Software-Defined Networking for Internet of Things: A Survey

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***Abstract*—Internet of things (IoT) facilitates billions of devices to be enabled with network connectivity to collect and exchange real-time information for providing *intelligent* services. Thus, IoT allows connected devices to be controlled and accessed remotely in the presence of adequate network infrastructure. Unfortunately, traditional network technologies such as enterprise networks and classic timeout-based transport protocols are not capable of handling such requirements of IoT in an efficient, scalable, seamless, and cost-effective manner. Besides, the advent of software-defined networking (SDN) introduces features that allow the network operators and users to control and access the network devices remotely, while leveraging the global view of the network. In this respect, we provide a comprehensive survey of different SDN-based technologies, which are useful to fulfill the requirements of IoT, from different networking aspects—*edge*, *access*, *core*, and *data center* networking. In these areas, the utility of SDN-based technologies is discussed, while presenting different challenges and requirements of the same in the context of IoT applications. We present a synthesized overview of the current state of IoT development. We also highlight some of the future research directions and open research issues based on the limitations of the existing SDN-based technologies.**

***Index Terms*—Access networking, core networking, data center networking, edge networking, Internet of Things (IoT), software-defined networking (SDN), survey.**

I. Introduction

THE TRADITIONAL networking infrastructure consists of different networking devices such as switches, routers, and intermediate devices, in which application-specific integrated circuits are installed to perform dedicated tasks [1], [2]. Therefore, the devices are preprogrammed with different complex rules (i.e., protocols), which cannot be modified in real-time, to perform the dedicated tasks. Moreover, due to the resource-constrained nature of the devices, they cannot be preprogrammed with multiple rules to provide optimal network services. Consequently, traditional network technologies are incapable of adapting adequate policies to meet the application-specific requirements of Internet of Things (IoT) in real-time.

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To address such limitations in the traditional networks, a new concept, known as software-defined networking (SDN), is proposed. SDN is an emerging network architecture, using which network control can be decoupled from the traditional hardware devices [3]. Therefore, the main objective of the SDN is to separate the *control plane* from the *data plane* involving the forwarding devices. As a result, adequate control logic can be implemented on the physical devices, depending on the application-specific requirements in real-time. In a generalized view, SDN consists of three layers—*infrastructure*, *control*, and *application* [4]. In addition to the layer-wise architecture of SDN, multiple application program interfaces (APIs) also exist—*northbound*, *southbound*, *eastbound*, and *westbound*. The *northbound* API is used to interface the application layer with the control layer, so that they can communicate with each other. Through the northbound API, the abstracted view of the network is also provided to the application layer. The *southbound* API is responsible for interfacing between the control and infrastructure layers, so that the controllers can deploy different rules in the forwarding devices such as routers and switches, and the latter can communicate with the controller in real-time. The *eastbound* and *westbound* APIs are responsible for interfacing between multiple controllers, so that they can take coordinated decisions. OpenFlow [5] is the most widely used protocol to enable communication between the control and data planes.

Concurrent prominent technological development of Internet of Things (IoT) enables different objects such as sensor nodes, embedded systems, and intermediate devices to collect and exchange data toward the fulfillment of the objectives of fully connected world, in the near future. Typically, an IoT architecture consists of several sensor and RFID nodes forming large-scale distributed embedded systems for different real-time applications such as smart health-care [6], [7], intelligent transportation systems [8], and smart energy systems [9]–[11].

Recently, Jagadeesan and Krishnamachari [12] discussed the applicability of SDN in wireless networks. The authors showed that some of the existing schemes support OpenFlow[1] protocol, whereas some of them are compatible with the OpenFlow. Consequently, the authors highlighted some of the key challenges present in wireless networks, which can be addressed using the concept of SDN. Sood *et al.* [13] discussed different opportunities and challenges of SDN in the context of

[1]OpenFLow is an SDN protocol.

