Foundations and Trends in Localization Technologies—Part I

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I. INTRODUCTION

The advent of new wireless technologies in recent years has created a tremendous increase in the demand for wireless connectivity. The estimated number of mobile device connections exceeds eight billion globally, more than the population of the world, and the growth trend is rapidly increasing as the developing world penetration rate is still in its infancy. With the Internet-of-Things (IoT), it is expected that the total number of connections will reach over fifty billion in the next few years. In conjunction with wireless connectivity technology, the need for location awareness is paramount.

This two-part special issue covers relevant aspects of network localization and navigation: theoretical foundations, localization technologies, positioning algorithms, and network operation.

Real-time location awareness is ancillary to fifth generation (5G), Wi-Fi, and IoT networks, fostering a wide range of emerging applications such as smart cities, crowd sensing, environmental monitoring, big data analysis, and autonomous driving. The coming years will see the emergence of location awareness with submeter accuracy using minimal infrastructure even in challenging environments. The diverse set of applications involving connected devices hinge on mobility, and therefore localization of these devices is of fundamental importance. While outdoor positioning systems such as global navigation satellite systems (GNSS) have seen tremendous success, they do not offer adequate localization accuracy for certain scenarios. Particularly difficult scenarios include indoors, urban canyons, and other GNSS-challenged environments.

Network localization and navigation (NLN), a new paradigm for location awareness, enables a variety of new applications that rely on position information of mobile objects. Some IoT applications will require real-time localization with submeter accuracy in GNSS-challenged environments. Increased precision capability will lead to new applications requiring high-accuracy location awareness. For example, asset tracking may need to resolve objects placed centimeters apart in a manufacturing environment, while flying drones may need to navigate and avoid collisions in dense airspace.

In difficult propagation environments with uncontrolled infrastructures, the problem of pervasive indoor localization still remains largely unsolved. Furthermore, emerging outdoor applications will rely on more stringent localization accuracy and capability than

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those provided by GNSS. These challenges have stimulated research activities in the field. This special issue covers the foundations and trends of localization and navigation technologies with contributions from both academia and industry worldwide.

II. OVERVIEW OF THE SPECIAL ISSUE

This special issue covers the relevant aspects of NLN: theoretical foundations, localization technologies, positioning algorithms, and network operation. The special issue consists of nine papers: "A Theoretical Foundation of Network Localization and Navigation;" "Received-Signal-Strength-Based Localization in Wireless Sensor Networks;" "A Survey on the Impact of Multipath on Wideband Time-of-arrival-based Localization;" "Distributed Localization: A Linear Theory;" "Collaborative Sensor Network Localization: Algorithms and Practical Issues;" "Network Operation Strategies for Efficient Localization and Navigation;" "Sensor Radar for Object Tracking;" "Localization via Visible Light Systems;" and "Acoustic Local Positioning with Encoded Emission Beacons." These papers present different aspects of location-aware networks including foundations for network design and analysis, new techniques overcoming the limitations of traditional approaches, different types of wireless localization networks, and advanced data fusion techniques. The special issue is divided into two parts, one published this month and the other in the following month. A brief description of the papers published this month is as follows.

The paper "Sensor Radar for Object Tracking" by Chiani *et al.* addresses the problem of detecting, localizing, and tracking noncollaborative objects that are not equipped with dedicated tags by scanning the region of interest using wideband radio signals. This paper presents a sensor network for radio imaging (sensor radar) along with the signal processing steps necessary to achieve high-accuracy object tracking in harsh propagation environments. The described sensor radar is based on ultra-wideband impulse radio technology, entailing the transmission of very short duration pulses. Experimental results in indoor environments confirm the potential of sensor radars in IoT applications.

The paper "Acoustic Local Positioning with Encoded Emission Beacons" by Ureña *et al.* investigates acoustic local positioning systems, presenting a review of the different challenges that must be addressed to achieve suitable performance. Both waveform design and signal processing are important aspects to consider in order to cope with multipath propagation, multiple-access interference, the near–far effect, and Doppler shifts. On the other hand, the deployment of beacons, calibration and positioning algorithms, and fusion of information determine the localization capability. This work also includes the description of a system that was implemented in a large area and tested for mobile robot navigation.

