# Edge Computing

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In recent years, with the proliferation of the Internet of Things (IoT) and the wide penetration of wireless networks, the number of edge devices and the data generated from the edge have been growing rapidly. According to International Data Corporation (IDC) prediction [20], global data will reach 180 zettabytes (ZB), and 70% of the data generated by IoT will be processed on the edge of the network by 2025. IDC also forecasts that more than 150 billion devices will be connected worldwide by 2025. In this case, the centralized processing mode based on cloud computing is not efficient enough to handle the data generated by the edge. The centralized processing model uploads all data to the cloud data center through the network and leverages its supercomputing power to solve the computing and storage problems, which enables the cloud services to create economic benefits. However, in the context of IoT, traditional cloud computing has several shortcomings.

This special issue provides state-of-the-art coverage of edge computing topics and highlights the current challenges and future opportunities in this area.

1) *Latency:* Novel applications in the IoT scenario have high real-time requirements. In the traditional cloud computing model, applications send data to the data center and obtain a response, which increases the system latency. For example, high-speed autonomous driving vehicles require milliseconds of response time. Serious consequences will occur once the system latency exceeds expectations due to network problems.
2) *Bandwidth:* Transmitting large amounts of data generated by edge devices to the cloud in a real-time manner will cause great pressure on network bandwidth. For example, Boeing 787 generates more than 5 GB/s of data, but the bandwidth between an aircraft and satellites is insufficient to support real-time transmission [10].
3) *Availability:* As more and more Internet services are deployed on the cloud, the availability of these services has become an integral part of daily life. For example, smartphones users who get used to voice-based services, e.g., Siri, will feel frustrated if the service is unavailable for a short period of time. Therefore, it is a big challenge for cloud service providers to keep the 24 × 7 promise.
4) *Energy:* Data centers consume a lot of energy. According to Sverdlik's research [2], the energy consumption of all data centers in the United States will increase by 4% by 2020, reaching 73 billion kilowatt-hours. With the increasing amount of computation and transmission, energy consumption will become a bottleneck restricting the development of cloud computing centers.
5) *Security and Privacy:* Data in the interconnection of thousands of households are closely related to users' lives. For example, indoor cameras transmitting video data from the house to the cloud will increase the risk of leaking users' private information. With the enforcement of EU General Data Protection Regulation (GDPR) [18], data security and privacy issues have become more important for cloud computing companies.

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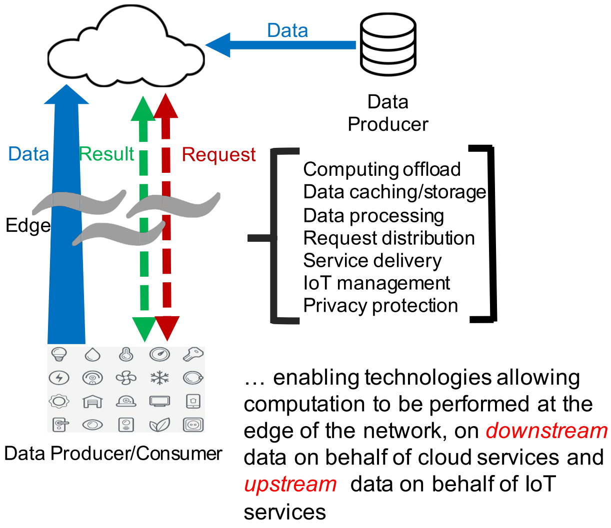

**Fig. 1.** ***Edge computing in a nutshell [15].***

These challenges have pushed the horizon of edge computing, which calls for processing the data at the edge of the network. It has developed rapidly since 2014 with the potential to reduce latency and bandwidth charges, address the limitation of computing capability of the cloud data center, and increase availability as well as protect data privacy and security.

## A. Edge Computing Basics

*1) Definition:* Edge computing is a new paradigm in which the resources of an edge server are placed at the edge of the Internet, in close proximity to mobile devices, sensors, end users, and the emerging IoT. Terms such as "cloudlets," "micro data centers," and "fog" have been used in the literature to refer to these types of small, edge-located computing hardware. They all represent counterpoints to the theme of consolidation and massive data centers that have dominated discourse in cloud computing. Shi *et al.* [15] defined edge computing as follows. Edge computing refers to the enabling technologies allowing computation to be performed at the edge of the network, on downstream data on behalf of cloud services and upstream data on behalf of IoT services. "Edge" is defined as any computing and network resources along the path between data sources and cloud data centers, and edge is a continuum.