IoT, and showed that SDN-based technologies will have major impact on IoT to make it successful for a connected world. The authors discussed recent developments of wireless and optical networks to integrate SDN and IoT together. The discussion of different scopes of SDN-based approaches in IoT is limited to wireless networks. Similarly, Caraguay *et al.* [14] discussed different challenges and opportunities of SDN-based IoT applications. They showed that SDN-based solution approaches are beneficial to address different challenges present in developing IoT applications compared to the conventional networking approaches. Moreover, there is a need to have a comprehensive discussion on SDN-based technologies in IoT from different networking aspects—*edge*, *access*, *core*, and *data center* networking, while presenting different challenges and requirements. Therefore, we believe that SDN-based solution approaches are capable of handling several issues and requirements of IoT. Consequently, we are motivated to explore different possibilities of SDN-based solution approaches in the context of IoT, while presenting different challenges involved in it.

Typically, an IoT network comprises of a combination of sensor and actuator networks, and end-users with smartphones—which acts as the edge network. Further, the edge network is supported by some gateways and access points (APs)—which is termed as access network. On top of the edge and access networks, the backbone network plays a crucial role to route the sensed and actuated data to the data center network for further processing. Therefore, the data center network also plays an important role in storing and processing the sensed and actuated information. Moreover, the architecture of a data center network is different from the backbone, access, and edge networks. To present an overview of the ongoing research efforts, in this paper, we provide a systematic overview of SDN-based technologies in IoT in different networking aspects—*edge*, *access*, *core*, and *data center* networking. For edge networking, we mainly discuss how SDN-based technologies can be used in sensor networks to manage the resource of sensor nodes efficiently. Subsequently, we also discuss the limitation of the existing SDN-based edge networking schemes in IoT. Based on the limitations, some of the future research directions are also presented. Access networking plays an important role to aggregate the sensed information. Therefore, different SDN-based data aggregation schemes are reviewed, which can be used to address different access networking challenges in IoT, while specifying several issues involved in it. Finally, we present the challenges and requirements present in *core* and *data center* network in the context of IoT, while briefly discussing the existing approaches from the aspects of IoT core and data center networks. In brief, the *contributions* of this paper are as follows.

1) Brief overview of software-defined IoT (SDIoT) is presented.
2) We discuss how SDN-based technologies can be used to overcome different issues in *edge*, *access*, *core*, and *data center* networks. Consequently, we present a comprehensive survey on the existing SDN-based technologies from the aspects of IoT.
3) Different potential future research directions are also presented on how the existing schemes can be extended further to address the limitations/challenges in order to have improved efficiency in IoT.
4) Finally, we present different *open research issues*, which are the crucial factors need to be addressed in establishing an efficient and effective IoT environment.

The rest of this paper is organized as follows. Section II presents an overview of SDIoT networking, i.e., how the SDN can address different challenges and requirements of IoT applications. Sections III and IV discuss existing SDN-based schemes in IoT from four different perspectives—*edge* and *access* networking, while describing their limitations and some potential future research directions. Additionally, Sections V and VI discuss the challenges and requirements involved in core and data center networking, while presenting a comparative analysis of the existing SDN-based approaches. Section VII presents different open research issues based on the detailed synthesis of existing solution approaches discussed in Sections III–IV. Finally, we conclude this paper in Section VIII.

II. SDIoT

In this section, we present some of the key requirements of IoT applications, which can be potentially fulfilled by SDN technologies to realize the concept of SDIoT.

A. Network Management

It is expected that in a decade or so, billions of *things* will be in use worldwide through the power of IoT technology [15]–[19]. Therefore, it is evident that huge data will be generated from the devices that need to be processed in a timely and efficient manner. Consequently, network management is an important factor for managing such an enormous collection of devices and the huge information generated by them. Thus, adequate technologies are required to distribute and control the traffic flows in the network for load balancing and minimization of network delay. Such requirements can be fulfilled by the SDN-based technology, as it leverages the global view of the network in a centralized manner. Thus, the SDN-based technologies can be applied for IoT network management such as load balancing, fine-grained traffic forwarding, and improved bandwidth utilization [20].

B. Network Function Virtualization

The predefined programmed nature of the traditional network technologies does not allow the devices to perform multiple tasks, although they are capable of doing so. Therefore, it is required to virtualize the functions of devices, and change them in real-time. The recently introduced the concept of network function virtualization (NFV) that allows the devices to perform multiple tasks, while changing their functions in real-time, depending on application-specific requirements [21]–[25]. Due to the separation of the control plane from the physical devices from the perspective of SDN, NFV is made easier to the Internet service providers. Consequently, SDN-based approaches play an important role in realizing the concept of NFV in a large-scale IoT network [26].