The paper "Localization Via Visible Light Systems" by Gezici *et al.* makes use of visible light for localization as an alternative to radio-frequency waves. This paper provides a survey of localization techniques for visible light systems, investigates a cooperative architecture using visible light communications, and presents a low-complexity iterative localization algorithm. The optimal strategies are also presented for power allocation among LED transmitters to maximize the localization accuracy subject to power and illumination constraints.

The paper "Collaborative Sensor Network Localization: Algorithms and Practical Issues" by Buehrer *et al.* surveys the state of the art in collaborative localization with an eye toward 5G cellular and IoT applications. In particular, it discusses algorithms and challenges associated with collaborative localization for range-based and range-angle-based techniques. ■

ABOUT THE GUEST EDITORS

Moe Z. Win (Fellow, IEEE) is a Professor at the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA and the founding director of the Wireless Information and Network Sciences Laboratory. Prior to joining MIT, he was with AT&T Research Laboratories and NASA Jet Propulsion Laboratory.

His research encompasses fundamental theories, algorithm design, and network experimentation for a broad range of real-world problems. His current research topics include network localization and navigation, network interference exploitation, and quantum information science. He has served the IEEE Communications Society as an elected Member-at-Large on the Board of Governors, as elected Chair of the Radio Communications Committee, and as an IEEE Distinguished Lecturer. Over the last two decades, he held various editorial positions for IEEE journals and organized numerous international conferences. Currently, he is serving on the SIAM Diversity Advisory Committee.

Dr. Win is an elected Fellow of the American Association for the Advancement of Science (AAAS) and the Institution of Engineering and Technology (IET). He was honored with two IEEE Technical Field Awards: the IEEE Kiyo Tomiyasu Award (2011) and the IEEE Eric E. Sumner Award (2006, jointly with R. A. Scholtz). Together with students and colleagues, his papers have received numerous awards. Other recognitions include the IEEE Communications Society Edwin H. Armstrong Achievement Award (2016), the International Prize for Communications Cristoforo Colombo (2013), the Copernicus Fellowship (2011) and the *Laurea Honoris Causa* (2008) from the Università degli Studi di Ferrara, and the U.S. Presidential Early Career Award for Scientists and Engineers (2004). He is an ISI Highly Cited Researcher.

R. Michael Buehrer (Fellow, IEEE) is a Professor in the Electrical and Computer Engineering Department, Virginia Tech, Blacksburg, VA, USA. He is the director of *Wireless @ Virginia Tech*, a comprehensive research group focusing on wireless communications, navigation, and radar. From 1996 to 2001, he was a Distinguished Member of Technical Staff at Bell Laboratories. During 2009, he was a Visiting Researcher at the Laboratory for Telecommunication Sciences (LTS), a federal research lab which

focuses on telecommunication challenges for national defense. While at LTS, his research focus was in the area of cognitive radio with a particular emphasis on statistical learning techniques. His current research interests include geolocation, cognitive radio, and spread spectrum.

Dr. Buehrer has authored or coauthored over 70 journal and approximately 200 conference papers and holds 12 patents in the area of wireless communications. In 2010, he was co-recipient of the Fred W. Ellersick MILCOM Award for the best paper in the unclassified technical program. Currently, he is an Associate Editor for the IEEE Transactions on Wireless Communications. He was formerly an Associate Editor for the IEEE Transactions on Communications, the IEEE Transactions on Vehicular Technologies, the IEEE Transactions on Wireless Communications, the IEEE Transactions on Signal Processing, and the IEEE Transactions on Education.

George Chrisikos (Fellow, IEEE) received the Ph.D. degree in electrical engineering from the University of Southern California (USC), Los Angeles, CA, USA, under the USC Dean's Doctoral Merit Fellowship. He received the M.S. and B.S. degrees in electrical engineering as a Presidential Scholar. He graduated *summa cum laude* with distinction and was the Valedictorian of his class.

