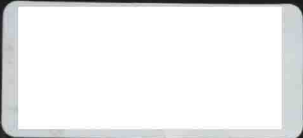


Volume 3



Academic Press Library in Signal Processing

Array and Statistical
Signal Processing

Rama Chellappa
Sergios Theodoridis



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Volume 3

Array and Statistical Signal Processing

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Introduction

Signal Processing at Your Fingertips!

Let us flash back to the 1970s when the editors-in-chief of this e-reference were graduate students. One of the time-honored traditions then was to visit the libraries several times a week to keep track of the latest research findings. After your advisor and teachers, the librarians were your best friends. We visited the engineering and mathematics libraries of our Universities every Friday afternoon and poured over the IEEE Transactions, Annals of Statistics, the Journal of Royal Statistical Society, Biometrika, and other journals so that we could keep track of the recent results published in these journals. Another ritual that was part of these outings was to take sufficient number of coins so that papers of interest could be xeroxed. As there was no Internet, one would often request copies of reprints from authors by mailing postcards and most authors would oblige. Our generation maintained thick folders of hard-copies of papers. Prof. Azriel Rosenfeld (one of RC's mentors) maintained a library of over 30,000 papers going back to the early 1950s!

Another fact to recall is that in the absence of Internet, research results were not so widely disseminated then and even if they were, there was a delay between when the results were published in technologically advanced western countries and when these results were known to scientists in third world countries. For example, till the late 1990s, scientists in US and most countries in Europe had a lead time of at least a year to 18 months since it took that much time for papers to appear in journals after submission. Add to this the time it took for the Transactions to go by surface mails to various libraries in the world. Scientists who lived and worked in the more prosperous countries were aware of the progress in their fields by visiting each other or attending conferences.

Let us race back to 21st century! We live and experience a world which is fast changing with rates unseen before in the human history. The era of Information and Knowledge societies had an impact on all aspects of our social as well as personal lives. In many ways, it has changed the way we experience and understand the world around us; that is, the way we learn. Such a change is much more obvious to the younger generation, which carries much less momentum from the past, compared to us, the older generation. A generation which has grew up in the Internet age, the age of Images and Video games, the age of IPAD and Kindle, the age of the fast exchange of information. These new technologies comprise a part of their "real" world, and Education and Learning can no more ignore this reality. Although many questions are still open for discussions among sociologists, one thing is certain. Electronic publishing and dissemination, embodying new technologies, is here to stay. This is the only way that effective pedagogic tools can be developed and used to assist the learning process from now on. Many kids in the early school or even preschool years have their own IPADs to access information in the Internet. When they grow up to study engineering, science, or medicine or law, we doubt if they ever will visit a library as they would by then expect all information to be available at their fingertips, literally!

Another consequence of this development is the leveling of the playing field. Many institutions in lesser developed countries could not afford to buy the IEEE Transactions and other journals of repute. Even if they did, given the time between submission and publication of papers in journals and the time it took for the Transactions to be sent over surface mails, scientists and engineers in lesser developed countries were behind by two years or so. Also, most libraries did not acquire the proceedings of conferences and so there was a huge gap in the awareness of what was going on in technologically advanced

countries. The lucky few who could visit US and some countries in Europe were able to keep up with the progress in these countries. This has changed. Anyone with an Internet connection can request or download papers from the sites of scientists. Thus there is a leveling of the playing field which will lead to more scientist and engineers being groomed all over the world.

The aim of Online Reference for Signal Processing project is to implement such a vision. We all know that asking any of our students to search for information, the first step for him/her will be to click on the web and possibly in the Wikipedia. This was the inspiration for our project. To develop a site, related to the Signal Processing, where a selected set of reviewed articles will become available at a first “click.” However, these articles are fully refereed and written by experts in the respected topic. Moreover, the authors will have the “luxury” to update their articles regularly, so that to keep up with the advances that take place as time evolves. This will have a double benefit. Such articles, besides the more classical material, will also convey the most recent results providing the students/researchers with up-to-date information. In addition, the authors will have the chance of making their article a more “permanent” source of reference, that keeps up its freshness in spite of the passing time.

The other major advantage is that authors have the chance to provide, alongside their chapters, any multimedia tool in order to clarify concepts as well as to demonstrate more vividly the performance of various methods, in addition to the static figures and tables. Such tools can be updated at the author’s will, building upon previous experience and comments. We do hope that, in future editions, this aspect of this project will be further enriched and strengthened.

