Guest Editorial Fundamental Performance Limits of Wireless Sensor Networks

I. INTRODUCTION

IN RECENT times much has been said about how, once deployed, networks of devices with wireless communication capabilities will affect the way we work, learn, interact, organize, get entertained, fight wars, and recover from disasters. This interest in wireless networks has spawned a vibrant research activity in the areas of mobile and ad hoc networking, addressing both systems and theory issues. Wireless sensor networks are a particular class of ad hoc networks which only recently have started to receive some attention. Wireless sensor networks are characterized by small, low power, unreliable devices equipped with limited sensing, actuation, and communication capabilities, and embedded in the environment.

In many respects, sensor networks are quite different from the types of networks that have been studied in the past. Certain well-accepted properties of other mobile ad hoc networks are not shared by sensor networks. For example, densely deployed sensors necessarily observe correlated signals, and actively cooperate to achieve a common goal such as, for example, locating, identifying, and tracking a signal source. In this context, some pessimistic results about the ability of general wireless ad hoc networks to scale in size are not directly applicable, since such results often assume that nodes generate independent information, and noncooperative communication strategies. Such scenarios illustrate the current rudimentary understanding of sensor networks. In that example, we see at work the principle that not only does the ability of the network to carry information depend on the number of nodes, but so does the amount of novel information generated at each node. Motivated by the strong current interest in the nascent area of wireless sensor networks, the main purpose of this special issue is to give a snapshot of the latest work from communications and signal processing communities in this new and exciting area of research.

II. OVERVIEW OF THE ISSUE

Among the large number of submissions we received, we identified papers covering five topic areas around which it would be possible to organize a coherent collection of reference material.

- Network capacity problems.
- Distributed signal detection and estimation problems.
- Medium access control problems.
- Cooperative MIMO techniques.
- Data aggregation problems.

These areas are intentionally not well defined, there is overlap among them, and most of the papers we selected do not fit squarely into any one of them. However, this coarse classification helps to outline the type of problems on which this special issue is focused.

Under the title of *network capacity*, we consider problems of an information theoretic nature, dealing primarily with capacity and coding problems. In this area, we have three papers. In "Side Information Aware Coding Strategies for Sensor Networks," Draper and Wornell develop modular and decentralized coding strategies for estimation under communication constraints in tree-structured sensor networks. In "An Upper Bound on the Sum-Rate Distortion Function and its Corresponding Rate Allocation Schemes for the CEO Problem," Chen *et al.* present some new results on the classical CEO problem. They develop new inner and outer bounds on its rate region, which they show to be tight in the case of Gaussian signals and equal signal-to-noise ratio across sensors. In "Correlated Sources over Wireless Channels: Cooperative Source-Channel Coding," Murugan *et al.* consider joint source/channel coding strategies for the transmission of correlated sources over a Gaussian multiple-access channel.

Under the title of *distributed signal detection and estimation*, we consider problems of an algorithmic nature, dealing with the design and analysis of techniques for detecting and estimating signals that are suitable for implementation in a sensor network. In this area, we have five papers. In "Estimating Inhomogeneous Fields Using Wireless Sensor Networks," Nowak *et al.* propose algorithms for estimating fields with discontinuities, for which they provide bounds on their energy consumption and estimation errors. In "Asymptotic Results for Decentralized Detection in Power Constrained Wireless Sensor Networks," Chamberland and Veeravalli obtain new results on the classical binary decentralized hypothesis testing problem, for the case when sensors operate under a total joint power constraint and where the measurements delivered to the fusion centered are corrupted by noise. In "Robust Location Detection with Sensor Networks," Ray *et al.* formulate the problem of source localization as a problem of code design, and present some code constructions which then they analyze both through analytical and simulation methods. In "Distributed Classification of Gaussian Space–Time Sources in Wireless Sensor Networks," D'Costa *et al.* present distributed classification algorithms, under the assumption that under each hypothesis the sensor readings form a stationary, ergodic, and band-limited Gaussian field. In "Dynamic Sensor Collaboration Via Sequential Monte Carlo," Guo and Wang consider the application of sequential

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Monte Carlo methods to the problem of extracting information from data collected by a sensor network.

Under the title of *medium access control*, we consider problems dealing with how multiple sensor nodes cooperate to efficiently share the wireless channel, taking into account specific properties of the sensor networking setup. In this area, we have three papers. In "Collision-Minimizing CSMA and its Applications to Wireless Sensor Networks," Tay *et al.* propose and analyze the performance of a medium access control (MAC) protocol well suited for the event-driven workloads typical of an important class of sensor networking applications. In "Sensor Networks with Mobile Access: Optimaltevc Random Access and Coding," Venkitasubramaniam *et al.* develop a MAC protocol for which they are able to prove that it achieves the best possible asymptotic throughput, and it does so with vanishingly small power at each sensor node. In "The Distance-2 Matching Problem and its Relationship to the MAC-Layer Capacity of Ad Hoc Wireless Networks," Balakrishnan *et al.* formulate the problem of determining network capacity as the standard maximum distance-2 matching problem of graph theory, and then use graph theoretic tools to approximate such capacity measures.