The edge of the Internet is a unique place. Located usually just one hop away from associated end devices, it offers ideal placement for low-latency offload infrastructure to support emerging applications such as augmented reality, public safety, connected and autonomous driving, smart manufacturing, and healthcare. It is an optimal site for aggregating, analyzing, and distilling bandwidth-hungry sensor data from devices such as video cameras. New challenges and opportunities arise as the consolidation of cloud computing meets the dispersion of edge computing. Next, we describe what functions can be performed at the edges, and how edge computing fits in today's cloud computing model by presenting a typical three-tier edge computing model.

*2) Functions:* As illustrated in Fig. 1 [15], edge computing has a two-way computing stream: one is from devices to the cloud (upstream) and the other is from the cloud to devices (downstream). In the edge computing paradigm, end devices not only are data consumers but they also serve as data producers. At the edge, things can not only request service and content from the cloud but they can also perform computing tasks from the cloud. Edge can perform computing offloading, data storage, caching, and processing, as well as distribute requests and deliver services from the cloud to the user. With those tasks along the data path, the edge itself needs to be well designed to meet the requirement efficiently, such as reliability, security, and privacy protection.

*3) Three-Tier Edge Computing Model:* By analyzing several representative application scenarios of edge computing, in Fig. 2, we abstract a typical three-tier edge computing model: IoT, edge, and cloud. The first tier is IoT, including drones, sensors in the connected health area, devices and appliances in the smart home, and equipment in the industrial Internet. Multiple communication protocols are used to connect IoT and the second tier, edge. For example, drones can connect to a cellular tower by 4G/LTE, and sensors in the smart home can communicate with the home gateway through WiFi. Edge, including connected and autonomous vehicles, cellular tower, gateway, and edge servers, requires the huge computing and storage capabilities of the cloud to complete complex tasks. The protocols between IoT and the edge usually have the characteristics of low power consumption and short distance, while the protocols between the edge and the cloud have large throughput and high speed. The Ethernet, optical fibers, and the coming 5G are the preferred communication protocols between the edge and the cloud.

*4) Edge Versus Cloud:* Edge computing and cloud computing are not substituted relationships; rather, they are complementary. The ubiquity of smart devices and rapid development of modern virtualization and cloud technologies have brought edge computing to the foreground, defining a new era in cloud computing. Edge computing needs powerful computing power and massive storage support of a cloud computing center, and the cloud computing center also needs the edge computing model to process massive data and privacy data.