In the previously stated context, the Online Reference in Signal Processing provides a revolutionary way of accessing, updating and interacting with online content. In particular, the Online Reference will be a living, highly structured, and searchable peer-reviewed electronic reference in signal/image/video Processing and related applications, using existing books and newly commissioned content, which gives tutorial overviews of the latest technologies and research, key equations, algorithms, applications, standards, code, core principles, and links to key Elsevier journal articles and abstracts of non-Elsevier journals.

The audience of the Online Reference in Signal Processing is intended to include practicing engineers in signal/image processing and applications, researchers, PhD students, post Docs, consultants, and policy makers in governments. In particular, the readers can be benefited in the following needs:

- To learn about new areas outside their own expertise.
- To understand how their area of research is connected to other areas outside their expertise.
- To learn how different areas are interconnected and impact on each other: the need for a “helicopter” perspective that shows the “wood for the trees.”
- To keep up-to-date with new technologies as they develop: what they are about, what is their potential, what are the research issues that need to be resolved, and how can they be used.
- To find the best and most appropriate journal papers and keeping up-to-date with the newest, best papers as they are written.
- To link principles to the new technologies.

The Signal Processing topics have been divided into a number of subtopics, which have also dictated the way the different articles have been compiled together. Each one of the subtopics has been coordinated by an AE (Associate Editor). In particular:

1. Signal Processing Theory (Prof. P. Diniz)
2. Machine Learning (Prof. J. Suykens)
3. DSP for Communications (Prof. N. Sidiropoulos)
4. Radar Signal Processing (Prof. F. Gini)
5. Statistical SP (Prof. A. Zoubir)
6. Array Signal Processing (Prof. M. Viberg)
7. Image Enhancement and Restoration (Prof. H. J. Trussell)
8. Image Analysis and Recognition (Prof. Anuj Srivastava)
9. Video Processing (other than compression), Tracking, Super Resolution, Motion Estimation, etc. (Prof. A. R. Chowdhury)
10. Hardware and Software for Signal Processing Applications (Prof. Ankur Srivastava)
11. Speech Processing/Audio Processing (Prof. P. Naylor)
12. Still Image Compression
13. Video Compression

We would like to thank all the Associate Editors for all the time and effort in inviting authors as well as coordinating the reviewing process. The Associate Editors have also provided succinct summaries of their areas.

The articles included in the current editions comprise the first phase of the project. In the second phase, besides the updates of the current articles, more articles will be included to further enrich the existing number of topics. Also, we envisage that, in the future editions, besides the scientific articles we are going to be able to include articles of historical value. Signal Processing has now reached an age that its history has to be traced back and written.

Last but not least, we would like to thank all the authors for their effort to contribute in this new and exciting project. We earnestly hope that in the area of Signal Processing, this reference will help level the playing field by highlighting the research progress made in a timely and accessible manner to anyone who has access to the Internet. With this effort the next breakthrough advances may be coming from all around the world.

The companion site for this work: <http://booksite.elsevier.com/9780124166165> includes multimedia files (Video/Audio) and MATLAB codes for selected chapters.

Rama Chellappa
Sergios Theodoridis

About the Editors

Rama Chellappa received the B.E. (Hons.) degree in Electronics and Communication Engineering from the University of Madras, India in 1975 and the M.E. (with Distinction) degree from the Indian Institute of Science, Bangalore, India in 1977. He received the M.S.E.E. and Ph.D. Degrees in Electrical Engineering from Purdue University, West Lafayette, IN, in 1978 and 1981, respectively. During 1981–1991, he was a faculty member in the department of EE-Systems at University of Southern California (USC). Since 1991, he has been a Professor of Electrical and Computer Engineering (ECE) and an affiliate Professor of Computer Science at University of Maryland (UMD), College Park. He is also affiliated with the Center for Automation Research, the Institute for Advanced Computer Studies (Permanent Member) and is serving as the Chair of the ECE department. In 2005, he was named a Minta Martin Professor of Engineering. His current research interests are face recognition, clustering and video summarization, 3D modeling from video, image and video-based recognition of objects, events and activities, dictionary-based inference, compressive sensing, domain adaptation and hyper spectral processing.



