Jeffrey R. Foerster

Xavier Costa-Pérez

R Venkatesha Prasad

Communications for IoT: Connectivity and Networking

The Internet of Things (IoT) is revolutionizing many industries by enabling machines to directly work with each other without human intervention, and communication and networking technologies are fundamental to enabling it. IoT systems are also creating a significant amount of new data which can now be processed to analyze and learn from using novel machine-learning techniques. However, the requirements for communications can vary significantly depending on the target applications, and they can range from ultra-low power for enabling a vast deployment of sensors with multi-year battery life to ultra-reliable low latency communications (URLLC) for smart factories and remote robot control. 5G, as an example, is expected to deliver a number of enhancements to support massive IoT deployments as well as URLLC capabilities for new verticals such as Smart Cities, Industrial IoT, E-Health, Public Safety, and Autonomous Vehicles (V2V, V2X).

The purpose of this Special Issue is to provide researchers and practitioners working on Connectivity and Networking technologies for IoT systems a means to share experiences and disseminate successful applications of IoT technologies and identify recent trends and opportunities poised to revolutionize the IoT industry. As such, we have selected a variety of papers which cover a broad range of topics including different radio technologies (from Bluetooth Low Energy to Wi-Fi to 5G) and applications (from Smart Cities to Vehicular Networks to Aerial Networks to Massive Wireless Sensor Networks). In addition, it is becoming more critical today to look at the overall systems challenges for deploying IoT networks, which includes how to best leverage computing resources at the edge or in the cloud, dealing with ultra-low power consumption requirements of many sensors, and new low-power, robust security requirements.

The first three articles in this Special Issue will start with a Smart Cities and Wireless Sensor Networks focus where massive scale and low power are critical. Then, the next two articles address enhanced vehicle communications and new applications enabled by low latency (URLLC) communications. The next two articles introduce opportunities for intelligent integration of Edge computing into the overall system and network design. Finally, the last article introduces a non-communications application using wireless RF fingerprinting for securing IoT devices. A short introduction to each article follows.

The first article, "Internet of MIMO Things: UAV-assisted Wireless-powered Networks for Future Smart Cities," presents a holistic view of a Smart City which tries to balance the ultra-low power energy consumption needs for sensors within a city while ensuring connectivity. The authors also propose a novel use of unmanned aerial vehicles (UAVs) to assist with network connectivity as well as providing RF energy for the sensors to harvest. Although the vision is compelling, a lot of research remains to be done to prove this out in realistic systems.

The second article, "BLE Beacons in the Smart City: Applications, Challenges, and Research Opportunities," deals with a BLE beacons based low cost and energy-efficient IoT solution for location applications. BLE based localization is an important field in itself. The selection of the proper beacon and the optimal configuration of the beacons are important factors for successful application deployments. The authors also provide a brief look at security and privacy. Low cost and low power BLE wireless transmitters make it a popular infrastructure for localization in indoors. The authors also provide information regarding the applications that can benefit and the challenges they pose.

The third article, "Transmit Power Reduction ≠ Proportional Power Savings," discusses the feasibility of transmit power control, which is an important design problem for applications of large-scale wireless sensor networks. The corresponding design issues and problem characteristics are obtained from an extensive set of commercial radios used in WSN scenarios. Based on their results the authors claim that reducing transmit power at the low-power RF transceivers does not lead to proportional energy savings.

The fourth article, "NR Sidelink Design Overview for

Advanced V2X Service," presents insights on the current 3GPP Release 16 NR SL design for NR V2X, the network architecture, security and the protocol enhancement, and discusses a QoS model for NR SL and connection establishment for both groupcast and unicast V2X communication. Further improvements for NR V2X are expected in Release 17 which will consider among others the mm-Wave physical layer design, support for multiple sidelink carriers, and MIMO.

The fifth article, "TIXT: An Extensible Testbed for Tactile Internet Communication," presents an architecture and a testbed for a Tactile Internet to support new emerging applications including telesurgery, human controlled robots, and virtual shopping. A new frontier for wireless is enabled by URLLC links which has the potential of creating new applications and usages which are not capable today. One area that is being transformed by this capability is the Industrial 4.0 market, which envisions flexible manufacturing capabilities and the ability to virtualize control functions at the edge of the network enabled by URLLC wireless links. The authors of this article make a strong call to action for both academia and industry to come together to help accelerate this technology development and deployment.

