Grand Challenges in IoT and Sensor Networks

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INTRODUCTION

The exponential growth in mobile traffic seen in the last couple of years, mainly due to the vast amount of wireless devices, such as smart phones and the Internet of Things (IoT), has resulted in the wireless network industry producing and collecting an unprecedented amount of data (Bi et al., 2015). According to the International Data Corporation, by 2025 the number of devices connected to the Internet will be around 42 billion, and a total of 80 zettabytes of data will be generated in the same year. There is no doubt that we are ushering in a new era, since IoT and Artificial Intelligence (AI) are deepening their integration in society and the roll-out of 5G technology will spur new innovations across all industries.

The innovation in the IoT ecosystem is bridging the gap between the real and digital world; we are creating a hyper-connected society where devices are no longer used only to exchange data but are becoming more and more intelligent and context aware. The advancements in sensing, data processing, and cloud and communication technology has enabled the systems to interact with the environment and optimize processes via learning through interactions. This will lead to the creation of smart spaces and self-aware interconnected "things" for health, mobility, digital society, food, energy, and environmental applications (Qiu et al., 2018).

In future, the IoT development process will most likely evolve from vertical to polymorphic applications, supporting both personal and industry users (Chen et al., 2014). To provide a pervasive, unified, and seamless experience to the end users, there are many challenges that need to be addressed, including: technology standards, interoperable module components supporting heterogeneous applications and requirements at several layers, the designing of low-cost IoT terminals with low-active power, and solutions guaranteeing end-to-end privacy and security (Chen et al., 2014). Several grand challenges inherent to IoT systems are outlined in the following sections.

GRAND CHALLENGES IN IoT

Scalability

Given the huge number of devices requiring simultaneous connectivity, scalability in IoT systems has become a concern. In IoT, there are mainly two types of scalability issues: vertical scalability, which refers to the addition or removal of computing resources of an IoT node; and horizontal scalability, which refers to the addition or removal of an IoT node. Given its importance, IoT scalability has been extensively addressed in the literature, with the proposal of cloud computing (Cabré et al., 2017; Cheng et al., 2017; Shirer and MacGillivray, 2020) or cloud-based architectures (Xu and Helal, 2015). However, despite these efforts, challenges still remain, such as IoT nodes needing to provide an increased number of services, such as functional scalability, access control, data storage, fault tolerance, and privacy and security, to name a few.

Security and Privacy

The lack of privacy standards and end-to-end security solutions has been an ongoing concern for conventional IoT deployment, and wireless IoT faces more challenges in terms of these aspects (Shafagh et al., 2017). Several technologies are aiming to solve privacy and security issues from both a hardware and software perspective. For hardware, RFID and newer releases of 5G and other local network protocol are key to tackling security issues at a hardware level. In terms of software, Key Management System (KMS) with a zero-trust network feature and blockchain are rapidly addressing the privacy and trust threats with reinforced security features (Sicari et al., 2015; Sun et al., 2019; Xu et al., 2020). With the help of newer communication protocols, KMS, and blockchain, the grand challenge of IoT devices is the interdependency of security, privacy, and trust for IoT ecosystems. The challenge shall always be considered as a holistic goal for optimal integrity and performance.

Self-Organization

There is an ongoing paradigm shift from Internet-of-Things to Internet-of-Everything due to the proliferation of IoT nodes which demands new approaches to autonomic management to make the network proactive rather than reactive. The main idea behind self-organization in IoT systems is to actively respond to the changing environments in an automatic and coordinated fashion through the use of one or more control loops that reconfigures the system behavior on-demand to keep it within desired bounds (Kephart, 2005). These systems proactively self-manage themselves by reacting to the changing environment using advanced algorithms in conjunction with high-level human-defined goals and policies. These self-organization capabilities are important to ensure the robustness and survival of the future dense IoT network and therefore have attracted an intense research interest (Milner et al., 2012; Ding et al., 2013; Qiu et al., 2017; Pang et al., 2020). However, there are many open challenges in this space and some notable research directions for the future include dealing with the heterogenous interoperability of the system, designing of optimal self-organizing protocols and routing strategies for large-scale distributed heterogenous IoT networks, and cross-platform behavior optimization.

Energy Efficiency

Researchers have used several approaches to address the problem of designing energy efficient IoT networks:

(a) developing energy-efficient routing protocols to reduce the number of hops (Machado et al., 2013), optimizing communication link status (Khan et al., 2016), adopting wake-sleep strategies based on network traffic (Xia and Li, 2013), and data reduction via controlling the network topology.

(b) incorporating renewable energy devices in the network alongside adopting load-balancing strategies (Li et al., 2015; Han et al., 2016).