Prof. Chellappa received an NSF Presidential Young Investigator Award, four IBM Faculty Development Awards, an Excellence in Teaching Award from the School of Engineering at USC, and two paper awards from the International Association of Pattern Recognition (IAPR). He is a recipient of the K.S. Fu Prize from IAPR. He received the Society, Technical Achievement, and Meritorious Service Awards from the IEEE Signal Processing Society. He also received the Technical Achievement and Meritorious Service Awards from the IEEE Computer Society. At UMD, he was elected as a Distinguished Faculty Research Fellow, as a Distinguished Scholar-Teacher, received an Outstanding Innovator Award from the Office of Technology Commercialization, and an Outstanding GEMSTONE Mentor Award from the Honors College. He received the Outstanding Faculty Research Award and the Poole and Kent Teaching Award for Senior Faculty from the College of Engineering. In 2010, he was recognized as an Outstanding ECE by Purdue University. He is a Fellow of IEEE, IAPR, OSA, and AAAS. He holds four patents.

Prof. Chellappa served as the Editor-in-Chief of IEEE Transactions on Pattern Analysis and Machine Intelligence. He has served as a General and Technical Program Chair for several IEEE international and national conferences and workshops. He is a Golden Core Member of the IEEE Computer Society and served as a Distinguished Lecturer of the IEEE Signal Processing Society. Recently, he completed a two-year term as the President of the IEEE Biometrics Council.

Sergios Theodoridis is currently Professor of Signal Processing and Communications in the Department of Informatics and Telecommunications of the University of Athens. His research interests lie in the areas of Adaptive Algorithms and Communications, Machine Learning and Pattern Recognition, Signal Processing for Audio Processing and Retrieval. He is the co-editor of the book "Efficient Algorithms for Signal Processing and System Identification," Prentice Hall 1993, the co-author of the best selling book "Pattern Recognition," Academic Press, 4th ed. 2008, the co-author of the book "Introduction to Pattern Recognition: A MATLAB Approach," Academic Press, 2009, and the co-author of three books in Greek, two of them for the Greek Open University. He is Editor-in-Chief for the Signal Processing Book Series, Academic Press and for the E-Reference Signal Processing, Elsevier.



He is the co-author of six papers that have received best paper awards including the 2009 IEEE Computational Intelligence Society Transactions on Neural Networks Outstanding paper Award. He has served as an IEEE Signal Processing Society Distinguished Lecturer. He was *Otto Monstead Guest Professor*, Technical University of Denmark, 2012, and holder of the *Excellence Chair*, Department of Signal Processing and Communications, University Carlos III, Madrid, Spain, 2011.

He was the General Chairman of EUSIPCO-98, the Technical Program co-Chair for ISCAS-2006 and ISCAS-2013, and co-Chairman and co-Founder of CIP-2008 and co-Chairman of CIP-2010. He has served as President of the European Association for Signal Processing (EURASIP) and as member of the Board of Governors for the IEEE CAS Society. He currently serves as member of the Board of Governors (Member-at-Large) of the IEEE SP Society.

He has served as a member of the Greek National Council for Research and Technology and he was Chairman of the SP advisory committee for the Edinburgh Research Partnership (ERP). He has served as Vice Chairman of the Greek Pedagogical Institute and he was for 4 years member of the Board of Directors of COSMOTE (the Greek mobile phone operating company). He is Fellow of IET, a Corresponding Fellow of the Royal Society of Edinburgh (RSE), a Fellow of EURASIP, and a Fellow of IEEE.

Section Editors

Section 1

Abdelhak M. Zoubir is a Fellow of the IEEE for contributions to statistical signal processing and an IEEE Distinguished Lecturer (Class 2010–2011). He received the Dipl.-Ing degree (B.Sc./B.Eng.) from Fachhochschule Niederrhein, Germany, in 1983, the Dipl.-Ing. (M.Sc./M.Eng.) and the Dr.-Ing. (Ph.D.) degree from Ruhr-Universität Bochum, Germany, in 1987 and 1992, respectively, all in Electrical Engineering. Early placement in industry (Klöckner-Moeller & Siempelkamp AG) was then followed by Associate Lectureship in the Division for Signal Theory at Ruhr-Universität Bochum, Germany. In June 1992, he joined Queensland University of Technology where he was Lecturer, Senior Lecturer, and then Associate Professor in the School of Electrical and Electronic Systems Engineering. In March 1999, he took up the position of Professor of Telecommunications at Curtin University of Technology, where he was Head of the School of Electrical & Computer Engineering from November 2001 until February 2003. He has been Professor of Signal Processing at Technische Universität Darmstadt since February 2003 and October 2012, respectively.



