Guest Editors' Introduction to the Special Issue on Fog, Edge, and Cloud Integration for Smart Environments

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The term Internet of Things (IoT) was coined in the late 1990s, and since then it has evolved considerably with a great impact on our daily life [1, 2]. IoT specifically refers to connecting "things" (devices, systems), the data they generate, the (human) users they interface with, and the services they host. IoT can span several technologies from computing to data management to communication and more.

IoT research has also led to the creation of new digital ecosystems that involve the collection of data generated by the services and objects distributed over these ecosystems (through sensors), data transmission with several protocols (such as WiFi, Bluetooth (BTLE), LoRaWAN, Sigfox, NB-IoT) [3], data processing in a Cloud infrastructure [4] to derive knowledge, and implementation of management strategies through dedicated actuators. IoT research is therefore often seen as a "closed-loop" from environment-based data capture and sensing to processing along the data transmission path to subsequent actuation in the environment.

The overall system is managed through software at different levels (firmware, middleware, application) and delivers advanced services to users, combining the real world and the virtual world in what is commonly referred to as Cyber-Physical Systems (CPSs) [5], and which some extend to Cyber-Physical-Social Systems. IoT is recognized as a key enabler of CPS.

An emerging theme that combines elements of cloud computing and the Internet of Things is centered on exploiting the capabilities of embedded smart devices that are closer (geographically and in terms of latency) to users and their decision-making. Fog Computing [6] aims to distribute some of the resources and services of computation, communication, control, and storage away from centralized data centers by exploiting the concept of cloudlets. Edge Computing [7] extends such concepts incorporating IoT devices.

The integration among Cloud, Edge, and Fog computing gives rise to research challenges spanning from design and implementation of mechanisms and policies for device management to issues in the enrollment of mobile devices and users and from trust and identity management in federated environments to distributed data analytics algorithms and frameworks. A central challenge is the effective orchestration of capabilities across edge devices and centralized data centers (which can be multiple hops away from a user).

This special section brings together peer-reviewed contributions that focus on enhancing the synergy among Cloud, Fog, and Edge computing and the use of these in smart environments and applications (e.g., smart cities, smart homes/building, and industry 4.0). The included contributions cover theoretical foundations, resource management mechanisms, and applications.

This special section starts with a survey [8] on how Fog Computing can support IoT devices and services, presenting the basic underlying principles and the reference literature. Six IoT application domains are identified that may benefit from the use of this paradigm. This contribution is intended to set the context for this special section and aims to highlight research directions that may be of interest to the community.

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Various aspects of “crowd sensing” are investigated in the following three papers. In Reference [9], Mobile Crowd Sensing (MCS) is introduced to develop context-aware applications by mining relevant information from a large set of devices selected in an ad hoc manner. More specifically, the authors propose the ContextAiDe architecture, comprising a combination of API, middleware, and optimization engine. The key innovation of the architecture is the context-optimized recruitment of resources for execution of computation and communication of heavy MCS applications in the Edge environment. Reference [10] proposes a multi-device Human Activity Recognition (HAR) framework that exploits the Fog computing paradigm to migrate computationally intensive processing from the sensing layer to intermediate devices and then to the Cloud. A performance evaluation of the entire platform provides a proof of the accuracy of the recognition process. In Reference [11], a framework enabling mobile crowd sensing in Fog environments with a hierarchical scheduling strategy is presented. The authors also formulate a scheduling problem in the hierarchical Fog structure and investigate it by using a deep reinforcement learning-based strategy.

Understanding how to distribute computation and processing between Cloud and Fog/Edge resources is a challenging question addressed in References [12–15]. Diverse application requirements and the limited resources (both in number and capability) at the Edge pose the question of how much processing should be done locally vs. offloaded to other devices. Reference [12] investigates such issues and presents an optimization framework to adapt the resource management at runtime, reducing overhead significantly while increasing user utility. In Reference [13], the authors deal with the problem of computation offloading in the context of the Mobile Cloud Computing paradigm. They devise a two-level resource allocation and admission control mechanism for a cluster of Edge servers that is able to optimize average response time for the application and the optimal utilization of the computational resources. A heuristic approach for the solution of the NP-hard problem of finding which tasks should be offloaded to which Cloudlets is presented in Reference [14]. Authors take into consideration task execution time and mobile energy consumption for computing their cost function and show an optimal policy that is able to scale to large-scale scenarios. In Reference [15], authors present an algorithm for selecting the best physical infrastructure among Fog, Mist, or Cloud computing based on cost, bandwidth, and latency criteria. Moreover, the concept of feasible Fog is introduced in order to limit the search time for the mobile device.

Security and privacy are important issues to address when dealing with highly distrusted systems. In Reference [16], the authors propose a privacy-preserving big data processing model using the synergy of Edge, Fog, and Cloud and describe how a cooperative data-processing strategy can be used without compromising users’ privacy for large-scale tensor data in Cyber-Physical-Social systems. The security and efficiency of the proposed privacy-preserving high-order Bi-Lanczos scheme are analyzed both theoretically and empirically on an intelligent surveillance system case study. The design of a secure, scalable, and resilient IoT network is addressed in Reference [17], where a solution that guarantees confidentiality of messages exchanged through semi-honest Fog nodes using a lightweight proxy re-encryption scheme is presented.