Edge computing has several obvious advantages. First, a large amount

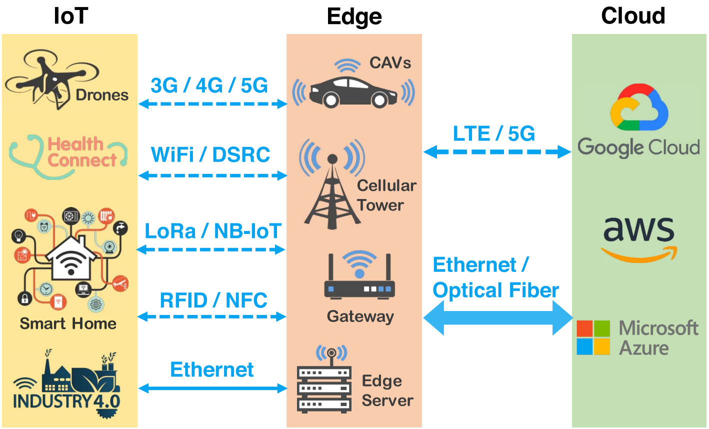

**Fig. 2.** ***Three-tier edge computing model.***

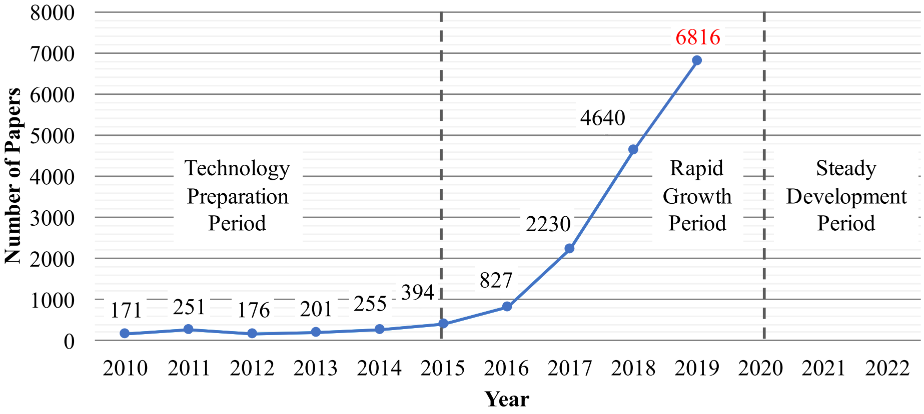

**Fig. 3.** ***Number of papers related to by "edge computing" on Google Scholar.***

of temporary data are processed at the edge of the network, but not all of it is uploaded to the cloud, which greatly reduces the pressure on the network bandwidth and data center power consumption. Second, data processing near the data producer does not require the response of the cloud computing center through the network, which greatly reduces the system latency and enhances the service response capability. Finally, edge computing stores users' private data on edge devices instead of uploading it, which reduces the risk of network data leakage and protects security and privacy.

## I. EDGE COMPUTING EVOLUTION

The field of edge computing has developed rapidly in recent years since 2014. We categorize the development process into three stages: technology preparation period, rapid growth period, and steady development period. We use "edge computing" as the keyword to search the number of articles published per year in Google Scholar. As shown in Fig. 3, before 2015, edge computing was in the technology preparation period. Since 2015, the number of papers related to "edge computing" has grown tenfold. Edge computing has entered the rapid growth period. Note that the number of papers in 2019 is estimated based on the results of the first five months. We predict that edge computing will continue to develop rapidly until 2020. After 2020, edge computing will step into the steady development period. In this period, edge computing will realize the integration of academia and industry, bring the product into the business, and finally facilitate peoples' daily lives. Fig. 4 illustrates typical events in the development process of edge computing.

### A. Technology Preparation Period

During the technology preparation period, edge computing went through the development process of dormancy, presentation, definition, and generalization. Edge computing can be traced back to the content delivery network (CDN) proposed by Akamai in 1998 [17]. CDN is an Internet-based caching network, which relies on caching servers deployed in different places and points users' access to the nearest caching server through load balancing, content distribution, scheduling, and other functional modules of the central platform. Therefore, CDN can reduce network congestion and improve user access response speed and hit rate. CDN emphasizes the

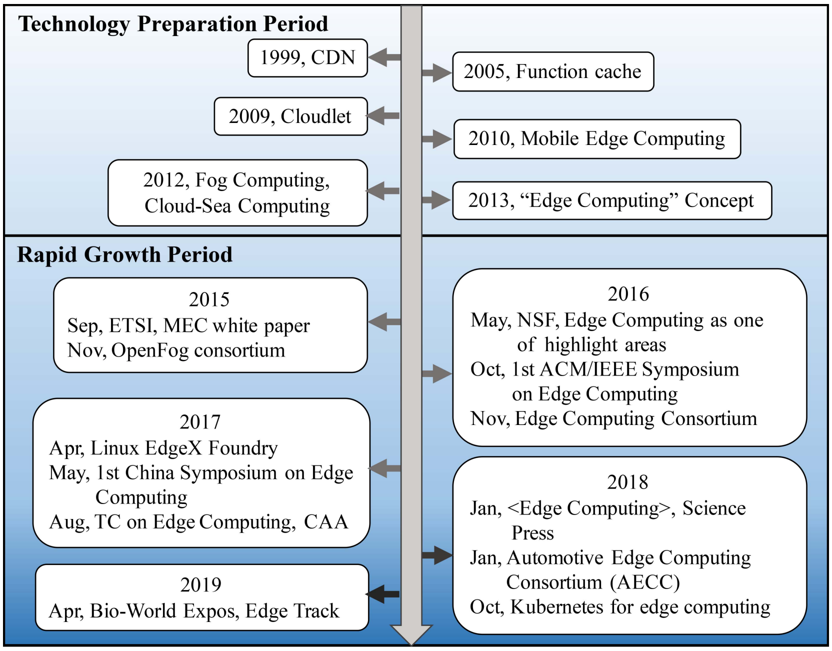

**Fig. 4.** *Typical events in the development process of edge computing.*

backup and caching of data, while the core idea of edge computing focuses more on function caching. Ravi *et al.* [13] first proposed the concept of function cache at the first time and applied it to personalized mailbox management services to save latency and bandwidth. Satyanarayanan *et al.* [14] put forward the concept of Cloudlet, which is a trusted and resource-rich host, deployed on the edge of the network, connected to the Internet, and can be accessed by mobile devices to provide services. Cloudlet is also known as "small cloud" as it can provide services for users, similar to the cloud server. At this point, edge computing emphasized downstream, that is, it downstreamed the functions from cloud servers to edge servers to reduce bandwidth and delay.