His research interest lies in statistical methods for signal processing with emphasis on bootstrap techniques, robust detection and estimation, and array processing applied to telecommunications, radar, sonar, automotive monitoring and safety, and biomedicine. He published extensively on these areas. He was/is General Co-Chair or Technical Co-Chair of numerous international conferences. His current editorial work includes member of the Editorial Board of the EURASIP journal Signal Processing and Editor-In-Chief of the IEEE Signal Processing Magazine (2012–2014). He was Chair of the IEEE SPS Technical Committee Signal Processing Theory and Methods (SPTM). He currently serves on the Board of Directors of the European Association of Signal Processing (EURASIP).

Section 2

Mats Viberg received the Ph.D. degree in Automatic Control from Linköping University, Sweden in 1989. He has held academic positions at Linköping University and visiting Scholarships at Stanford University and Brigham Young University, USA. Since 1993, he is a Professor of Signal Processing at Chalmers University of Technology, Sweden. During 1999–2004 he served as the Chair of the Department of Signals and Systems. Since 2011, he holds a position as First Vice President at Chalmers University of Technology.

His research interests are in Statistical Signal Processing and its various applications, including Antenna Array Signal Processing, System Identification, Wireless Communications, Radar Systems, and Automotive Signal Processing.



He has served in various capacities in the IEEE Signal Processing Society, including Chair of the Technical Committee (TC) on Signal Processing Theory and Methods (2001–2003) Chair of the TC on Sensor Array and Multichannel (2011–2012), Associate Editor of the Transactions

on Signal Processing (2004–2005), member of the Awards Board (2005–2007), and member at large of the Board of Governors (2010–2012).

He has received two Paper Awards from the IEEE Signal Processing Society (1993 and 1999 respectively), and the Excellent Research Award from the Swedish Research Council (VR) in 2002. He is a Fellow of the IEEE since 2003, and his research group received the 2007 EURASIP European Group Technical Achievement Award. In 2008, he was elected into the Royal Swedish Academy of Sciences (KVA). He has published more than 45 journal papers, together cited more than 6800 times, and his H-index is 32 (Google Scholar, April 2013).

Authors Biography

CHAPTER 2

Visa Koivunen received the D.Sc. degree from the University of Oulu, Finland. He was a visiting researcher at the University of Pennsylvania from 1992 to 1995. Since 1999, he has been a Professor at Aalto University (Helsinki University of Technology, Finland), where he is currently Academy Professor. He is Vice Chair and one of the principal investigators in the Smart Radios and Wireless Systems Centre of Excellence in Research nominated by the Academy of Finland. He has been an adjunct faculty member at the University of Pennsylvania and a visiting fellow at Nokia Research Center. He spent his sabbatical term at Princeton University and makes frequent research visits there.



His research interests include statistical, communications, and array signal processing. He has published over 350 journal and conference papers in these areas. He received the 2007 IEEE Signal Processing Society Best Paper Award. He is an Editorial Board Member of the IEEE Signal Processing Magazine and a Fellow of the IEEE.

Esa Ollila received the M.Sc. degree in mathematics from the University of Oulu, in 1998, Ph.D. degree in statistics with honors from the University of Jyväskylä, in 2002, and the D.Sc. (Tech) degree with honors in signal processing from Aalto University, in 2010. From 2004 to 2007 he was a post-doctoral fellow of the Academy of Finland. He has also been a Senior Researcher and a Senior Lecturer at Aalto University and University of Oulu, respectively. Currently, from August 2010, he is appointed as an Academy Research Fellow of the Academy of Finland at the Department of Signal Processing and Acoustics, Aalto University, Finland. He is also Adjunct Professor (statistics) of University of Oulu.



During the Fall-term 2001 he was a Visiting Researcher with the Department of Statistics, Pennsylvania State University, State College, PA while the academic year 2010–2011 he spent as a Visiting Post-doctoral Research Associate with the Department of Electrical Engineering, Princeton University, Princeton, NJ. His research interests focus on theory and methods of statistical signal processing, independent component analysis and blind source separation, complex-valued signal processing, array and radar signal processing, and robust and non-parametric statistical methods.