(c) exploiting wireless charging mechanisms to solve the fundamental issue of power management, especially for large-scale heterogenous IoT networks (Madhja et al., 2016). However, from a hardware perspective there is a significant need to develop net-zero-energy sensor nodes, since the current trend is to pack an energy constrained node with more and more functionality, which could lead to a possible compromise between fidelity and power efficiency.

GRAND CHALLENGES IN SENSING

Sensing constitutes a vital part within IoT and wireless sensor networks. In a typical setting, sensed data is sent over the IoT network for post-analysis and inference to get insights. For the post-processing inference to be valuable, the accuracy of sensors is fundamental. For this accord, ISO standard 5725:1994 separates accuracy into precision and trueness while emphasizing the integrity of a sensor (Suzuki et al., 2019). In contrast, RF sensing utilizes the channel state information for sensing and, due to its inherent EM nature, it utilizes machine learning for classifying sensed information and presents additional challenges, such as linearity, repeatability, resolution, hysteresis, temperature coefficients, stability, and calibration.

Addressing these challenges consequently improves the reliability of RF sensing, ultimately realizing a possible future for ambient RF sensing. Furthermore, RF sensing has the advantage of a tactile nature, making it feasible for use in numerous applications, easily deployable, and cost-effective. The subsequent advances in ML techniques and RF characterization are envisaged to make RF sensing an integral part of IoT networks. This is also evident from the recent developments in the THz band for sensing and communications. Currently, THz is potentially being used for sensing food and water security (Ren et al., 2019a,b), sensing the cornea of eyes (Ozheredov et al., 2018), freezing of gait detection in Parkinson's disease (Tahir et al., 2019), sensing for real time near field imaging (Hillger et al., 2018), detecting corneal tissue water content (Grundfest et al., 2019), etc. Nevertheless, for the true success of IoT, we envisage that a variety of sensing instruments will be part of the network and the above challenges would need to be effectively addressed.

VERTICALS OF IoT AND SENSOR NETWORKS

Road and Transportation

By using wireless sensor networks (WSM) on roads, timely signaling control, precise traffic prediction, and road environment monitoring can be realized with high reliability (Pascale et al., 2012; Ramson and Moni, 2017). However, there are also some challenges associated with the design of WSN-based transportation systems. From the power consumption aspect, various solutions have been proposed to achieve balance between cost and reliability (Qin et al., 2010), such as cooperative transmission with reduced power consumption (Bai et al., 2008) or redesigning the duty cycle of the nodes (Lai et al., 2007; Nan et al., 2008). From the latency requirement aspect, various grant-based and grant-free-based access techniques are discussed (Birk et al., 2009; Franceschinis et al., 2009; Qin et al., 2010; Losilla et al., 2011). However, given the scarce resources and heterogeneous and dynamic characteristics of WSN in transportation systems, an efficient resource allocation scheme

and network management are challenges to be dealt with. Additionally, WSNs may be used for safety related monitoring and control, thus posing very high requirements on both device and communication reliabilities.

Buildings

Future smart buildings (SB) will be prime examples of cyber-physical systems, where physical and virtual worlds connect and work together. SBs are the epitome of big data. However, there are several critical issues that hinders the adoption of this technology, such as security, user privacy, context-aware computing, and personal data stream management. To maintain the confidentiality and integrity of the SB data, various privacy-preserving encryption techniques have been proposed (Islam et al., 2012; Pérez et al., 2018). From a device perspective, there is a clear research trend of utilizing machine learning methods for anomaly detection and resolution in building management systems (Araya et al., 2016), however there is still a need to improve privacy enhancement technologies for user identity (Bandyopadhyay and Sen, 2011). Additionally, context-aware computing is an essential element of SB systems, however due to complex dependencies between humans and the apps, formalizing an accurate model is still a challenge for the current systems (Stankovic, 2014). Likewise, interconnecting multiple SB systems and processing large streams of heterogenous information are some of the open challenges that must be addressed through agreement on architectural and technological standards, as well as development of advanced and efficient algorithms.

Healthcare

It is evident that future healthcare systems will rely on an interplay of various technologies, including communication, sensing, cloud, and data analytics. From a communication perspective, short-range and long-range communication technologies are both needed to realize an end-to-end system. This leads to a co-existence issue between the two communication technologies, and therefore, SmartBAN or IEEE 802.15.6 has been proposed, which offers both in-body and off-body communication (Hämäläinen et al., 2015). However, the bottleneck is that the complaint devices are still not currently available in the market. On the other hand, the non-cellular and cellular low-power wide area network (LPWAN) technologies suffer from quality of service and high energy consumption issues, respectively (Alam et al., 2018). In terms of data analytics, designing of explainable AI algorithms is a real challenge and Complex Event Processing (CEP) domain is a promising research area to explore for designing future healthcare systems (Sandha et al., 2017). Lastly, data privacy is a key challenge for healthcare applications; sophisticated models of in-memory computation and processing and federated learning schemes are promising ways forward (Viceconti et al., 2015).

