Software Defined Networking (SDN) Enhanced Edge Computing – A Network Centric Survey

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Abstract

Edge Computing is burgeoning along with the rapidly increasing adoption of the Internet-of-Things (IoT). While there are studies on various aspects of Edge Computing, we find there is a lack of network perspective. In this paper, we thus first present an overview of how Software Defined Networking (SDN) and related technologies are being investigated in Edge Computing. Our purpose is to survey the state-of-the-art and discuss the potential (remaining) challenges for future research. For this, we survey how SDN and related technologies are integrated to facilitate the management and operations of edge servers and various IoT devices. For the former, we review how SDN has been utilized in the access network, the core network, and the wide area network (WAN) between the edge and the cloud. For the latter, we focus on how SDN is leveraged to provide unified and programmable interfaces to manage devices. Through our discussion, we suggest that the SDN related network support for Edge Computing deserves more in-depth investigations. We also identify several challenges and open issues to be addressed in the future.

Keywords— Edge Computing, Infrastructure-as-a-Service, Platform-as-a-Service, Software-as-a-Service, Architecture

I. INTRODUCTION

The explosive growth of the Internet of Things (IoT) and mobile devices leads to an explosion of new applications and services, increasing the burden of what today's Internet could carry. What makes it worse is the heterogeneous platforms that support these applications and the diverse requirements of the applications from multiple perspectives, such as service quality, security and privacy, and computing and storage resources. Edge Computing has been proposed to address these pressing needs as a complementary solution to Cloud Computing. Although a lot of research has been investigated on various aspects of Edge Computing prior research has been mainly focused on the architecture, resource provisioning and management, programming models, new application development, etc. The networking perspective is lacking, especially with the newly available networking support of Software Defined Networking (SDN) and related technologies.

Some previous efforts have investigated Mobile Edge Computing (MEC). For example, Mao *et al.* surveyed MEC, with a focus on joint radio and computational resource management. The challenges and opportunities of radio communication techniques were discussed for facilitating resource management. In our investigation, we instead focus on the general design and deployment of the state-of-the-art network management techniques (e.g., SDN) in the Edge Computing environment. Mach *et al.* conducted another survey on the user-oriented use cases in the MEC system. Several MEC concepts were introduced to integrate cloud capabilities

We instead focus on how advanced network technologies enhance Edge Computing. Abbas et al. also surveyed relevant research and technological development in MEC. The authors mentioned that the SDN technology can help the control in MEC be more efficient and reliable. Wang et al. surveyed the key technologies in MEC computing and caching and provided a summary of MEC applications and use cases. They envisioned SDN and NFV as the key enablers for the concept of MEC ascribable to the flexibility and operating efficiency they provided. Tran et al. illustrated the benefits and applicability of MEC collaboration in 5G networks by discussing three use cases. discussed the capabilities of SDN and aligned them with the technical shortcomings of Edge Computing implementations. The discussions were also focused on the integration of the Edge Computing and SDN by demonstrating multiple use case scenarios. However, no systematic comparisons among different SDN-enhanced Edge Computing architectures are available.

For this purpose, we thus start from the development of Edge Computing and SDN and Network Function Virtualization (NFV), by discussing their background. Then, we discuss why SDN could benefit Edge Computing by surveying several use cases. We also classify the current research in this area into four categories based on the architectural designs and implementations. Since IoT is one of the thrusts behind Edge Computing, we also discuss the different applications of SDN in such an environment. We expect that this study not only gives a comprehensive overview of the current networking research in supporting Edge Computing, but also identifies future challenges and open issues that are worth further in-depth explorations.

II. EVOLVEMENT OF EDGE COMPUTING AND SDN

In this section, we provide some background information on the Edge Computing and the evolvement of SDN and the relevant technology.

Edge Computing

Since Amazon released its Elastic Compute Cloud product in 2006, cloud computing has gained tremendous success by reaping its field from various business sectors to personal end users in the past decade or so. By providing centralized (and elastic) resources and a flexible pay-as- you-go cost model, cloud computing provides services with different service models, including Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), Software-as-a-Service (SaaS), to its customers with great performance-cost ratio and convenience. As a result, a significant portion of the enterprise services have been migrated onto clouds and an increasing number of end users also rely on clouds for daily activities.