C. Accessing Information From Anywhere

As discussed in the above points, billions of devices are envisaged to be connected in IoT. Further, the owners of the devices should be able to access them from anywhere and at anytime, so that they are able to control and change the functions of their devices, depending on requirements, in a seamless manner [27]. It is possible to control such devices in the network with the help of SDN-based technologies, while preserving the privacy of others [28].

D. Resource Utilization

Under-utilization or over-utilization may decrease the network performance, which, in turn, minimizes the network utility. Therefore, efficient mapping of users' requests is required for improved resource utilization to maximize the utility of the network [29]. In SDN, flow-rule-based traffic forwarding helps in improved network resource utilization. Consequently, request from multiple users can be forwarded through the desired path according to the flow-rules decided by the SDN controller [30].

E. Energy Management

Huge number of data centers will be involved in processing the huge volume of data collected from billions of devices in IoT [31], [32]. Therefore, huge amount of energy will be consumed to power the data centers. Consequently, smart energy management systems also need to be ensured for energy-efficient data center networking. In SDN-based data center networking, traffic can be mapped to the adequate servers efficiently. Thus, the devices at the data center can be switched ON/OFF dynamically, depending on the requirements [33], which, in turn, establishes an energy-efficient data center networking. This feature can be used from the perspective of IoT network [34].

F. Security and Privacy

Finally, securing the devices and network is an important consideration for allowing multiple devices, vendors, and users to participate in a single platform [35], [36]. For example, a set of devices is associated with a particular service provider. Therefore, the control of such devices should only be allowed to the particular service provider. Moreover, other service providers should not be able to get access to the data generated by the devices although they have the data. Concurrently, privacy is a major issue to the users present in an IoT network. Due to the integration of multiple devices into a single platform, multiple authorities may have the information of who is doing what, which, in turn, violates the privacy of the users. Consequently, researchers need to consider such cases in order to preserve the privacy of the users, while integrating multiple devices into a single platform. The fine-grained control of flows using SDN enhance security and privacy of network traffic [37].

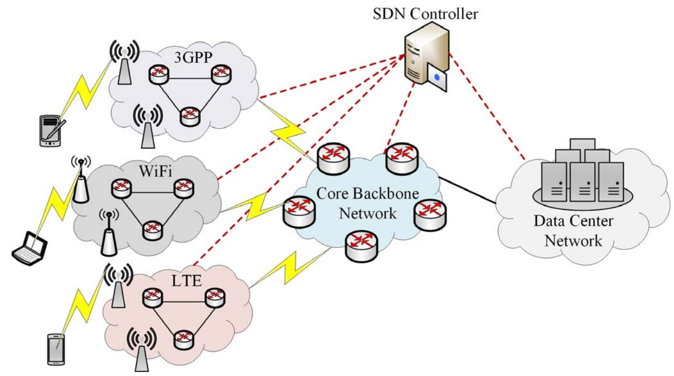

Fig. 1. Schematic of SDIoT.

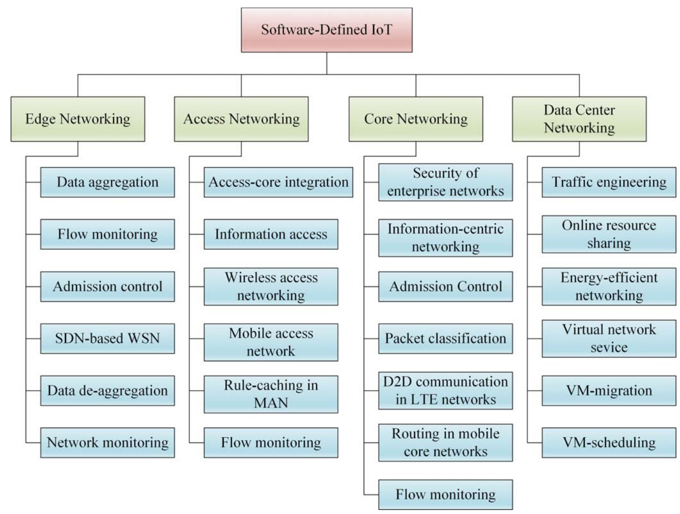

Fig. 2. Overview of different aspects of SDN-based IoT networks.

From the above mentioned facts, it is evident that SDN-based technologies will have major impact in managing the IoT network from the aspects of edge, access, core, and data center networks.