Under the title of *cooperative MIMO techniques*, we consider problems in which multiple sensor nodes cooperate to achieve communication capabilities that none of them would be able to achieve individually, typically due to the extreme resource constraints under which individual sensors must operate. In this area, we have three papers. In "Cooperative Multihop Broadcast for Wireless Networks," Maric and Yates propose a solution to the minimum-energy broadcast problem, based on the idea that nodes can collect energy from multiple transmissions by different nodes and only make a decision on the symbol being broadcast once enough energy has been accumulated. In "Energy-Efficiency of MIMO and Cooperative MIMO Techniques in Sensor Networks," Cui *et al.* observe that in short-range communication, as is typical in some sensor networks, it is the energy consumed by the circuitry (and not transmitted energy) what dominates total energy consumption. Based on that observation, they propose a model for energy consumption that takes those factors into account, and use the model to evaluate the performance of different transceiver architectures. In "Fading Relay Channels: Performance Limits and Space-Time Signal Design," Nabar *et al.* present performance analysis and code designs for a fading relay channel in which the source, the relay, and the sink nodes are all equipped with a single antenna.

Finally, under the title *data aggregation*, we consider problems in which sensor nodes perform some type of processing on their readings inside the network, to enable more efficient use of their limited communication resources. In this area, we have four papers. In "Lower Bounds on Data Collection Times in Sensory Networks," Florens *et al.* develop lower bounds on the time needed for data collection and distribution in different sensor network topologies, and present scheduling algorithms that in some cases are able to achieve those bounds. In "Optimal Information Extraction in Energy-Limited Wireless Sensor Networks," Ordoñez and Krishnamachari present an optimization theoretic approach to deal with design aspects in various sensor networking applications such as, for example, gathering data under energy constraints. In "Minimizing Energy Consumption in Large-Scale Sensor Networks through Distributed Data Compression and Hierarchical Aggregation," Baek *et al.* propose a hierarchical model for a sensor network made up of source, aggregation/relay, and sink nodes. The energy requirements for this network model are then determined using stochastic geometry tools. In "Game-Theoretic Models for Reliable Path-Length and Energy-Constrained Routing With Data Aggregation in Wireless Sensor Networks," Kannan and Iyengar present a game theoretic formulation of the routing problem in sensor networks.

III. Conclusion

A new paradigm is emerging in wireless communications and in digital signal processing: powerful sensing, communication, and actuation systems built out of very many simple ones. Such systems hold the promise to help us develop solutions to problems of this world (such as homeland security and health care), and to problems outside of this world as well (such as robotic space exploration). Indeed, distributed sources, distributed channels, and large-scale issues open up a number of fascinating research questions in information technology. The papers we have selected for inclusion in this special issue present a sampling of recent progress in the general area of distributed communications and distributed signal processing in sensor networks. We hope you will enjoy reading this collection of papers as much as we enjoyed putting it together.

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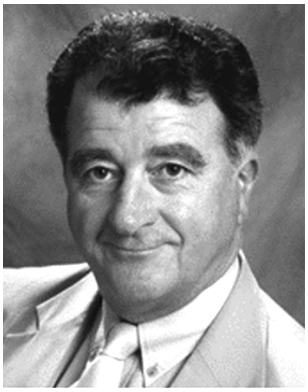
Sergio D. Servetto (S'94–M'99) was born in Argentina, on January 18, 1968. He received the Licenciatura en Informática degree from the Universidad Nacional de La Plata (UNLP), La Plata, Argentina, in 1992, the M.Sc. degree in electrical engineering, and the Ph.D. degree in computer science from the University of Illinois at Urbana-Champaign (UIUC), in 1996 and 1999, respectively.

From 1994 to 1999, he was a Graduate Research Assistant at UIUC. From 1999 to 2001, he worked at the Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland. Since Fall 2001, he has been an Assistant Professor in the School of Electrical and Computer Engineering, Cornell University, Ithaca, NY. He is also a member of the field of Applied Mathematics at Cornell University. He is currently writing a book, tentatively entitled *Digital Communications over Packet-Switched Networks*, to be published by Kluwer. His research interests are centered around information theoretic aspects of networked systems, with a current emphasis on problems that arise in the context of large-scale sensor networks.