The sixth article, "Toward Developing Fog Decision Making on Transmission Rate of Various IoT Devices Based on Reinforcement Learning," presents a decision-making problem of a fog node by using a reinforcement learning approach in a smart city as an example of a smart environment and then develop a Q-learning algorithm to achieve efficient decisions for the IoT's transmission rates to the fog node. In the future, several fog nodes having full cooperation might be considered to handle multiple smart city zones simultaneously.

The seventh article, "FemtoClouds Beyond The Edge: The Overlooked Data Centers," deals with a new computing hierarchy that highlights new computational opportunities, FemtoClouds, beyond Fog/Edge architectures. The authors present a thorough analysis of the potential performance of FemtoClouds vis-à-vis traditional data centers. The article highlights the cost reductions and the opportunity that FemtoClouds present as an entity that is complementary to the available compute resources. The authors outline challenges to realize the potential FemtoClouds.

The eighth and final article, "Deep Learning for RF Fingerprinting: A Massive Experimental Study," presents a very different application of wireless to enable a low cost and low power solution for securing IoT devices. The key idea is to leverage the unique characteristics of individual radios to provide an 'RF fingerprint' to uniquely identify devices. The article includes data from approximately 10,000 devices covering different radios, and the authors propose a Deep CNN architecture for classification of the devices which they are making publicly available for other researchers to use. The promise of using RF fingerprinting for low complexity and highly secure links is compelling for IoT devices, but how this can scale to 100,000+ devices remains a challenge.

To conclude, we'd like to thank the authors, numerous reviewers, and Editor-in-Chief for helping to put together this Special Issue. We hope the breadth and diversity of the articles provides inspiration of what is possible with new IoT systems and connectivity solutions coming in the future.

Biographies

Jeff Foerster (jeffrey.r.foerster@intel.com) [F] joined Intel in August 2000 and is currently Senior Director of Emerging Connectivity Solutions in the Wireless Communications Research Lab at Intel Labs. He currently leads a team focused on next generation Wi-Fi, emerging IoT systems, in-home networking, and future end-to-end media solutions which co-optimize compression, analytics, and communications. His team has made significant contributions to the Wi-Fi 6 (802.11ax) standard, led the development of the Wake-up Radio standardized in 802.11ba, and is currently developing several technologies which are targeting the next generation Wi-Fi standard (802.11be). His team is also leading the development of a new wireless time sensitive network (WTSN) solution for Wi-Fi as well as cellular/5G to support Industrial 4.0 applications using wireless connectivity. Finally, his team investigates new and emerging applications for wireless, including wireless sensing and applications of Artificial Intelligence (AI) for wireless. He is a member of the Federal Communications Commission (FCC) Technical Advisory Committee, has published over 30 papers in journals, magazines, and conferences, and has been an invited panelist and presenter at several conferences. He received his B.S., M.S., and Ph.D. degrees from the University of California, San Diego.

Xavier Costa-Pérez (xavier.costa@neclab.eu) is Head of 5G Networks R&D and Deputy General Manager of the Security and Networking Research Division at NEC Laboratories Europe. His team contributes to product roadmap evolution as well as to European Commission H2020 projects and received several awards for successful technology transfers. In addition, his team contributes to related standardization bodies: 3GPP, ETSI NFV, ETSI MEC, IETF and OPNFV. He has served on the Program Committees of several conferences, including IEEE Greencom, WCNC, and INFOCOM, published at top research venues and holds several patents. He received both his M.Sc. and Ph.D. degrees in telecommunications from the Polytechnic University of Catalonia (UPC) in Barcelona and was the recipient of a national award for his Ph.D. thesis.

R Venkatesha Prasad (R.R.VenkateshaPrasad@tudelft.nl) [SM] received a Ph.D. from the Indian Institute of Science, Bangalore, India in 2003. Currently, he is an associate professor with the Embedded Networked Systems group at Delft University of Technology (TU Delft). He has supervised 18 Ph.D. students and 50 M.Sc. students. He has (co-) authored more than 250 publications in peer-reviewed international transactions/journals and conferences in the areas of Tactile Internet, Internet of Things (IoT), cyber physical systems (CPS), energy-harvesting, 60 GHz mmWave networks, smart-energy systems, personal networks, cognitive radios and voice over Internet Protocol (VoIP). He has been successful in acquiring and executing several European and Dutch national projects. He is the mentor for the IEEE Tactile Internet standardization group and previously the vice-chair. He is also leading many IEEE activities through positions on standards boards. He is on the editorial board of many international transactions and magazines and is a regular TPC member for many prestigious journals and conferences. Immediately after his Ph.D. he was also working at a startup called Esqube Communications in Bangalore realizing the contributions of his thesis. He is a senior member of ACM. He is a Fellow of IETE.