Fig. 1 presents a schematic of SDN-enabled IoT architecture with edge, access, core, and data center networking. In the subsequent sections, we discuss these networking aspects in detail with different challenges and requirements in the context of IoT applications. Further, Fig. 2 presents an overview of SDN-based IoT networks aspects, which are considered in the existing works.

III. SDN-BASED EDGE NETWORKING

In this section, we discuss the different requirements of IoT applications, and the existing approaches which are useful to address these requirements in respect of edge networking.

A. Requirements at Edge Network

In IoT, several sensors and actuators are integrated into multiple devices to monitor/measure different parameters (such as health condition). Therefore, it is necessary to gather and aggregate the sensed and actuated data from the nodes[2]

[2]Combination of sensor and actuators.

in an efficient manner. We excerpt below some of the crucial issues involved in data collection in IoT.

1) Unified Information Collection From Devices: Typically, in an IoT edge network, multiple sensors and actuators, which are heterogeneous in nature, are interconnected. Therefore, it is necessary to have adequate technologies to bridge such heterogeneity, so that the devices can communicate with one another and exchange information in a unified manner. However, the vendor-specific requirements [38] of the traditional devices do not allow them to participate into a single platform. Consequently, it is required to have a unified data collection mechanism from the sensors and actuators present in the IoT edge network.

2) Unstructured Data: As mentioned in Section III-A1, heterogeneous devices participate in a single platform. Therefore, it is evident that data format of the sensed/actuated information can be different due to the *vendor-specific* properties. However, the sensed/actuated information must be gathered/aggregated in a precise manner. Adequate data aggregation mechanism is also an important aspect to consider in the IoT edge networks. For example, the heterogeneous data is collected by a single aggregator, but it should be possible to extract the original data from the aggregated one.

3) Adoption of New Technologies: Another important issue in the IoT edge network is the adoption of new technologies by its users. Users always prefer new technologies to get efficient QoS from their service operators [39]. As a result, devices must be supported to adopt new technologies without changing the hardware. The SDN-based approaches are useful to support the new technology in a unified manner, due to the separation in the control and data planes.

B. Existing SDN-Based Edge Networking Schemes

Recently, researchers proposed several SDN-based schemes for efficient data collection and network flow monitoring in the context of edge networking, which can be applied for IoT applications. We discuss the existing schemes in three different aspects—data aggregation, network monitoring, and information collection in wireless sensor networks (WSNs) [34].

1) Data Aggregation: Das and Sahni [40] studied the configurations of network topology for data aggregation. They analyzed the limitations and complexity of a single aggregator network optimization (SANTO) approach. Further, the network traffic optimization using SANTO is studied. They showed that the optimization problem of data aggregation is NP hard, even in the presence of single aggregator in the network. Consequently, they proposed an SDN-based data aggregation scheme, in which a longest processing time-based approximation algorithm is used to solve the problem. The proposed scheme is divided into two optimization problems. First, an optimization problem is formulated through which the nodes form different tree topology to minimize the aggregation time. Second, the constructed tree topology is optimized, for which the total network traffic is minimized. Therefore, they used a combined approach for data aggregation and network traffic optimization. It is observed that the proposed scheme can be applied in an IoT network consisting of several sensors/actuators to minimize the data aggregation time and network traffic optimization.

In OpenFlow-based flow-rule placement, the SDN controller controls the entire network, while leveraging the global view of the latter. Consequently, the network flows can be monitored and analyzed for taking improved decisions. However, per-flow analysis increases the complexity and control overhead in the network. In this respect, Huang *et al.* [41] proposed an admission control mechanism with flow aggregation in SDN. Network calculus is used to optimize the admission control, while checking the available buffer space and bandwidth in the network. Therefore, the proposed scheme ensures that the performance of the flows, which are already admitted, does not get affected due to the admission of a new flow in the network. Additionally, the proposed scheme also consumes less amount of buffer space through the admission control and data aggregation. This feature would help seamless aggregation of traffic from billions of devices.