Supply Chain—Farm to Folks

A proactive supply chain, based on the IoT networking, has become increasingly essential for the growing population. An effective supply chain helps in attacking the problem well in time, along with reducing all potential threats and risks (Arora et al., 2020). Internet of things relying on sensors, radio frequency identification tags (RFID), and wireless communications can help in tracking and tracing products along the entire supply chain and in delivering the right product to the right place at the right time to the right person. Furthermore, movement and quality of the supply chain products can be monitored while streamlining the problematic association of goods. For IoT to complement the supply chain, it relies on good connectivity to be able to transmit their positions to GPS satellites or RFID receivers (Lee, 2020). It also relies on being installed and powered properly, demanding the use of trained personnel for handling, attaching, and removing. With a variety of sensors and devices, it is also crucial to choose the right device for the right job.

Education and Training

There exists a huge potential for education and training sectors to couple the collected information from IoT nodes with other data sources, including user mobility and data analytics, to enable new services and experiences (Abdelrahman et al., 2017). There are studies that capitalize on this collected information to understand user learning patterns, quantifying their online learning experience by measuring their concentration levels, measuring the impact of ease of accessibility of the learning content (Banica et al., 2017), and collecting IoT-based feedback. Likewise, the use of electronic devices was shown to be an effective pedagogical tool during a pilot study for students undertaking vocational training. However, there exists challenges in adopting IoT-based educational solutions, such as wireless coverage, high sensor costs, battery life, and crucially a lack of standard security and privacy measures. The adoption of IoT-based solutions for education is still very scarce, and there is room to further examine the factors that hinders the deployment of IoT solutions in the education sector (Al-Emran et al., 2020).

Data Collection Storage and Processing

As a massive number of sensors will be installed, data collection would mainly be concerned with the idea of how to implement it efficiently, where relative data compressing would be considered (Wu et al., 2014; Karim and Al-kahtani, 2016). To ensure the security of data collection, sensitive data needs to be protected by ciphering and leveraging the distributed system (Luo et al., 2018; Tao et al., 2019). Optimum energy transmission and path selection will also be considered to reduce the energy consumption (Orsino et al., 2016; Ang et al., 2018). Data storage, as the next step, is facing the same problems for energy reservation and data compressing, where some solutions are given through the improvement of data routing (Xu et al., 2015) and popular blockchain tech to secure data storage (Shafagh et al., 2017). As data processing might consider each corner of the whole IoT sensor network, the problems include, but are not limited to, in-network processing, data aggregation, and computing where relative signal processing techs are applied to solve the issues (Karim and Al-kahtani, 2016; Ahmed et al., 2017; Kim et al., 2017; Firoozi et al., 2018).

CONCLUSION AND OUTLOOK

New technologies and applications are surfacing every day; however, there still exists challenges and gaps that need to be addressed. In this editorial article, we have outlined a few important challenges in IoT and sensing technologies and addressed important issues, including scalability, self-organization, security, and energy efficiency that must be catered for when deploying this emerging technology for the betterment of our society. Additionally, advancement in sensing technologies will pave the way for effective IoT solutions and, as outlined in this article, will fuel innovation across various verticals including transport, healthcare, buildings, supply chains, education, and many aspects of our daily lives. The progress toward the standardization of architectures, cross-sector application designs, device interoperability, privacy and end-to-end security, and highly efficient multi-standard communication systems and sensors, along with innovative device charging mechanisms, will inevitably bridge the gap between the physical and digital world and create information societies and knowledge economies. The combination of tactile internet and ultra-responsive and ultra-reliable low-latency communication offered by 5G systems will add a new dimension to human-machine interaction and future IoT applications and will further push for the rise of fog and mobile edge computing architecture. There are many hyperconnected actors in this evolving ecosystem, whether that be machines, organizations, algorithms, or humans, and if we want the digital and physical world to go hand in hand, these relationships must be managed well through well-defined policies and regulations.

AUTHOR CONTRIBUTIONS

MI led the presented idea. MI, AZ, LZ, and QA contributed to the writing of the manuscript. AZ led the editing of the manuscript, and MI further provided the critical feedback and editing to help shape the manuscript. All authors contributed to the article and approved the submitted version.

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