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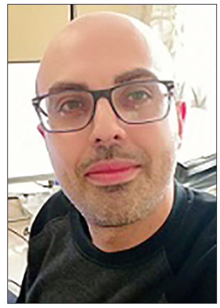

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Pervasive, Efficient, and Smart Signal Processing for IoT

The Internet of Things (IoT) lies at the core of the unprecedented connected era we are currently speeding towards. Both Academia and the Industry strive to push the limits of technology fueled by vertical applications such as: factory 4.0, eHealth, human-centric and tactile IoT, wearable IoT, smart city/building, digital twin, etc., which will shape our future society and significantly impact both economic and societal aspects. Signal Processing (SP) plays an important role in expanding the number of IoT technologies and capitalizing on their applications. This is due to the sophisticated processing of signals and data gathered and shared by connected things.

In this context, the unique challenges from the SP point of view are:

- System design taking into account the applications' practical limitations and requirements;
- Gather collective intelligence from heterogeneous and inexpensive IoT sensors/devices (e.g. to perform an inference task in decentralized fashion);
- Minimize device cost and energy consumption while allowing perpetual monitoring/sensing;
- Grant adaptivity to cope with device mobility use cases;
- Leverage fine-grained "programming" of wireless environments to cope with massive IoT scenarios.

These challenges give rise to the need for developing pervasive, inexpensive, fast, and low-power algorithms (including those performing learning and data fusion), as well as novel theoretical tools, evaluation benchmarks, and methodologies to characterize the performance of the proposed algorithms. The wide diversity of these challenges pushes for a more collaborative effort from engineers and scientists with complementary and interdisciplinary expertise going beyond the standard SP techniques.

Accordingly, the main goal of this Special Issue is to address these challenges and present advanced and innovative SP tools and algorithms for IoT systems. The SI attracted 25 high quality submissions from authors worldwide. All articles received at least three reviews and the accepted articles went through at least one revision round. Eventually, 8 magazine articles were accepted covering various aspects of SP for IoT.

Below, we briefly summarize the 8 peer-reviewed papers composing this SI, which balances well the theory vs. practice: the first three papers focus on SP aspects enabling novel IoT communications, the next three papers capitalize on the use of SP to support efficient & collaborative IoT data processing, and the last two papers provide concrete examples of unique SP challenges in vertical IoT applications.

In "Goal-Oriented Communications for the IoT and Application to Data Compression," the authors analyze the important role of sensing, actuation, processing, and wireless communication capabilities in IoT devices to stimulate data collection, transmission and decision processes of smart applications IoT devices. Indeed, new challenges arise from their widespread popularity, including the need for processing more complicated data structures and high dimensional data/signals. More importantly, the unprecedented volume, heterogeneity, and velocity of IoT data calls for a communication paradigm shift from the focus on accuracy or fidelity to semantics extraction and goal accomplishment. To this end, the authors provide an insightful overview of recent research efforts in this emerging area of goal-oriented (GO) and semantic communications, focusing on the problem of GO data compression for IoT applications.

In "How Far Are Wireless Networks from Being Truly Deterministic?," various emerging applications sustained by IoT technology and machine-type communications are discussed. Specifically, the authors focus on applications that require an extremely low latency and a very small jitter such as: industrial sensing and controlling, remote surgery, and automatic driving. For such applications, delivering information in a deterministic fashion is crucial and one of the the biggest challenges in modern wire-line and wireless communications. In this article, a review of currently available wire-line deterministic networks is presented and the main challenges behind wireless deterministic networks are discussed. Several promising techniques to enable deterministic communications in wireless networks are then proposed. By elaborating on the physical layer coding/modulation schemes and the channel-access/packet-scheduling at the media access control (MAC) layer, a significant contribution is made towards the realization of wireless deterministic communications in the near future.

In "Surface-Based Techniques for IoT Networks: Opportunities and Challenges," an overview of recent techniques in the area of surface-based communications is provided by the authors, describing their high potential and advantages for IoT networks. Specifically, the use of reconfigurable intelligent surfaces is argued to bring significant advantages in terms of energy consumption, self-sustainment, programmability, and self-organization of IoT networks, possibly enabling the use of mmWaves for IoT, and the improvement of back-scattering techniques. The emerging paradigms in the area of surface-based communications are described, including holographic surfaces, active surfaces, and plug-and-play surfaces, and fitted into the IoT context. Some numerical examples are shown to substantiate the potential gains that surface-based communications can provide for IoT. Finally, open research directions are identified together with the main research challenges towards the implementation of energy-neutral, self-organizing surface-based IoT environments.