As discussed in Section III-A, an IoT network comprises of heterogeneous devices. Therefore, the control and communication technologies vary from device to device. Due to the separation of the control plane from the physical devices using the concept of SDN, it is possible to control the devices in a uniform manner. Consequently, device virtualization plays an important role to provide a unified control mechanisms for all devices present in an IoT network. Patouni *et al.* [22] proposed SDN-based virtualization techniques for sensors management. In the proposed scheme, integration of wireless services, cell management, and sensor management are discussed, while utilizing the benefits of SDN. The authors showed that using SDN-based technologies, virtualization of network services can be done for improved network services over the traditional disruptive networking paradigms.

Malboubi *et al.* [42] proposed an SDN-based traffic aggregation and measurement paradigm for optimal data aggregation. Two optimization problems are formulated—the aggregation of traffic flows and de-aggregation of the most important flows from the aggregated ones. Ternary content addressable memory (TCAM) is used for both aggregation and de-aggregation processes. In such an approach, the TCAM is divided into two parts—one for aggregation of flows and the other for de-aggregation of the important flows. Consequently, the important flows are analyzed to effectively analyze the network behavior through multiarmed bandit-based optimization approach. Thus, the overhead in analyzing per-flow statistics is minimized. It is observed that the proposed scheme is capable of measuring network behavior through the aggregation and de-aggregation techniques.

Consequently, it is evident that the SDN-based solution approaches are useful to aggregate the data coming from heterogeneous devices in an IoT environment, while optimizing the traffic flow in the network.

2) Network Monitoring: SDN is capable of providing a global view of the network to its operators. Therefore, in contrast to the traditional network flow monitoring schemes (such as NetFlow [43] and sFlow [44]), global network can be monitored efficiently with SDN, while installing a suitable monitoring module. The network monitoring in SDN can be done in two ways—probing by the controller and reporting from switches while there is a change in the network behavior. In the former, the controller sends probe messages to the switches to get network statistics. This is typically done in a periodic manner. Consequently, network probing increases OPEX cost and network control overhead. On the other hand, in the latter approach, the switches send network statistics while there is a change in the network. Although such method poses less control overhead, accuracy of network behavior measurements is compromised, i.e., per-flow statistics are not available to the controller. Therefore, there exists a tradeoff between the control overhead and the accuracy. In this respect, Su *et al.* [45] proposed a flow monitoring scheme to minimize communication cost in the network. In their work, a heuristic-based optimization approach is used to aggregate polling requests from devices and responses, in order to optimize the communication cost, while enabling the tracking of the global view of the network. Similarly, Liu *et al.* [46] proposed a flow-update mechanism in the network, while considering available bandwidth and flow-table capacity constraints. In such a scheme, heuristic optimization is used to update the flow-table rules in an effective and efficient manner.

Sándor *et al.* [47] analyzed end-to-end transmission performance in an IoT network in the presence of communication anomalies. The authors proposed a hybrid network infrastructure (i.e., combination of SDN and non-SDN) to improve the network performance. Therefore, based on the requirements and network statistics, SDN and non-SDN-based control mechanisms are deployed. Boussard *et al.* [48] proposed software-defined LAN-based interconnection mechanism for heterogeneous devices present in the network, while manipulating control logic of the devices. Therefore, the devices in the network are interconnected and established a smart environment. The authors presented two types of controller architecture—*network controller* and *virtual object controller*. Network controller corresponds to the traditional SDN controller. On the other hand, the virtual object controller is the extension of network controllers, which can be controlled by the latter one.

3) SDN-Based Information Collection in WSN: A software-defined WSN architecture is proposed by Jayashree and Princy [49] to minimize the energy consumption of sensor nodes. The authors assumed that the cluster-head nodes can act as switches, and they can interact with a centralized controller situated at the base-station (BSs). Therefore, the sensor nodes can be programmed dynamically in real-time depending on the requirements. Moreover, the cluster nodes can also be selected dynamically, and associated flow-rules can be deployed at the cluster head nodes. However, the resource-constrained nature of the sensor nodes should be taken into consideration, while controlling the network in a centralized manner. Similarly, Zeng *et al.* [50] proposed software-defined sensor networks for energy consumption minimization, in which the sensor nodes are enabled with multitasking facility. The authors formed the energy consumption minimization problem as a mixed integer quadratic constraints programming (MIQP). Further, the formed MIQP is formulated as mixed integer linear programming to solve the problem with low computation complexity, while linearizing the optimization problem. Subsequently, the authors showed that using the proposed scheme, the sensing task of the nodes can be switched from one to another efficiently, depending on the application-specific requirements. Luo *et al.* [51] proposed an software-defined WSN platform and addressed different technical challenges involved in it. Two-types of forwarding table format are presented—*node-based* and *value-based*. In *node-based* forwarding, sensed information from the nodes is compared with their node-IDs in order to forward the further down-stream. For example, a node A is allowed to forward the data from node B, however, it is not allowed to forward the data of node C. On the other hand, the value of sensed information is compared in the *value-based* forwarding scheme. For example, when the temperature is above 40 °C, a node forwards the data. Otherwise, it drops the data coming from other nodes.