The rationale of edge computing is that computing should happen at the proximity of the data source with the "edge" constituting any computing and network resources along the path between data sources and the cloud [16]. In this context, sensory data are converted from raw signals to contextually relevant information in the proximity of the data source. Subsequently, edge data ushered in an explosive growth in the context of IoT. In order to address the challenges of computing offload and data transmission, researchers began to explore how to increase data processing capability near the data producer. The representative computing models are mobile edge computing (MEC), fog computing, and cloud-sea computing.

MEC [11] is a network structure that provides information services and cloud computing capabilities within the wireless access network near mobile users. Since MEC is located in a wireless access network and close to mobile users, it can achieve lower latency and higher bandwidth to improve the quality of service and user experience. MEC emphasizes the establishment of edge servers between the cloud server and edge devices to do computing, which is similar to the architecture and hierarchy of an edge computing server, so MEC is regarded as an important part of edge computing.

Cisco introduced fog computing in 2012 and defined fog computing as a highly virtualized computing platform for migrating cloud computing center tasks to network edge devices [8]. It relieves the bandwidth load and energy consumption pressure of main links by reducing the number of communications between cloud computing centers and mobile users. Fog computing and edge computing have great similarities, but fog computing focuses more on communication optimization at the infrastructure level, while edge computing pays attention to computing needs and network demand of both end devices and infrastructure, including the collaboration among end devices, edges, and clouds.

Meanwhile, in 2012, the Chinese Academy of Sciences launched a ten-year strategic priority research initiative called the Next Generation Information and Communication Technology (NICT) initiative. Its main purpose is to carry out research of the "Cloud-Sea Computing System Project" [19]. It aims to augment cloud computing by cooperation and integration of the "cloud computing" system and the "sea computing" system. "Sea" refers to an augmented client side consisting of human facing and physical world facing devices and subsystems. Cloud-sea computing focuses on the two ends "sea" and "cloud," while edge computing focuses on the data path between "sea" and "cloud."

In 2013, Ryan LaMothe from the Pacific Northwest National Laboratory proposed the term “edge computing” in a two-page internal report, which is the first time modern “edge computing” [12] was formulated. At this time, the concept of edge computing includes both the downstream of cloud services and the upstream of IoT.

### B. Rapid Growth Period

Since 2015, edge computing has been in a rapid growth period, attracting intensive close attention from academia and industry.

At the government level, in May 2016, the National Science Foundation (NSF) of the United States listed edge computing as one of the highlighted areas in the research of computer systems. In August 2016, NSF and Intel formed a partnership in information center networks in wireless edge networks (ICN-WEN) [3]. In October 2016, the NSF held the NSF Workshop on Grand Challenges in edge computing [9]. The workshop focused on three topics: the vision of edge computing in the next five to ten years; the grand challenges to achieving the vision; and the best mechanisms for academia, industry, and the government to attack these challenges in a cooperative way. This indicates that the development of edge computing has attracted great attention at the government level.

In academia, Shi *et al.* [15] gave a formal definition of edge computing in the paper “Edge computing: Vision and challenges.” They defined edge computing as enabling technologies allowing computation to be performed at the edge of the network, on downstream data on behalf of cloud services and on upstream data on behalf of IoT services. This paper pointed out the challenges of edge computing and has been cited more than 1000 times in three years. In October 2016, ACM and IEEE jointly organized the first ACM/IEEE Symposium on Edge Computing (SEC). Since then, ICDCS, INFOCOM, MiddleWare, and other important international conferences have added an edge computing track and/or workshops to their main conferences. In January 2018, the world’s first textbook on edge computing was published by Science Press.