Prof. Servetto was the recipient of the 1998 Ray Ozzie Fellowship given to "Outstanding Graduate Students in Computer Science," and of the 1999 David J. Kuck Outstanding Thesis Award, for the Best Doctoral Dissertation of the year, both from the Department of Computer Science, UIUC. He is also the recipient of a 2003 National Science Foundation (NSF) CAREER Award. He has served on the Technical Program Committee of various conferences (IEEE INFOCOM, GLOBECOM, ICC, SECON; ACM MobiCom, MobiHoc, SenSys, WSNA). He presented a tutorial at ACM MobiHoc 2004, on the topic of "Efficient Architectures for Information Transport in Wireless Sensor Networks."

Raymond Knopp (S'92–A'97–M'00) was born in Montreal, Canada, on January 20, 1969. He received the B.Eng. (Honors) and the M.Eng. degrees in electrical engineering from McGill University, Montreal, QC, Canada, in 1992 and 1993, respectively, and the Ph.D. degree (docteur ès sciences) in communication systems from the Swiss Federal Institute of Technology (ETH), Lausanne, Switzerland.

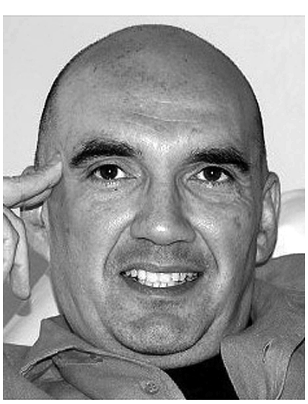
During his doctoral studies (1993–1997), he was a Research and Teaching Assistant in the Mobile Communications Group, Institut Eurécom, Sophia Antipolis, France. In 1997, he joined the Mobile Communications Laboratory, Communications Systems Department, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland, as a Senior Research and Teaching Assistant. He returned to Institut Eurécom's Mobile Communications Group in 2000 as an Assistant Professor. His current research interests are in the area of digital communication theory and systems. Specific subjects include coding, multiple-access and power-control techniques in radio communications, software radio architectures, and implementation technology.



Anthony Ephremides (S'68–M'71–SM'77–F'84) received the B.S. degree from the National Technical University of Athens, Athens, Greece, in 1967, and the M.S. and Ph.D. degrees from Princeton University, Princeton, NJ, in 1969 and 1971, respectively, all in electrical engineering.

He has been at the University of Maryland, College Park, since 1971, and currently holds a joint appointment as Professor in the Electrical Engineering Department and in the Institute of Systems Research (ISR) of which he is a Founding Member. He is Cofounder of the NASA Center for Commercial Development of Space on Hybrid and Satellite Communications Networks, established in 1991, as an off-shoot of the ISR. He served as Co-Director of the Center for Commercial Development of Space on Hybrid and Satellite Communications Networks from 1991 to 1994. He was a Visiting Professor at the National Technical University, Athens, Greece, in 1978, at the Electrical Engineering and Computer Science Department, University of California, Berkeley, in 1979, and at the Institut National de Recherche en Informatique et en Automatique (INRIA), Le Chesnay Cedex, France. From 1985 to 1986, he was on leave from the Massachusetts Institute of Technology (MIT), Cambridge, and the Swiss Federal Institute of Technology (ETH), Zurich, Switzerland. He has been the Dissertation Supervisor of over twenty Ph.D. students who now hold prominent positions in academia, industry, and research laboratories. He is the Founder and President of Pontos, Inc., a Maryland company that provides technical consulting services, since 1980. He has served on the Editorial Boards of the *Journal of Wireless Networks* and the *International Journal of Satellite Communications*. He has authored or coauthored over 100 technical journal papers and 300 technical conference presentations. He has also contributed chapters to several books and edited numerous special issues of scientific journals. His interests are in the areas of communication theory, communication systems and networks, queueing systems, signal processing, and satellite communications. His research has been continuously supported since 1971 by the National Science Foundation (NSF), NASA, Office of Naval Research (ONR), Applied Research Laboratory (ARL), Naval Research Laboratory (NRL), NSA, and Industry.

