories he studied indoor microwave propagation and modeling, packet reservation multiple access for wireless systems, and optical WDM networks. He became manager of the Voice Research Deptartment at Motorola Codex, involved in implementation of integrated voice and data packet systems. On returning to Bell Laboratories he led a multidisciplinary team to create a software tool for wireless system engineering (WiSE), now in widespread use in Lucent Technologies. He received the Distinguished Member of Technical Staff award and is director of the Wireless Communications Research Department. He is interested in microwave propagation measurements and models, intelligent antennas, third-generation wireless systems, and space-time systems achieving high capacities using transmit and receive antenna arrays. He has published over 80 papers and has 12 patents. He is an editor for *IEEE Transactions on Communications* and *IEEE Transactions on Wireless*.

MIGUEL ANGEL LAGUNAS [S'73-M'78-SM'89-F'97] received his Telecommunications Engineer degree in 1973 from UPM, Madrid, and his Ph.D. degree in telecommunications from UPB, Barcelona. During 1971–1973 he was a research assistant at the Semiconductor Lab ETSIT, Madrid; during 1973–1979 he was a teaching assistant in network synthesis and semiconductor electronics; during 1979–1982 he was an associate professor of digital signal processing. Since 1983 he has been a full professor, teaching courses in signal processing, array processing, and digital communications. He was project leader of high-speed SCMA (1987–1989) and ATM (1994–1995) cable networks. He is also co-director of the first projects for the European Space Agency and European Union, providing engineering demonstration models on smart antennas for satellite communications using DS and FH systems (1986) and antenna arrays for mobile communications GSM (Tsunami, 1994). His research activity is devoted to spectral estimation, DSP on communications, and array-MIMO processing. His technical activities are in advanced front-ends for digital communications combining spatial with frequency-time and coding diversity. He was vice- president for research of UPC from 1986 to 1989 and vice-secretary general for research, CICYT, Spain, from 1995 to 1996. Currently, he is director of the Telecommunications Technological Center of Catalonia , Barcelona. He is a member-at- large of Eurasip. He is an elected member of the Academy of Engineers of Spain, and the Academy of Science and Art of Barcelona. He was a Fullbright scholar at the University of Boulder, Colorado.

DAVID GESBERT is a professor at Eurecom Institute, France. He obtained a Ph.D degree from Ecole Nationale Superieure des Telecommunications in 1997. From 1993 to 1997 he was with France Telecom Research, Paris, France. From April 1997 to October 1998 he was a research fellow at the Information Systems Laboratory, Stanford University. He took part in the founding team of Iospan Wireless Inc, San Jose, California, a startup company that pioneered MIMO-OFDM. Since 2001 he has been with the University of Oslo as an adjunct professor. He has published about 100 papers and several patents, all in the area of signal processing and communications. He has co-edited several special issues for *IEEE JSAC* (2003), *EURASIP JASP* (2004), and *IEEE Communications Magazine* (2006). He is an elected member of the IEEE Signal Processing for Communications Technical Committee. He authored or co-authored three award winning papers (2004 IEEE Best Tutorial Paper Award [IEEE Communications Society) for a 2003 *JSAC* paper on MIMO systems, 2005 Best Paper [Young Author] Award for Signal Processing Society journals, Best Paper Award for the 2004 ACM MSWiM workshop). He is a co-organizer and Technical Chair for the IEEE Workshop on Signal Processing Advances in Wireless Communications, 2006, Cannes, France.