In tandem with the fast development of cloud computing services, the past decade has also witnessed another radical change over the Internet: there are more and more smart and mobile devices, such as smartphones and tablets, and various sensors and actuators, becoming available and pervasive, benefiting from the advancement of wireless communication technology. While smart and mobile devices provide a full-fledged computing stack, sensors and actuators often are dedicated to data collection and communication, forming the basis of IoT systems or various Cyber-Physical Systems (CPS). A lot of such applications have also been conceived and/or prototyped accordingly, such as healthcare, smart cities, auto- driving, and smart spaces. With the ever-decreasing hardware cost and the ever-improving CPU speed/wireless communication technology, Cisco has estimated that there will be 500 billion devices to be connected to the Internet by 2030.

Despite the ever-improving technology, smart devices and sensors are constrained by the limited on-device resources, namely, the slow CPU, the limited memory, and the short battery lifetime. This is especially true when compared to their counterparts on the popular cloud platforms. Naturally, this has motivated the ideas of utilizing the plentiful cloud resources to support applications running on smart devices and sensors. The key of this idea is to wisely offload complicated or computing-intensive applications on the smart and mobile devices or sensors to clouds. These efforts led to mobile cloud computing (MCC) initially. MCC nicely complements the mobility offered by the smart/mobile devices while also being able to leverage the powerful computing capability of clouds. Therefore, a lot of efforts have been made to investigate how to efficiently utilize the cloud and the smart device for the best user experience and/or system performance. cloud is one of such early efforts that seek to utilize virtual machine techniques to create an identical running environment for mobile devices on the cloud.

However, with more and more emerging applications, MCC often suffers from unpredictable network latency, which is
detrimental to the latency-sensitive mobile applications or location constrained ones. For example, a decision for auto- driving needs to be made in milliseconds while the communication latency to the cloud is often much larger. In addition, utilizing MCC often requires transmitting a large amount of data collected from the mobile devices and sensors to the cloud before the processing can take place. For example, the cameras on the cars need to upload the images continuously to the cloud for processing in order to know the hazards on the road. Such a data demand can easily make the communications a bottleneck. Furthermore, along the emerging of various new applications, such as healthcare and smart home, the users' security and privacy concerns further aggravate the challenge since the data generated by the smart devices and/or sensors often carry some private or sensitive information.

To this end, a new computing paradigm, edge computing, emerged to deal with such challenges. Albeit being named differently, efforts such as Cloudlets, Fog Computing, Mobile Edge Computing or Multi-access Edge Computing (MEC), share similar goals with entirely or largely over- lapping principles and application scopes. The fundamental of such a computing paradigm is to deploy resources on the edge of a network, namely edge nodes (or edge cloud or edge servers or fog nodes, cloudlets, micro cloud, etc.1), in close proximity to the edge devices or sensors so that the capability of such edge nodes can be utilized to reduce the network latency, to save bandwidth, and to improve security and privacy. With the increasing adoption of the big data applications, additional services could also be offered by these edge nodes, such as data analytics.

At a high level, edge computing can be viewed as cloud services migrated from remote clouds to nearby network edge. While Edge Computing comes from a different direction from the IoT applications, these days they are often heavily intertwined. In some occasions, they are even regarded inter- exchangeable. In this study, we treat them differently, where Edge Computing is more of a computing diagram and IoT are more of applications. On the other hand, IoT applications can be broadly defined to include most of today's applications using some sensors and/or mobile devices and thus include smart home, smart space, smart cities, etc. In our study, instead, we separate these applications from IoT applications as separate categories (e.g., healthcare, smart city, auto-driving) as they are important and have enough challenges to overcome.

SDN and NFV

The creation of the modern Internet offers universal connectivity that jump-started the digital age and tremendously improved people's daily life. The packet based switching and distributed architecture are key design principles adopted by the Internet that contribute to the networks' scalability, flexibility, and fault tolerance. While successful, traditional IP networks become increasingly complex, hard to configure/manage, slow to incorporate new innovations, and expensive to buy equipment, operate networks, and provide services.