The next three papers address important data processing challenges in the IoT context. In "Personalized Online Federated Learning for IoT/CPS: Challenges and Future Directions," the authors focus on federated learning (FL) as a powerful paradigm for distributed learning thanks to its privacy-preserving capabilities. With the use of FL, a network of edge devices can make intelligent decisions without exposing their data to others. Despite its success, the traditional FL is not well suited to many practical applications such as those involving the IoT or cyber-physical systems (CPS), where data access can be intermittent, and edge devices are semi-independent with device-specific dynamic behavior characteristics. The so-called semi-independent devices need to make decisions based on their own data and device characteristics, often independent of other devices and of the information obtained from other devices. Additionally, as new information becomes available, traditional FL must repeat the entire learning process and may not be able to provide timely and tailored solutions to clients. At the opposite, personalized online FL retains the collaborative and privacy-preserving abilities while learning in real time from intermittent data. It further enables devices to learn models customized to the device and the specific tasks it performs. In light of these reasons, personalized Online-FL is ideal for applications where the learning relies on heterogeneous data streams, and local optimization is beneficial. In this work, the authors highlight this new learning paradigm, present some potential applications, and discuss the major challenges in developing successful personalized Online-FL.

In "Impact of Embedded Deep Learning Optimizations for Inference in Wireless IoT Use Cases," the authors investigate the inference problem via deep learning when the data is processed locally at the edge and on constrained embedded devices. The aim of this approach is to eliminate the need for high-throughput links in wireless IoT toward high-end computing platforms (such as edge or cloud servers) for further processing. Although most published oversized models (trained at the cloud) cannot run on typical embedded devices, with optimizations, efficient embedded inference can be achieved while mitigating the need for raw data transmissions and thus preserving privacy. This approach provides several benefits in terms of latency, reliability, privacy and energy consumption. In this article, the authors overview different optimization strategies to enable embedded deep learning inference on constrained devices and demonstrate via numerical results the potential benefits in terms of energy consumption vs. accuracy performance. Finally, several trends in embedded deep learning use cases are discussed and valuable insights between design- and run-time metrics to predict model memory, storage and energy consumption together with model inference time are also provided.

In "Collaborative Inference for AI-Empowered IoT Devices," the authors build on the similar setup of IoT inference at the edge using neural networks, but taking a different perspective and investigating candidate collaboration strategies among several edge devices, which perform local data processing via neural networks. As opposed to the aforementioned article focused on how to embed neural network processing on a single edge device, this work leverages the devices' communication capabilities to establish collaborative inference among multiple such devices. The need to operate in different mobility and connectivity constraints is used as a motivating factor to consider multiple schemes, which can be roughly divided into methods where inference is done remotely, i.e., on the cloud, and those that infer at the edge. The authors identify the key characteristics of each strategy in terms of inference accuracy, communication latency, privacy, and connectivity requirements, providing a systematic comparison between existing approaches. The article is concluded with future research challenges and opportunities arising from the concept of collaborative inference.

As a first concrete application, in "Stand-Alone, Affordable IoT Satellite Terminals and Their Opportunistic use for Rain Monitoring," the authors investigate IoT communication via satellite, which represents an essential emerging technology for a variety of applications such as agriculture, financial technology, and homeland security in rural or isolated areas. In this article, the system under study is a two-way low cost, stand-alone IoT satellite terminals communicating over geostationary satellites at Ku-band frequencies, already deployed in isolated areas in Africa and South America. On top of their designated use for specific IoT applications, the authors propose to exploit such terminals for opportunistic rain monitoring, based on the two-way link quality measurements that are being regularly collected for network management. The local measurements are transmitted to the cloud, where their transformation to rain-intensity estimates is carried out. Preliminary results using real measurements show a good alignment with direct rainfall measurements recorded by a rain gauge. Enabling this feature in two-way communication of IoT satellite terminals would be highly beneficial, as it will provide the ability to monitor the rain in areas where designated weather monitoring equipment is sparse, helping to improve local weather-based applications, and to better track the climate change globally.

Finally, in "IoT-based Monitoring in Carbon Capture and Storage Systems," another important application is investigated:

the task of Carbon capture and storage (CCS), which is critical for climate-change policies and strategies targeting global warming within the Paris Agreement. The overarching technological requirements are well described in the strategic plans, yet several barriers exist to the technology widespread deployment, including improved cost-effectiveness and enhanced process integration. For the safe and reliable operation of large-scale CCS systems, the development of effective IoT-based monitoring tools to ensure flow assurance of CO2 throughout the CCS value chain is crucial. Furthermore, reliable sensor measurements related to different transport parameters such as temperature, pressure, and flow across the process are essential to develop these methods. However, sensors are prone to errors due to inherent issues or environmental conditions which result in performance degradation of the overall monitoring system. Developing techniques for detecting anomalies in the measurements, identifying the faulty sensors and accommodating them with appropriately estimated data is one of the paramount requirements for the reliable operation of the CCS systems. In this context, the last article provides an overview of CCS monitoring and control requirements, emphasizing data-fusion synergies. The state-of-the-art methods for sensor validation are overviewed and a clear roadmap to further deploy metering technologies for industrial needs is proposed.