Research is also progressing through the design and implementation of reference frameworks to deal with Edge and Fog computing, offering mechanisms and API to easily develop new services. In Reference [18], the authors propose an OpenStack-based middleware platform to discover, combine, and provision to end users and applications resource containers at the Edge, Fog, and Cloud levels. In such way offloaded processes are facilitated and orchestrated, as shown through a proof of concept of an intelligent surveillance system. In Reference [19], a unified model for managing the life-cycle of applications in the Mobile-, Edge-, and Cloud-computing continuum is provided. The model leverages the Functions-as-a-Service paradigms, selecting where to execute functions in the form of microservices based on context and requirements. In Reference [20] the authors introduce an architecture for Edge Cognitive Computing (ECC) and describe its design issues in detail. An ECC-based dynamic service migration mechanism is presented to provide an insight into how cognitive computing is combined with Edge computing. The proposed system is evaluated, and the experimental results show that the ECC architecture has an ultra-low latency and provides better service to the user, saving computing resources and achieving high energy efficiency.

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REFERENCES

[1] Luigi Atzori, Antonio Iera, and Giacomo Morabito. 2010. The internet of things: A survey. *Comput. Netw.* 54, 15 (2010), 2787–2805.

[2] Xia Feng et al. 2012. Internet of things. *Int. J. Commun. Syst.* 25, 9 (2012), 1101–1102.

[3] Jasenka Dizdarević, Francisco Carpio, Admela Jukan, and Xavi Masip-Bruin. 2019. A survey of communication protocols for internet of things and related challenges of fog and cloud computing integration. *ACM Comput. Surv.* 51, 6, Article 116 (January 2019), 29 pages.

[4] Anna Kobusińska, Carson Leung, Ching-Hsien Hsu, Raghavendra S., and Victor Chang. 2018. Emerging trends, issues and challenges in internet of things, Big Data and cloud computing. *Future Generation Computer Systems* 87 (2018), 416–419.

[5] Borja Bordel, Ramón Alcarria, Tomás Robles, and Diego Martín. 2017. Cyber–physical systems: Extending pervasive sensing from control theory to the internet of things. *Pervasive and Mobile Computing* 40 (2017), 156–184.

[6] Amir Vahid Dastjerdi and Rajkumar Buyya. 2016. Fog computing: Helping the Internet of Things realize its potential. *Computer* 49, 8 (2016), 112–116.

[7] Weisong Shi et al. 2016. Edge computing: Vision and challenges. *IEEE Iof T J.* 3, 5 (2016), 637–646.

[8] Carlo Puliafito, Enzo Mingozzi, Francesco Longo, Antonio Puliafito, and Omer Rana. 2019. Fog computing for the internet of things: A Survey. *ACM Trans. Internet Technol.* 19, 2 (2019), 18:1–18:41.

[9] Madhurima Pore, Vinaya Chakati, Ayan Banerjee, and Sandeep K. S. Gupta. 2019. Contextaide: End to end architecture for mobile crowd sensing applications. *ACM Trans. Internet Technol.* 19, 2 (2019), 19:1–19:23.

[10] Federico Concone, Giuseppe Lo Re, and Marco Morana. 2019. A fog-based application for human activity recognition using personal smart devices. *ACM Trans. Internet Technol.* 19, 2 (2019), 20:1–20:20.

[11] He Li, Kaoru Ota, and Mianxiong Dong. 2019. Deep reinforcement scheduling for mobile crowdsensing in fog computing. *ACM Trans. Internet Technol.* 19, 2 (2019), 21:1–21:18.

[12] Farzad Samie, Vasileios Tsoutsouras, Lars Bauer, Sotirios Xydis, Dimitrios Soudris, and Jörg Henkel. 2019. *Oops*: Optimizing operation-mode selection for IoT edge devices. *ACM Trans. Internet Technol.* 19, 2 (2019), 22:1–22:21.

[13] Marios Avgeris, Dimitrios Dechouniotis, Nikolaos Athanasopoulos, and Symeon Papavassiliou. 2019. Adaptive resource allocation for computation offloading: A control-theoretic approach. *ACM Trans. Internet Technol.* 19, 2 (2019), 23:1–23:20.

[14] Houssemeddine Mazouzi, Nadjib Achir, and Khaled Boussetta. 2019. Dm2-ecop: An efficient computation offloading policy for multi-user multi-cloudlet mobile edge computing environment. *ACM Trans. Internet Technol.* 19, 2 (2019), 24:1–24:24.

[15] Danilo Reis de Vasconcelos, Rossana Maria de Castro Andrade, Valdenir de Sousa Severino, and José Neuman de Sousa. 2019. Cloud, fog or mist in IoT, that is the question. *ACM Trans. Internet Technol.* 19, 2 (2019), 25:1–25:20.

[16] Jun Feng, Laurence T. Yang, and Ronghao Zhang. 2019. Practical privacy-preserving high-order Bi-lanczos in integrated edge-fog-cloud architecture for cyber-physical-social systems. *ACM Trans. Internet Technol.* 19, 2 (2019), 26:1–26:18.

[17] Luca Ferretti, Mirco Marchetti, and Michele Colajanni. 2019. Fog-based secure communications for low power IoT devices. *ACM Trans. Internet Technol.* 19, 2 (2019), 27:1–27:21.

[18] Giovanni Merlino, Rustem Dautov, Salvatore Distefano, and Dario Bruneo. 2019. Enabling workload engineering in edge, fog and cloud computing through openstack-based middleware. *ACM Trans. Internet Technol.* 19, 2 (2019), 28:1–28:22.

[19] Luciano Baresi, Danilo Mendonça, Martin Garriga, Sam Guinea, and Giovanni Quattrocchi. 2019. A unified model for the mobile-edge-cloud continuum. *ACM Trans. Internet Technol.* 19, 2 (2019), 29:1–29:21.
[20] Min Chen, Wei Li, Giancarlo Fortino, Yixue Hao, Long Hu, and Iztok Humar. 2019. A dynamic service-migration mechanism in edge cognitive computing. *ACM Trans. Internet Technol.* 19, 2 (2019), 30:1–30:15.