We summarize in Table I the existing SDN-based data aggregation schemes which are suitable for IoT applications.

IV. SDN-Based Access Networking in IoT

In this section, we present different challenges and requirements of IoT applications and the existing solution approaches from the perspective of access networking.

A. Requirements at Access Network

1) Access-Core Network Layer Integration: The integration of two network layers (corresponding to two different devices heterogeneous in nature), so that they can communicate with each other in an efficient manner, thereby improving the scalability and flexibility of the network [55]. Additionally, to meet the requirements of the digital world, existing technologies are required to be replaced with newer technologies [51]. It is evident that newer technologies would be expensive, while replacing the existing ones. Consequently, we need novel interoperability mechanisms which can balance the replacement of existing technologies to a large extent, i.e., existing technologies can be used with minor modification/integration. Therefore, the integration of network layers among multiple devices is required to ensure, so that the access devices can exchange the flow-table information with the devices present in core network.

2) Dynamic Resource Allocation: Dynamic resource allocation is an important factor to ensure load balancing of the network traffic. Therefore, the network must be programmable to support application-specific requirements of IoT. For example, *delay-sensitive* flows must be forwarded through the shortest path. Whereas *loss-sensitive* flows must be forwarded through reliable path, i.e., the path may be the longest one with minimum loss. However, the existing networking technologies do not support such dynamic requirements of IoT through which control logic can be reconfigured [56]. As a result, available resources may be under-utilized due to the lack of dynamic rule-placement facility.

TABLE I
SUMMARY OF SDN-BASED EDGE NETWORKING SCHEMES

Application	SDN-Based Applications	Future Research Directions
Data aggregation (as in [40])	Two optimization problems are formulated — a) construction of tree topology with single aggregator for minimizing data aggregation time; b) Minimization of total network traffic of constructed topologies in first step.	• Use of multiple aggregators can be studied instead of single aggregator, where the data can be aggregated in a hierarchical manner. • The proposed scheme is an NP-hard problem. Therefore, heuristic optimization approaches can be applied.
FlowCover (as in [45])	Flow monitoring scheme is proposed using heuristic optimization to minimize communication cost, while leveraging global view of network topology and active network flows.	• The proposed scheme can be extended to use in multi-tenant scenarios where multiple parties are expected to participate. • In addition to the communication cost, network traffic load and latency can be optimized.
Flow-update (as in [46])	• Flow-update mechanism is proposed, while considering link bandwidth and flow-table capacity constraints. • Heuristic optimization is used to update the rules in an efficient and effective manner.	• Devices' mobility can be considered with link bandwidth and flow-table capacity to update the flow-table rules.
Admission control with flow aggregation (as in [41])	Admission control with flow aggregation is proposed to determine required bandwidth and buffer space for maintaining QoS using network calculus.	• Prioritized flow-scheduling can be implemented, so that the flows with higher priorities are admitted first. • Dynamic VM integration depending on the density of flows.
SDN-based WSN (as in [49]–[51])	Software-defined WSN is proposed for efficient data aggregation, task scheduling and energy consumption minimization of sensor nodes.	• Network connectivity and communication overhead can be analyzed in addition with the energy consumption minimization of sensor nodes. • Preserving privacy of sensor nodes and sensed information is also a crucial factor which needs to be ensured. • Novel rule caching mechanism is required as the sensor nodes are resource constraint in nature.
Distributed Aggregation (as in [52])	SDN-based optical network architecture is proposed for efficient distributed data aggregation.	• Global view of the network can be enabled with SDN and open networking models to optimize the performance further.
Intelligent traffic (de)aggregation (as in [42])	Proposed data aggregation scheme is divided into two parts — optimal aggregation of incoming flows and de-aggregation of most informative flows.	• Optimal use of TCAM can be incorporated with the proposed scheme, as it is highly cost-expensive. • Additionally, TCAM is also energy-expensive. Therefore, energy consumption of the switches can be optimized, while using the TCAM frequently.
Software-defined aggregation networks (as in [53])	Dynamic bandwidth optimization algorithm is proposed in software-defined aggregation networks for efficient resource utilization.	• The proposed scheme can be extended for multi-user scenario, and the performance of the proposed scheme can be studied in terms of traffic scheduling, network delay and resource utilization.
PayLess (as in [54])	• Application monitoring framework is proposed which provides flexible data aggregation at different levels. • RESTfull-APIs are proposed to monitor different applications, such as intrusion detection, link-usage monitoring, user billing, and differentiated QoS management.	• Supporting application-specific requirements of IoT on top of the proposed PayLess architecture. • Autonomous QoS management policy can be incorporated on top of the proposed scheme.
Software-defined LANs (as in [48])	Proposed SDN-based LAN architecture for interconnecting heterogeneous devices in order to establish a smart environment.	Security and privacy issues are important concerns, while allowing heterogeneous devices to be interconnected in a single platform.