At the same time, multiple industry sectors have actively promoted the development of edge computing. In September 2015, the European Telecommunications Standards Institute (ETSI) published a white paper on MEC [11]. In November 2015, Cisco, ARM, Dell, Intel, Microsoft, and Princeton University jointly established the OpenFog Consortium, which is dedicated to the development of Fog Reference Architecture [4]. The OpenFog Consortium merged into the Industrial Internet-of-Things (IIoT) in January 2019. In November 2016, Huawei, Shenyang Institute of Automation of Chinese Academy of Sciences, China Academy of Information and Communications Technology (CAICT), Intel, ARM, and iSoftStone established the Edge Computing Consortium (ECC) in Beijing, which is dedicated to advancing cooperation among industry resources from government, vendor, academic, research, and customer sectors, and pushing forward the sustainable development of the edge computing industry [1]. In March 2017, the MEC Industry Specification Working Group was formally renamed as multiaccess edge computing, aiming to better meet the requirement of edge computing and related standards. Linux EdgeX Foundry was also built in 2017; it is a vendor-neutral open-source project hosted by The Linux Foundation. It aims to build a common open framework for IoT edge computing. In January 2018, Automotive ECC (AECC) was established to drive the network and computing infrastructure needs of automotive big data [5], which indicates that edge computing is valued in the vehicle domain. In the same year, Cloud Native Computing Foundation (CNCF) Foundation and Eclipse Foundation cooperated to bring Kubernetes, which has been widely used in the ultralarge-scale cloud computing environment, into the edge computing scene of the IoT. Subsequently, KubeEdge, a Kubernetes native edge computing framework, was accepted into the CNCF sandbox in March 2019 [7]. In April 2019, Bio-World Conference and Expos added the Edge track [6], which means that edge computing is important to the health domain as well.

## II. ABOUT THE SPECIAL ISSUE

Although edge computing is very promising, there are still many challenges faced by the community, ranging from fundamental technologies to novel application scenarios and potential business models. To help the computing community get a better understanding of where we are and how to leverage edge computing in their own fields, we think it is important to develop a special section presenting the state of the art of edge computing. We have witnessed a wide range of progress, particularly in the past five years, spanning the following topics: systems and tools, which provide the basis for the edge computing; innovative edge networks; edge computing applications in multiple domains, such as smart cities, public safety, and autonomous driving, industry IoT, and so on; and new security and privacy threats. We have formed an international team of Guest Co-Editors, and assembled 13 papers from North America, Europe, and China, covering edge computing foundations, technologies, security and privacy, applications, and case studies.

This special issue contains 13 invited papers from prominent scientists relating to edge computing, which witnesses the rapid development of relevant core technologies, including virtualization and migration, software-defined networking (SDN), computing offloading, programming models and operating systems, security, privacy, systems and tools, and fast penetration of edge computing in several applications scenarios, including video analytics for public safety, autonomous driving, deep learning, wireless communication, and edge intelligence.

Although edge computing brings the computation closer to delay-sensitive services, challenges that restrict the cloud model still remain as the pace of generated data continues to rise. Edge nodes can be mobile, and the rapid changes can occur anytime in dynamic networks (e.g., connectivity failure and bandwidth fluctuation); therefore, the orchestration of edge services becomes more challenging. Specifically, service discovery, resource coordination, coping with resource heterogeneity, lifecycle management, and task offloading are open research challenges. Moreover, scheduling data management and processing tasks to derive analytics insights requires "intelligent" consideration. The following six articles present state-of-the-art studies that address these challenges.

1) "A survey of virtual machine (VM) management in edge computing" provides an overview on the industrial and research projects on VM management in edge computing. The paper focuses on the virtualization frameworks and virtualization techniques, serverless management, and security advantages and issues that virtualization brings to edge computing.
2) "Software-defined networking (SDN) enhanced edge computing: A network-centric survey" discusses how SDN and related technologies are integrated to facilitate the management and the operations of edge servers and various IoT devices. The authors discuss the current status and present new perspectives on this topic.
3) "Dependable resource coordination on the edge at runtime" introduces a methodology and technical framework for engineering resource coordination for the edge-enabled IoT. The authors use bounded model checking as the key technique to compute coordination plans, which satisfy device, edge, and system goals.
4) "A survey on edge computing systems and tools" reviews existing systems and open-source projects for edge computing by categorizing them according to their design demands and innovations. In addition, topics that are related to energy efficiency and deep learning optimization of edge computing systems are discussed.
5) "Ecosystem of things: Hardware, software, and architecture" surveys the state of the art in supporting smart edge computing and makes some concluding observations with respect to hardware, system software, and ecosystem architecture. Within this survey, the paper deals with the following research challenges: how much raw computing capability and energy efficiency the hardware of things provides, what abstractions the system software supports to utilize the hardware capabilities, and what ecosystem architectures are proposed to harmonize innovation and fragmentation.
6) "Computation offloading toward edge computing" surveys recent research efforts made on exploring computation offloading toward edge computing. The authors highlight the challenges of computation offloading with respect to task partitioning, allocation, and execution over the new architecture of edge computing and investigate disruptive application scenarios, such as real-time video analytics, autonomous driving, smart home, and cloud gaming.