Conclusions

To sum up, this SI contains 8 peer-reviewed articles that address key challenges in the future IoT networks, with a focus on novel signal processing techniques both in terms of the IoT communication and the IoT data processing aspects. This SI is conceived to reach a large number of researchers, scientists, engineers, industry experts and practitioners (even those not familiar with SP) and help them advancing research practices by digesting these concepts. We thank our readers and we hope that each article in this SI provides novel ideas and a deeper understanding of the variety of SP challenges & tools in the deployment of pervasive, smart and efficient IoT systems.

Acknowledgments

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Dinh-Thuy Phan Huy [SM'22] is currently a research project manager in Orange Innovation/Networks entity. She received a degree in engineering from Supelec, in 2001, and the Ph.D. degree in electronics and telecommunications from the National Institute of Applied Sciences of Rennes, France, in 2015. In 2001, she joined France Telecom R&D (now Orange Innovation), Châtillon, France. She led the national French collaborative research projects TRIMARAN (2011–2014) and SpatialModulation (2016–2019). She participated in the following 5G PPP projects: METIS, Fantastic 5G, mmMAGIC, and 5GCAR. She is co-inventor of more than 40 patents and the co-author of more than 50 papers. She is also the co-recipient of several best paper awards (IEEE RFID-TA 2021, EURASIP JWC 2021, IEEE PIMRC 2018). She is the recipient of several awards in France: "Prix Impact Economique des Rencontres du Numérique 2016" from the French National Research Agency, "Grand Prix de l'Electronique du General Ferrié 2018" from the French Society of Electricity, Electronics and Information and Communication Technologies and the "Prix Irène Joliot Curie 2018 — catégorie Femme-Recherche-Entreprise" from the French Ministry of Education and Research. Her research interests include wireless communications and beamforming, time reversal, spatial modulation, backscattering and intelligent reconfigurable surfaces. She is involved in the EU Flagship project on 6G Hexa-x and leads the work package on sustainability and security in RISE-6G EU project on reconfigurable intelligent surfaces for 6G. She is a member of the Future Networks community of Orange Experts since 2012, and senior Orange Expert since 2022.

Tirza Routtenberg [S'07, M'13, SM'18] received the B.Sc. degree (magna cum laude) in biomedical engineering from the Technion Israel Institute of Technology, Haifa, Israel, in 2005, and the M.Sc. (magna cum laude) and Ph.D. degrees in electrical engineering from the Ben-Gurion University of the Negev, Beer-Sheva, Israel, in 2007 and 2012, respectively. She was a Postdoctoral Fellow with the School of Electrical and Computer Engineering, Cornell University, in 2012–2014. Since October 2014, she has been with the School of Electrical and Computer Engineering, Ben-Gurion University of the Negev, Beer-Sheva, Israel, where she is now an Associate Professor. In 2022–2023, she is a William R. Kenan, Jr. Visiting Professor for Distinguished Teaching at Princeton University. Her research interests include signal processing in smart grids, statistical signal processing, estimation and detection theory, and signal processing on graphs. She is an Associate Editor of *IEEE Transactions on Signal and Information Processing Over Networks* and of *IEEE Signal Processing Letters*, SPS Education Center Editorial Board Member on the IEEE Signal Processing Society Education, and a member of the IEEE Signal Processing Theory and Methods Technical Committee. She was a recipient of the Best Student Paper Award in International Conference on Acoustics, Speech and Signal Processing (ICASSP) 2011, in IEEE International Workshop on Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP) 2013 (coauthor), in ICASSP 2017 (coauthor), and IEEE Workshop on Statistical Signal Processing (SSP) 2018 (coauthor). She was awarded the Negev scholarship in 2008, the Lev-Zion scholarship in 2010, the Marc Rich foundation prize in 2011, and the Toronto Prize for Excellence in research in 2021.

Chau Yuen [S'02, M'06, SM'12, F'21] received the B.Eng. and Ph.D. degrees from Nanyang Technological University (NTU), Singapore, in 2000 and 2004, respectively. He was a Post-Doctoral Fellow with Lucent Technologies Bell Labs, Murray Hill, in 2005. From 2006 to 2010, he was with the Institute for Infocomm Research (I2R), Singapore. Since 2010, he has been with the Singapore University of Technology and Design. He was a recipient of the Lee Kuan Yew Gold Medal, the Institution of Electrical Engineers Book Prize, the Institute of Engineering of Singapore Gold Medal, the Merck Sharp and Dohme Gold Medal, and twice a recipient of the Hewlett Packard Prize. He received the IEEE Asia Pacific Outstanding Young Researcher Award in 2012 and IEEE VTS Singapore Chapter Outstanding Service Award on 2019. Currently, he serves as an Editor for the *IEEE Transactions on Vehicular Technology*, *IEEE System Journal*, and *IEEE Transactions on Network Science and Engineering*. He served as the guest editor for several special issues, including *IEEE Journal on Selected Areas in Communications*, *IEEE Wireless Communications Magazine*, *IEEE Transactions on Cognitive Communications and Networking*. He is a Distinguished Lecturer of IEEE Vehicular Technology Society.