CHAPTER 3

Ljubiša Stankovic was born in Montenegro on June 1, 1960. He received a B.S. in electrical engineering from the University of Montenegro in 1982, with the award as the best student at the University. In 1984, he received an M.S. in communications from the University of Belgrade, and a Ph.D. in theory of electromagnetic waves from the University of Montenegro in 1988. As a Fulbright grantee, he spent the 1984–1985 academic year at the Worcester Polytechnic Institute in Worcester, MA. Since 1982, he has been on the faculty at the University of

Montenegro, where he has been a Full Professor since 1995. In 1997–1999, he was on leave at the Ruhr University Bochum in Germany, supported by the Alexander von Humboldt Foundation. At the beginning of 2001, he was at the Technische Universiteit Eindhoven in the Netherlands as a Visiting Professor. During 2003–2008, he was the Rector of the University of Montenegro. He is the Ambassador of Montenegro to the United Kingdom, Ireland, and Iceland. His current interests are in signal processing. He published about 350 technical papers, more than 120 of them in the leading journals, mainly the IEEE editions. He received the highest state award of Montenegro in 1997 for scientific achievements. He was a member the IEEE Signal Processing Society's Technical Committee on Theory and Methods, an associate editor of the IEEE Transactions on Image Processing, and an associate editor of the IEEE Signal Processing Letters. He is an associate editor of the IEEE Transactions on Signal Processing. He has been a member of the National Academy of Science and Arts of Montenegro (CANU) since 1996 and a member of the European Academy of Sciences and Arts. He is a Fellow of the IEEE for contributions to time-frequency signal analysis.



Miloš Dakovic was born in 1970 in Nikšić, Montenegro. He received a B.S. in 1996, an M.S. in 2001, and a Ph.D. in 2005, all in electrical engineering from the University of Montenegro. He is an Associate Professor at the University of Montenegro. His research interests are in signal processing, time-frequency signal analysis, and radar signal processing. He is a member of the Time-Frequency Signal Analysis Group (www.tfsa.ac.me) at the University of Montenegro, where he is involved in several research projects.

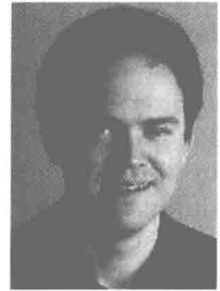


Thayananthan Thayaparan earned a B.S. (Hons.) in physics at the University of Jaffna, Sri-Lanka, an M.S. in physics at the University of Oslo, Norway in 1991, and a Ph.D. in atmospheric physics at the University of Western Ontario, Canada in 1996. From 1996 to 1997, he was employed as a post-doctoral fellow at the University of Western Ontario. In 1997, he joined the Defence Research and Development Canada-Ottawa, Department of National Defence, Canada, as a defense scientist. His research interests include advanced radar signal and image processing methodologies and techniques against SAR/ISAR and HFSWR problems, such as detection, classification, recognition, and identification. His current research includes synthetic aperture radar imaging algorithms, time-frequency analysis for radar imaging and signal analysis, radar micro-Doppler analysis, and noise radar technology. Thayaparan is a Fellow of the IET (Institute of Engineering & Technology). Currently, he is an Adjunct Professor at McMaster University. He received IET Premium Award for Signal Processing for the best paper published in 2009–2010. He is currently serving in the editorial board of IET Signal Processing. He has authored or coauthored over 174 publications in journals, proceedings, and internal distribution reports.



CHAPTER 4

Simon Godsill is Professor of Statistical Signal Processing in the Engineering Department at Cambridge University and a Professorial Fellow and tutor at Corpus Christi College, Cambridge. He coordinates an active research group in Signal Inference and its Applications within the Signal Processing and Communications Laboratory at Cambridge, specializing in Bayesian computational methodology, multiple object tracking, audio and music processing, and financial time series modeling. A particular methodological theme over recent years has been the development of novel techniques for optimal Bayesian filtering and smoothing, using Sequential Monte Carlo or Particle Filtering methods.



He has published extensively in journals, books, and international conference proceedings. He was technical chair of the IEEE NSSPW workshop in 2006 on sequential and nonlinear filtering methods, was Technical Chair for Fusion 2010 in Edinburgh, and has been on the conference panel for numerous other conferences workshops. He has served as Associate Editor for IEEE Tr. Signal Processing and the journal Bayesian Analysis. He was Theme Leader in Tracking and Reasoning over Time for the UK's Data and Information Fusion Defence Technology Centre (DIF-DTC) and Principal Investigator on grants funded by the EU, EPSRC, QinetiQ, General Dynamics, MOD, Microsoft UK, Citibank, and Mastercard. In 2009–2010 he was co-organizer of an 18-month research program in Sequential Monte Carlo Methods at the SAMSI Institute in North Carolina, and will coorganize an Isaac Newton Institute Programme on Sequential Monte Carlo in 2014. He is a Director of CEDAR Audio Ltd. (which has received a technical Oscar for its audio processing work), and Input Dynamics Ltd., both companies which utilize his research work in the audio area.