The root cause rests on the design of network routers/switches and overall distributed network architecture. A traditional IP router/switch consists of two layers: a data plane and a control plane. The data plane is designed to forward network packets at a very high speed, while the control plane implements the configuration and management functions that govern how forwarding plane routes the packets. Although the data plane functions locally, the control plane typically implements distributed algorithms/protocols that collectively provide certain services, e.g., distributed network routing. A traditional router becomes a complex proprietary box that is hard to configure (need to remotely log in to configure individual routers), difficult to roll out new services (need to coax the distributed protocols to realize new services), and incurs high Capital Expenditure (CAPEX) and Operating Expense (OPEX).

III. SDN Integration with Edge Computing

A typical edge computing environment is composed of an array of connected edge servers (interchangeable with edge nodes or fog nodes). They are usually generic virtualized equipment with three fundamental capabilities: storage, computing and communications. To reduce the storage demand, various proactive caching mechanisms have been proposed and applied. Computations are also performed at the edge servers that are transparent to users with cross-platform and cross-application support. The glue that holds different components together in edge computing is the underlying network architecture. It allows the service providers to extend their services and functions closer to the end users. A typical architecture of such an environment is sketched in Figure 1. As shown in the figure, to support the applications and interact with various devices, the network layer needs various support. In this section, we focus on the integration of the state-of-art networking technologies, SDN and NFV, into the network layer of edge computing.

Figure 1 demonstrates a detailed layout of the network layer in an Edge Computing environment. The access network connects the heterogeneous devices to the services deployedat the edge. MEC, among others, was proposed in response to the emerging benefits of edge computing technology that reached beyond mobile networks and into Wi-Fi and fixed access technologies. The core network refers to the data center clouds at the core that manage resources and applications with a centric view. WAN connects many different actuators, gateways and devices sending transmissions from the edge to the cloud. As a network control paradigm, SDN should be compatible with access, WAN, and cloud technologies.

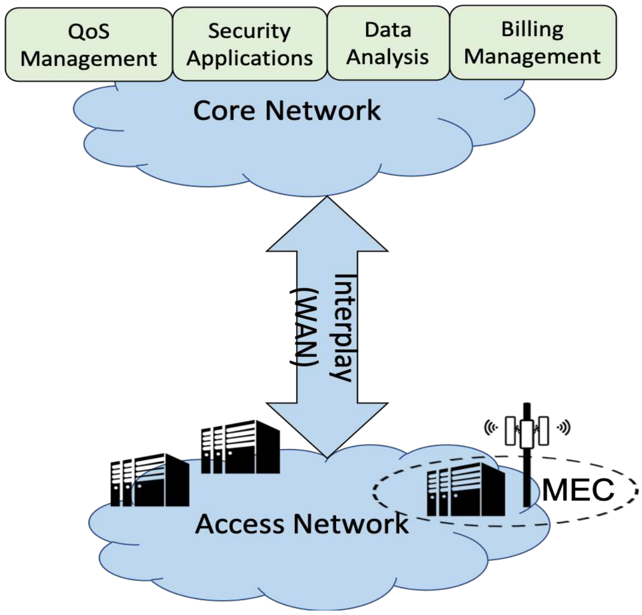

Fig. 1. A general architecture of the network layer in Edge Computing

On one hand, SDN/NFV deployed at the access network could support diverse requirements and agile service creation. On the other hand, such techniques are often employed in the data centers and clouds to configure and orchestrate services on the edge servers. For time-sensitive services, such as in an Industrial IOT (IIOT) environment, software defined wide area network (SD-WAN) has also been introduced. We next discuss some existing research efforts following these paradigms.

SDN-assisted Multi-access/Mobile Edge Computing

An important effort in standardizing edge computing in mobile network was initiated by ETSI in 2015. The framework that provides an IT service environment and cloud-computing capabilities at the edge is called Mobile Edge Computing or Multi-access Edge Computing (MEC). It is deployed within the Radio Access Network (RAN) and in close proximity to mobile subscribers. Conceptually, MEC specifies one form of the edge computing architectures and is dedicated to serve mobile devices. The key element of MEC is the MEC IT application server that is integrated at the RAN element. The MEC server provides computing resources, storage capacity, connectivity, and access to user traffic and radio and network information. According to a recent technical white paper of the architectural blueprint of the MEC server is shown in Figure 2.

