

Beyond Testbeds: Real-World IoT Deployments

Florian Michahelles
Siemens Corporation

Fahim Kawsar
Nokia Bell Labs
TU Delft

Simon Mayer
University of St. Gallen
ETH Zurich

Luca Mottola
Politecnico di Milano and
RI.Se SICS Sweden AB

For a long time, the Internet of Things initiative was driven by academics—developing embedded hardware, sensing algorithms, network protocols, software frameworks, applications, business scenarios, and interaction paradigms. Only recently industrial stakeholders realized the unparalleled potential of these technologies, instigating a paradigm shift that we refer to as the *fourth industrial revolution*. However, as this shift starts entering the mainstream and disrupting a multitude of business dynamics, it also uncovered myriads of challenges—some are technical, some are political, and some are ethical.

In this special issue, together with our guest authors, we focus our attention on some of the daunting system development challenges in bringing bleeding-edge Internet of Things (IoTs) technologies to the real world. Each of the five articles featured in this issue tackles unique challenges associated with the

deployment of real-world IoT systems. Their reported findings provide valuable lessons for building practical, efficient, and reliable IoT systems in the wild. However, before introducing these articles, we take a historical perspective and revisit some of the numerous research efforts that led us to the present-day IoT. We hope this chronological summary will help readers acknowledge the rich science underpinning modern-day IoT technology.

The IoTs started as an academic project on RFID technology and supply chain management. In 1999, the Auto-ID Labs, a global research alliance of seven universities, developed a number-based identifier for RFID tags attached to goods in supply-chain logistics. These identifiers served as a reference to store recorded movements of goods in a supply chain in a global database. In addition to RFID-based location updates, real-time information about the goods themselves, such as the environmental conditions they were exposed to during transportation, gained interest and required mechanisms to harvest and to handle these data: the *Internet of Things* was born. Researchers from the Web community realized that shrinking size and cost of hardware would allow implementing Web servers on embedded hardware. Thus, they started experimenting with embedded Web servers on goods and things and went far beyond the limited capabilities of passive RFID tags: suddenly, accessing data from a mobile sensor node became a simple Web request, re-using the Web's http(s) protocol. Additionally, a broad community of makers started building upon open-source hardware, e.g., Arduino

boards and triggered an avalanche of demonstrators, prototypes, and applications in emerging fields such as urban sensing, smart homes, and remote monitoring. Meanwhile, consumers started to quietly embrace the IoTs, first in the form of remotely controlling devices over the Internet for home automation, security, and connected car services. Other typical applications include quantifying physical activities using personal wearables, patient surveillance, and assisted living solutions.

As conferences on the IoTs have started spreading and first business startups matured, governments (e.g., US, Germany, Japan, and Finland) and trade organizations (e.g., OECD and WEF) recognized the IoTs as an opportunity for economic growth. Research funding programs were published, university positions created, and governments released national programs with the aim of upgrading established industries with data capture and analytics services. The transformation of manufacturing and other industries was kick-started with the creation of connected environments of data, people, processes, services, and IoT-enabled industrial assets that are expected to foster industrial innovation.

However, although the IoTs is upon us, we still witness a gap between the existing body of research in these subjects and applications that are deployed in the field. To this end, in this special issue, we turn our attention onto five real-world IoT deployment case studies that highlight a set of challenges, and credible approaches in building IoT systems in the wild. The very first article “Moving Beyond Testbeds? Lessons (We) Learned About Connectivity” addresses the reliable and resilient connectivity challenge in which Brun-Laguna *et al.* investigate to what extent testbeds can help determine the performance of a protocol in a real-world environment. The authors have gathered 11 datasets and derive a 5-point checklist to evaluate the feasibility of a planned testbed deployment. The article “Supporting the IoT Business Value Through Platformization of Pilots” looks at the reusability challenge where Martinez *et al.* argue that pilots would be more effective for experimentation in real environments and demonstrate an effective platform-based approach to develop IoT pilots with a lower barrier of entry and faster turnaround opportunity. In “The BIG IoT API: Semantically Enabling Interoperability in IoT Ecosystems,” Broering *et al.* address the challenge of interoperability by describing an API for the IoT with self-description and semantic annotations. They illustrate the viability of their approach by various examples in the mobility domain. In the last two articles, we shift our focus onto IoT applications. In the article “Enabling Sustainability and Energy Awareness in Schools Based on IoT and Real-World Data,” Mylonas *et al.* discuss how the IoT can be integrated into education in schools and provide hands-on experience based on real data with an objective to increase awareness on sustainability and behavioral change toward energy savings. Finally, in the last article “Pervasive Agriculture: IoT Enabled Greenhouse for Plant Growth Control,” Somov *et al.* describe an IoT deployment in a greenhouse illustrating various system aspects including wireless sensing, cloud computing, and artificial intelligence. The work demonstrates how AI-assisted IoT solutions can help informed decision-making in an agricultural facility.

We hope these five selected articles span a fruitful space for further investigations on real-world deployments of the IoT and trigger discussions of new thoughts and ideas for future research.

ABOUT THE GUEST EDITORS

Florian Michahelles heads the Artificial & Human Intelligence Research Group, Siemens Corporation, Berkeley, CA, USA. Contact him at florian.michahelles@siemens.com.

Fahim Kawsar leads pervasive systems research at Nokia Bell Labs, Cambridge, U.K., and holds a Design United Professorship at TU Delft. Contact him at fahim.kawsar@nokia-bell-labs.com.

Simon Mayer is a Professor of computer science with the University of St. Gallen, St. Gallen, Switzerland, where he heads the Chair for Interaction- and Communication-Based Systems. Contact him at simon.mayer@unisg.ch.

Luca Mottola is an Associate Professor with Politecnico di Milano and a Senior Researcher with RI.Se SICS Sweden AB. Contact him at luca.mottola@polimi.it.