CHAPTER 5

Pramod K. Varshney (S'72–M'77–SM'82–F'97) was born in Allahabad, India, on July 1, 1952. He received the B.S. degree in electrical engineering and computer science (with highest honors), and the M.S. and Ph.D. degrees in electrical engineering from the University of Illinois at Urbana-Champaign in 1972, 1974, and 1976 respectively.



From 1972 to 1976, he held teaching and research assistantships at the University of Illinois. Since 1976, he has been with Syracuse University, Syracuse, NY, where he is currently a Distinguished Professor of Electrical Engineering and Computer Science and the Director of CASE: Center for Advanced Systems and Engineering. He served as the Associate Chair of the department from 1993 to 1996. He is also an Adjunct Professor of Radiology at Upstate Medical University, Syracuse. His current research interests are in distributed sensor networks and data fusion, detection and estimation theory, wireless communications, image processing, radar signal processing, and remote sensing. He has published extensively. He is the author of *Distributed Detection and Data Fusion* (New York: Springer-Verlag, 1997). He has served as a consultant to several major companies.

He was a James Scholar, a Bronze Tablet Senior, and a Fellow while with the University of Illinois. He is a member of Tau Beta Pi and is the recipient of the 1981 ASEE Dow Outstanding Young Faculty Award. He was elected to the grade of Fellow of the IEEE in 1997 for his

contributions in the area of distributed detection and data fusion. He was the Guest Editor of the Special Issue on Data Fusion of the Proceedings of the IEEE, January 1997. In 2000, he received the Third Millennium Medal from the IEEE and Chancellor's Citation for exceptional academic achievement at Syracuse University. He is the recipient of the IEEE 2012 Judith A. Resnik Award. He serves as a Distinguished Lecturer for the IEEE Aerospace and Electronic Systems (AES) Society. He is on the Editorial Board of the Journal on Advances in Information Fusion. He was the President of International Society of Information Fusion during 2001.

Engin Masazade (S'03–M'10) got his B.S. degree from Electronics and Communications Engineering Department from Istanbul Technical University in 2003. He then obtained his M.S. and Ph.D. degrees from Sabanci University, Electronics Engineering Program, Istanbul, Turkey in 2006 and 2010 respectively. He is currently an Assistant Professor with the Department of Electrical and Electronics Engineering, Yeditepe University, Istanbul, Turkey. Before joining Yeditepe University, he was a Postdoctoral Research Associate with the Department of Electrical Engineering and Computer Science, Syracuse University, Syracuse, NY, USA. His research interests include distributed detection, localization, and tracking for wireless sensor networks, dynamic resource management in sensor/communication networks.



CHAPTER 6

Venugopal V. Veeravalli (M'92–SM'98–F'06) received the B.Tech. degree (Silver Medal Honors) from the Indian Institute of Technology, Bombay, in 1985, the M.S. degree from Carnegie Mellon University, Pittsburgh, PA, in 1987, and the Ph.D. degree from the University of Illinois at Urbana-Champaign, in 1992, all in electrical engineering.

He joined the University of Illinois at Urbana-Champaign in 2000, where he is currently a Professor in the Department of Electrical and Computer Engineering and the Coordinated Science Laboratory. He served as a Program Director for communications research at the US. National Science Foundation in Arlington, VA from 2003 to 2005. He has previously held academic positions at Harvard University, Rice University, and Cornell University, and has been on sabbatical at MIT, IISc Bangalore, and Qualcomm, Inc. His research interests include wireless communications, distributed sensor systems and networks, detection and estimation theory, and information theory.

He was a Distinguished Lecturer for the IEEE Signal Processing Society during 2010–2011. He has been on the Board of Governors of the IEEE Information Theory Society. He has been an Associate Editor for Detection and Estimation for the IEEE Transactions on Information Theory and for the IEEE Transactions on Wireless Communications. Among the awards he has received for research and teaching are the IEEE Browder J. Thompson Best Paper Award, the National Science Foundation CAREER Award, and the Presidential Early Career Award for Scientists and Engineers (PECASE).