As illustrated in the figure, a MEC server has three layers, including the application layer, the application platform layer and the hosting infrastructure. MEC is based on a virtualized platform that should also host VNFs so that the network operators could benefit as much as possible from their investment by reusing the infrastructures.

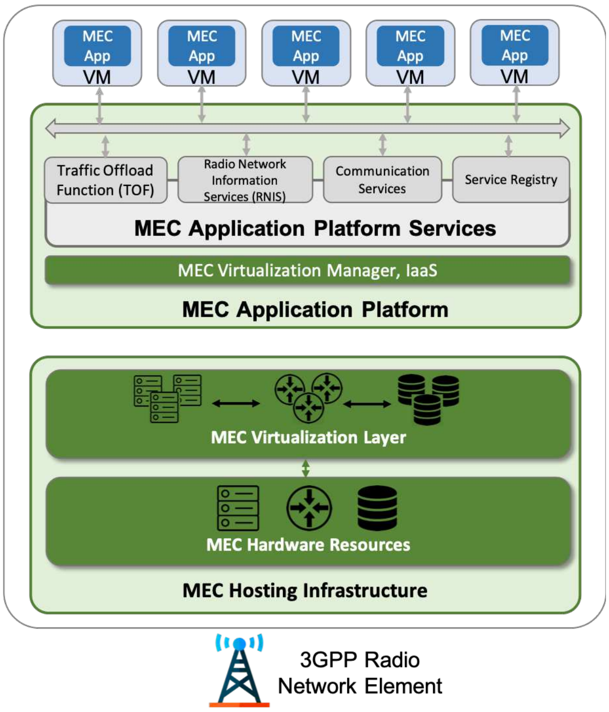

Fig. 2. A general architecture of MEC Server

The MEC hosting infrastructure provides connectivity to the radio network element (Evolved Node B (ENB) or Radio Network Controller (RNC)) and/or the network. The MEC application platform provides the capabilities for hosting applications and consists of the application's virtualization manager and application platform services. Specifically, the virtualization manager provides IaaS facilities. The MEC application-platform services provide a setof middleware services as shown in the figure.

For the management of the MEC server, there are three corresponding management systems, i.e., Application Management System, MEC Application Platform Management System and MEC Hosting Infrastructure Management System. These systems provide interfaces for network operators to manage the MEC application platform as well as the life cycle and operability of the applications and services that are hosted on the MEC platform. MEC has many market drivers that enable MEC to support a wide variety of use cases, such as e-Health, connected vehicles, industry automation, augmented reality, gaming and IoT services. ETSI encourages the proof-of- concept implementations of MEC to demonstrate the viability of MEC in various scenarios. Enormous research efforts have been invested following this direction. From the architecture perspective, these works could be further categorized into two groups, i.e., integrating SDN techniques into the virtualization manager and virtualization layer of the MEC servers and extending the management of MEC with the SDN techniques.

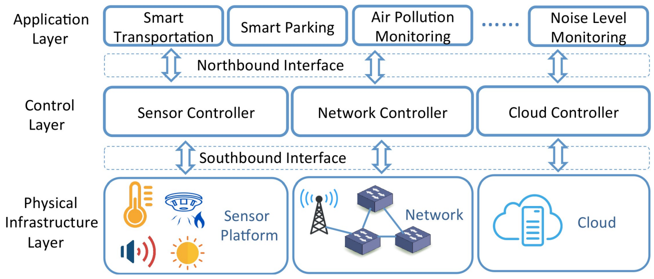

Fig. 3. Architecture of software defined IoT.

In, Liu *et al.* proposed a software-defined IoT (SD- IoT) architecture for smart urban sensing (as shown in Figure 9), decoupling high level applications from the physical infrastructure, including sensor platforms, forwarding devices and servers. It provides well-defined service APIs in terms of data acquisition, transmission and processing, through which each application (e.g., smart transportation, air pollution monitoring, noise level monitoring) could customize their own service requirements. This work also presents some open problems, such as mobility management, conflict resolution and optimization for the sensor platform and QoS enable trafficscheduling, followed with their potential solutions. The architecture of SD-IoT enables flexible control and management ofthe physical infrastructure and facilitates the development of urban sensing applications.