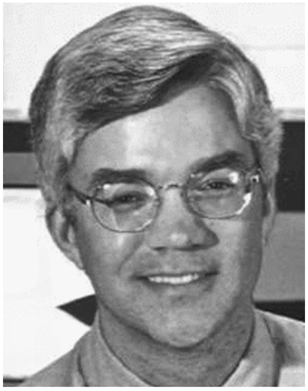
Dr. Ephremides received the IEEE Donald E. Fink Prize Paper Award in 1992 and was the first recipient of the Sigmobile Award of the Association of Computer Machinery (ACM), for contributions to wireless communications in 1997. This year, he was awarded the Cynthia Kim Eminent Professorship in Information Technology at the University of Maryland. He has also won awards from the Maryland Office of Technology Liaison for the commercialization of products and ideas stemming from his research. He was the General Chairman of the 1986 IEEE Conference on Decision and Control, Athens, Greece, and the 1991 IEEE International Symposium on Information Theory, Budapest, Hungary. He also organized two workshops on Information Theory in 1984 (Hot Springs, VA) and in 1999 (Metsovo, Greece). He was the Technical Program Co-Chair of the IEEE INFOCOM, New York City, in 1999 and the IEEE International Symposium on Information Theory, Sorrento, Italy, in 2000. He has also been the Director of the Fairchild Scholars and Doctoral Fellows Program, an academic and research partnership program in satellite communications between Fairchild Industries, and the University of Maryland. He has been the President of the Information Theory Society of the IEEE (1987) and has served on its Board of Governors almost continuously from 1981 until the present. He was elected to the Board of Directors of the IEEE in 1989 and 1990. He has served on the Editorial Boards of the IEEE TRANSACTIONS ON AUTOMATIC CONTROL and the IEEE TRANSACTIONS ON INFORMATION THEORY.



Sergio Verdú (S'80–M'84–SM'88–F'93) was born in Barcelona, Catalonia, Spain, on August 15, 1958. He received the telecommunications engineering degree from the Polytechnic University of Barcelona, Barcelona, Spain, in 1980 and the Ph.D. degree in electrical engineering from the University of Illinois at Urbana-Champaign in 1984.

He is a Professor of Electrical Engineering, Princeton University, Princeton, NJ. He has held visiting appointments at the Australian National University, the Technion-Israel Institute of Technology, the University of Tokyo, the University of California, Berkeley, and the Mathematical Sciences Research Institute, Berkeley. He is the author of *Multiuser Detection* (Cambridge, U.K.: Cambridge University Press, 1998).

Prof. Verdú is a recipient of several paper awards including the IEEE Donald Fink Paper Award, a Golden Jubilee Paper Award from the Information Theory Society, the 1998 Information Theory Society Paper Award, and the 2002 Leonard G. Abraham Prize Award from the IEEE Communications Society. He also received a Millennium Medal from the IEEE and the 2000 Frederick E. Terman Award from the American Society for Engineering Education. He served on the Board of Governors of the Information Theory Society from 1989 to 1999, and was President of the Society in 1997. In addition to organizing several IEEE Workshops on Information Theory, he was Co-Chair of the Program Committee of the 1998 IEEE International Symposium on Information Theory, and Co-Chair of the 2000 IEEE International Symposium on Information Theory. He served as an Associate Editor for Shannon Theory of the IEEE TRANSACTIONS ON INFORMATION THEORY. He served as Guest Editor of the 1998 Special Commemorative Issue of the IEEE TRANSACTIONS ON INFORMATION THEORY, reprinted as the IEEE Press volume "Information Theory: Fifty Years of Discovery." He is currently Editor-in-Chief of *Foundations and Trends in Communications and Information Theory*.



Stephen B. Wicker (S'83–M'84–SM'93) received the B.S.E.E. degree (High Honors) from the University of Virginia, Charlottesville, in 1982, the M.S.E.E. degree from Purdue University, West Lafayette, IN, in 1983, and the Ph.D. degree in electrical engineering from the University of Southern California, Los Angeles, in 1987.

He is a Professor and Associate Director for Research in the School of Electrical and Computer Engineering, Cornell University, Ithaca, NY. He is the author of *Codes, Graphs, and Iterative Decoding* (Norwell, MA: Kluwer, 2002), *Turbo Coding* (Norwell, MA: Kluwer, 1999), *Error Control Systems for Digital Communication and Storage* (Englewood Cliffs, NJ: Prentice-Hall, 1995), and *Reed-Solomon Codes and Their Applications* (Piscataway, NJ: IEEE Press, 1994). He teaches and conducts research in wireless information networks, digital systems, self-configuring systems, and artificial intelligence. He has served as a consultant in wireless telecommunications systems, error control coding, and cryptography for various companies in North America, Europe, and Asia. His current research focuses on the use of probabilistic models and game theory in the development of highly distributed, adaptive networks.

Prof. Wicker was awarded the 1988 Cornell College of Engineering Michael Tien Teaching Award and the 2000 Cornell School of Electrical and Computer Engineering Teaching Award. He has served as an Associate Editor for Coding Theory and Techniques for the IEEE TRANSACTIONS ON COMMUNICATIONS and has served two terms as a Member of the Board of Governors of the IEEE Information Theory Society.