He is responsible for advanced technology development at Qualcomm Inc., and has been working in the research, design, and development of communication systems and algorithms for wireless and mobile applications. Previously, he was the Engineering Director and Systems Product-Line Manager at Applied Wave Research (AWR) Inc., where he was responsible for architecting and leading the development of a design automation technology product that gained widespread adoption by the wireless communication industry worldwide. Earlier, he was responsible for the design of CDMA and WLAN semiconductor chipsets for startup companies, and advanced satellite systems for commercial and government sectors at The Aerospace Corporation.

His work has resulted in over 115 granted and pending U.S. and international patents. He has been an invited speaker and delivered keynotes at various corporations and conferences worldwide, published numerous papers in international journals and conferences, and contributed to textbooks. He has received a number of accolades, including the 2014 IEEE Kiyo Tomiyasu Award and the Aerospace Corporate Achievement Award. He serves on the Advisory Board of the USC Department of Electrical Engineering, as Editor of the IEEE Signal Processing Magazine, and on the Advisory Board of IEEE Communications Letters. He was named a Guest Editor of IEEE Proceedings and Journals, and served on the executive committees of IEEE conferences.

Andrea Conti (Senior Member, IEEE) received the Laurea (*summa cum laude*) degree in telecommunications engineering and the Ph.D. degree in electronic engineering and computer science from the University of Bologna, Bologna, Italy, in 1997 and 2001, respectively.

He is currently an Associate Professor at the University of Ferrara, Ferrara, Italy. Prior to joining the University of Ferrara, he was with the CNIT and with the IEIIT-CNR. In summer 2001, he was with the Wireless Systems Research Department, AT&T Research Laboratories. Since 2003, he has been a frequent visitor with the Wireless Information and Network Sciences Laboratory, Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, where he currently holds the Research Affiliate appointment. His research interests are in theory and experimentation of wireless systems and networks including network localization, distributed sensing, adaptive diversity communications, and network secrecy.

Dr. Conti was recipient of the HTE Puskás Tivadar Medal and corecipient of the IEEE Communications Society's Stephen O. Rice Prize in the Field of Communications Theory and of the IEEE Communications Society's Fred W. Ellersick Prize. He was an Editor for IEEE journals, as well as chaired international conferences. He has been Elected Chair of the IEEE Communications Society's Radio Communications Technical Committee. He is a Co-Founder and Elected Secretary of the IEEE Quantum Communications & Information Technology Emerging Technical Subcommittee. He is an elected Fellow of the Institution of Engineering and Technology (IET) and has been selected as an IEEE Distinguished Lecturer.

H. Vincent Poor (Fellow, IEEE) received the Ph.D. degree in electrical engineering and computer science from Princeton University, Princeton, NJ, USA, in 1977.

From 1977 until 1990, he was on the faculty of the University of Illinois at Urbana-Champaign, Urbana, IL, USA. Since 1990, he has been on the faculty at Princeton University, where he is currently the Michael Henry Strater University Professor of Electrical Engineering. During 2006–2016, he served as Dean of Princeton's School of Engineering and Applied Science. He has also held visiting appointments at several other universities, including most recently at Berkeley and Cambridge. His research interests are in the areas of information theory and signal processing, and their applications in wireless networks, energy systems, and related fields. Among his publications in these areas is the recent book *Information Theoretic Security and Privacy of Information Systems* (Cambridge, U.K.: Cambridge Univ. Press, 2017).

Dr. Poor is a member of the National Academy of Engineering and the National Academy of Sciences, and is a foreign member of the Chinese Academy of Sciences, the Royal Society, and other national and international academies. Recent recognition of his work includes the 2017 IEEE Alexander Graham Bell Medal, Honorary Professorships at Peking University and Tsinghua University, both conferred in 2017, and a D.Sc. *honoris causa* from Syracuse University also awarded in 2017.