Network heterogeneity and ultra-densified deployment of base stations and access points pose great challenges for future smart cities, including load balancing, handover, interference issues. To cope with these issues, a converged cell-less communication architecture is proposed in. Specifically, a mobile device does not associate with any BS/AP before data transmission, whereas a centralized SDN controller isemployed to dynamically adjust which BS/APs perform the transmission based on the requirement of the mobile terminal and wireless channel status. Simulation results demonstrate that the converged scheme improves the coverage probability and energy saving at both base stations and mobile terminals.

With the growing number and extensive heterogeneity of smart devices in smart homes, current management platforms fall short in providing the convenience and flexibility to the users. To address the challenges, Xu *et al.* proposed a softwaredefined smart home platform (SDSH), by using SDN's featuresof centralization, optimization and virtualization [90]. The SDSH platform consists of three layers: a smart hardware layer, a controller layer, and an external service layer, where the controller layer could be deployed either in physical hardware at the user's home or in abstract equipment in the cloud. To achieve the intelligent and adaptive control and management of the smart home devices, the control layershields the hardware details, perceives user demands and manages system resources and task scheduling in a centralized manner. Nonetheless, a real-world deployment of such a management platform still faces several challenges.

For example, the restricted battery capacity and home obstacles pose challenges for the communication between the devices and the controller. Besides, security mechanisms are needed to protect the privacy of users' data.

Aside from its application in smart cities and smart homes, SDN is also employed in health surveillance systems. Hu *et al.* presented a general software defined healthcare net- working architecture for intelligent health surveillance based on the healthcare Internet of Things (HealthIoT) [92]. A centralized controller manages the shared infrastructure, and provides APIs for health surveillance and intelligent healthcare applications. The integration of SDN into health monitoring systems facilitates elastic control and management of the shared infrastructure.

IV. DISCUSSION

The fast development of Edge Computing and IoT applications brings a lot of new opportunities and motivates many active research projects and products in SDN, of which some representative ones have been discussed before. This leads to amix of various setups and platform configurations, as depicted in Figure 11. As we can see, the edge computing platforms usually consists of five layers: device layer, edge cloud layer, WAN (network) layer, back-end cloud layer, and application layer.

Such mixtures introduce complexities and lead some challenges that future networking research, in particular, SDN and NFV, needs to address. Not exclusively, we discuss some of these challenges in each layer, particularly focusing on how they impact the network layer.

(1) Heterogeneity. One of the ultimate goal of edge computing is to accommodate many devices and to provide various services. As a result, the heterogeneity could only increase along time. Such heterogeneity includes not only the devices and sensors used for different applications (e.g., auto-driving uses a different set of sensors and actuators than these used for smart and connected health), but also the way how these devices communicate with each other and with their service providers, e.g., using Bluetooth, wifi, celluar direct interfaces and running HTTP/TCP or UDP protocols. While the OpenFlow is the de facto standard to communicate between the SDN controller and the switch, there is no such standard for the communication from the devices to the access points. With the proliferation and the varieties of the sensors and edge devices, new standards are needed to be in place to enable smooth communication with the network layer.

(2) Interoperability. The existing literature shows that a lot of edge computing innovations, platforms, and architectures are application driven. That is, they are designed or built for a specific type of applications, such as auto-driving with RSUs or smart-homes with smart gateways. In the future, applications may be composed on such existing services, which will require the interoperability and coordination among different edge platforms and edge computing nodes. Moreover, different edge computing nodes may belong to different organizations. In addition, interoperability and coordination are essential to address the mobility of different devices. Although SDN can quickly facilitate the deployment of different nodes, how SDN can help with the coordination and interoperability of different edge computing nodes remains to be addressed. Ultimately, we envision that specialized and generic edge computing platforms would co-exist.

(3) Mobility/connectivity. In the application layers, some IoT devices naturally demand mobility support from the edge computing nodes. For example, with auto-driving, when the vehicle is traveling, the vehicle is interacting with the RSUs for traffic light information and other road condition information. Existing studies often focus on the smooth handover, with different prediction strategies, to make sure the shortest connection break. From the information or data perspective, such communications may be intermittent or sporadic depending on weather or other external factors. Given such considerations, how to properly arrange the information delivery (e.g., caching and CDN) with the SDN support so that critical information will not get lost deserves more in-depth study.