Along with the benefits that edge computing brings, there are numerous challenges we should take into account, especially with respect to data security and privacy. The limited processing power of connected devices can restrict the use of security measures making them especially vulnerable to both cyber and physical attacks, while mobility and the rapid provisioning of edge nodes require efficient mechanisms for establishing and attesting trust in the edge. The next two articles deal with security and privacy issues in edge computing:

1) "Edge computing security: State of the art and challenges" reviews the most influential and basic attacks as well as the corresponding defense mechanisms that can be practically applied to edge computing systems. Moreover, the article outlines the challenges and future directions toward securing edge computing systems.
2) "Privacy techniques for edge computing systems" discusses approaches for privacy-preserving data aggregation at the edge. The article focuses on techniques by which the edge can provide services to users while assuring user privacy as well as privacy-preserving crowd-sourcing techniques.

Edge computing brings together IoT, big data, and mobile computing into an integrated and ubiquitous computing platform. The capability offered to deliver on-demand computing power at the edge and the ability to process the vast amount of data coming from an abundance of devices/sensors provide a huge impetus to artificial intelligence (AI) technologies. The following five articles focus on these topics.

1) "Deep learning with edge computing: A review" provides an overview of applications where deep learning is used at the network edge. Computer vision, natural language processing, network functions, and virtual and augmented reality are discussed as example application drivers. The authors discuss different architectures and methods to speed up deep learning inference and training

deep learning models on edge devices, with an emphasis on distributed training across devices and privacy.

2) “Edge video analytics for public safety: A review” provides a survey of applications, algorithms, and platforms that have been proposed to facilitate edge video analytics for public safety.
3) “Edge computing for autonomous driving: Opportunities and challenges” surveys the designs of autonomous driving edge computing systems. In addition, this article presents the security issues in autonomous driving as well as how edge computing designs can address these issues.
4) “Wireless edge computing with latency and reliability guarantees” discusses the feasibility and potential of providing edge computing services with latency and reliability guarantees. The article proceeds by presenting selected use cases that reflect the interplay between edge computing and ultrareliable low-latency communication (URLLC).
5) “Edge intelligence: Paving the last mile of AI with edge computing” conducts a comprehensive survey of the research efforts on edge intelligence. This article provides an overview of the architectures, frameworks, and emerging key technology for a deep learning model toward training and inference at the network edge.

We hope that through this special section, we have delivered a state-of-the-art glimpse of current edge computing topics, bringing novel problems that must be investigated to the attention of the community. We also hope that it will serve as a valuable reference for researchers and practitioners working in the edge computing domain and its emerging applications. Furthermore, we envision this special section will help to establish a pathway toward a smart edge computing continuum. Finally, we would like to express our gratitude to the invited authors and reviewers for their contributions. ■

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## ABOUT THE GUEST EDITORS

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Prof. Shi has been actively involved in the activities of the IEEE Computer Society. He served as Chair of the Technical Committee on the Internet (TCI) from 2012 to 2016. He is the Founding Steering Committee Chair of the ACM/IEEE Symposium on Edge Computing (SEC) and the IEEE/ACM Connected Health: Applications, Systems and Engineering (CHASE). He is an ACM Distinguished Scientist. He currently serves on the Research Advisory Board of the IEEE Computer Society. He is the Inaugural Editor-in-Chief of *Smart Health* (Elsevier), an Associate Editor-In-Chief of the *IEEE Internet Computing Magazine*, and an Associate Editor of several journals, including the IEEE TRANSACTIONS ON SERVICES COMPUTING, and the ACM *Transactions on Internet of Things*, to name a few.

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