There are some cross-layer applications that require joint efforts from each layer, such as QoS and security. However, network layer plays a significant role to enforce policies of certain requirements.

(4) QoS and SLAs. Similar to the cloud computing, there are different QoS requirements from the application perspectives to the edge computing servers. For example, virtual reality is both delay sensitive and bandwidth intensive, while monitoring the heartbeat is only delay sensitive. On the other hand, the healthcare traffic deserves a higher priority than the entertainment traffic. Given the multi-tenant environment, how SDN can provision the available network resources to support different levels of QoS so as to meet the SLAs will be a critical challenge before they can be practically adopted. Virtualization (e.g., NFV) can help, but we envision that the proper interactions between the NFV and SDN is a key.

(5) Security and privacy. While delay and bandwidth are two key motivations for edge computing, an equally important one is the security and privacy by which the local data with sensitive information does not have to be uploaded to the cloud. However, when the edge servers may belong to different organizations, and multiple applications may co- exist on an edge server, security and privacy concerns again become prominent. Furthermore, with SDN networking with different edge devices, it greatly increases the attack surface and it becomes harder to defend against attacks. On the other hand, SDN also makes it more agile and scalable to deploy security functions at the edge. How SDN can help properly separate the traffic from different devices, applications, and users and provide sufficient security and privacy protection yet maximally utilizing the available communication channel deserves more research. The monitoring capabilities need to be improved for more inclusion and flexibility.

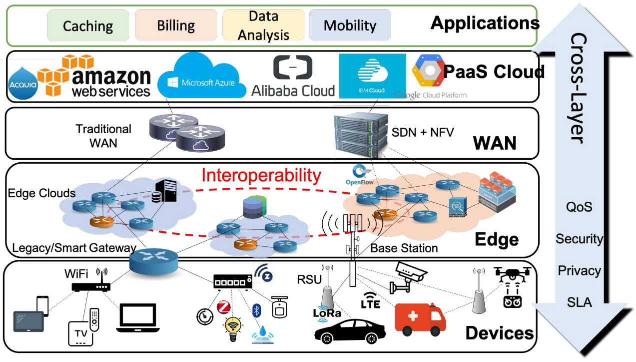

Fig. 4. The architecture of Edge Computing Platforms

V. CONCLUSION

In this paper, we have surveyed some recent and representative work in designing and implementing edge computing framework equipped with the most advanced network technologies, e.g., SDN, and how they have been applied to different application scenarios. Our investigation focuses on the network layer (including both access network and WAN) of the framework. Without loss of generality, we consider two types of "edge" devices in our explorations: mobile or stationary devices that are equipped with computing and storage capabilities, e.g., wearable devices and smart gateways; and servers and storage units deployed at the edge to provide services for other IoT devices. Considering different situations, SDN and NFV could be deployed in either access network, or core network, or the WAN between the edge and the core.

For the deployment of SDN in the access network, most existing frameworks are proposed to address the QoS or network reliability issues for mobile devices or vehicles. For the core deployment of SDN, it is usually utilized to coordinate traffic or services for different purposes, e.g., to reduce the amount of traffic being sent to the cloud, to improve the resource utilization at the edge, or to save operation energy. SD-WAN is usually deployed in a smaller scale and controllable environment, such as industry, airport or enterprise. It could serve different application requirements.

However, some challenges need further investigations for the marriage of edge computing and SDN/NFV technologies. For example, SDN is designed to be a network layer architecture. To accommodate and interact with different IoT and edge devices, it needs to support various physical and data link layer protocols, e.g., Zigbee. Furthermore, due to the different communication channels, the network functions deployed in SDN need to be carefully designed to work in such a hybrid environment. With the development of auto-driving and unmanned aerial vehicles (UAV), mobility and network connectivity of these vehicles become imperative to be addressed. Especially for the long-distance movements, interoperability of different edge clouds belonging to different organizations has not been considered yet. Some critical service requirements, such as QoS and security, layer tasks that require joint effort. In these cases, a hierarchical SDN design might be necessary. Through our investigation, we find that edge computing facilitated by SDN/NFV is still in its infancy stage. It is a promising areafull of opportunities and challenges.

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