3) Distributed Architecture: The network architecture must be simple to minimize the complexity, so that multiple vendors can participate in a single platform to provide services. Therefore, a simplified architecture would enable platform independent networking among multiple devices [57]. The concept of Web of things [58] addresses the heterogeneity issues by allowing multiple devices to communicate with one another, based on open-protocols such as HTTP and REST. However, the existing solutions do not support scalability and security aspects of IoT [56], [59]. Specifically, it does not support the distributed publish-subscribe (pub-sub) architecture which is a key requirement of IoT.

In the subsequent section, we discuss the existing SDN-based access networking technologies, which have the potential to address different issues and challenges mentioned above in the context of IoT applications.

B. SDN-Based Access Networking in IoT

To address the above mentioned requirements, researchers proposed several schemes in the past decade. We discuss the existing schemes which are beneficial to address different problems and challenges present in access networking.

1) Access-Core Integration by Simplifying Network Architecture: Due to the growing interests of machine-to-machine communications and massive connectivity of IoT devices, it is expected that the access network will experience a major strain in near future. Integration of heterogeneous access networks into a single platform facilitates seamless data exchange among multiple devices. In this aspect, Orphanoudakis *et al.* [52] proposed a hybrid long-range optical access network architecture to minimize operating cost and energy consumption. In such a scheme, an active remote node (ARN) is introduced as the interface between the end-users and the backhaul network. Therefore, the ARN is responsible for short range communication, mainly wireless, and the long range passive optical networks (PONs) work in the backhaul network to provide log-range connectivity. Such architecture can provide improved network virtualization and efficient resource management, while enabled with SDN. The proposed scheme also integrates the access network with core network for efficient data exchange with one another. Surligas *et al.* [60] discussed a heterogeneous wireless networking architecture with software-defined radio (SDR). Using the SDR-based system, desired frequency can be achieved in real-time to enable communication between two heterogeneous devices. Consequently, the heterogeneous devices present in an IoT network can be connected together without having complex architecture and multiple transceivers. The authors developed a prototype with two different wireless technology—IEEE 802.11 and IEEE 802.15.4—to show the effectiveness of the proposed scheme. It is evident that the SDR-based access technology will play an important role to connect heterogeneous devices into a single platform. Similarly, Riera *et al.* [61] introduced an ARN between central network and end-user premises in order to deal with wired-wireless convergence issues in an IoT environment. The ARN acts as an intermediate device between fixed backbone networks and wireless networks. Consequently, the ARN also deals with associated bandwidth issues between two different networks.

Due to the advent of SDN, it is expected that the traditional network devices will be replaced by SDN-enabled devices. Consequently, service providers will experience a huge increase in the CAPEX cost. In contrast to the replacement of the traditional network devices, can we have some policy through which the former can be used along with new devices enabled with SDN? To address such issue, Clegg *et al.* [62] proposed an SDN-based network architecture, which is capable of enabling different access technologies with minimal changes in the network. Thus, enabling new networking technologies in the existing networking devices is done, while minimizing the associated cost in the process. The proposed scheme is tested on a gigabit Ethernet PON (GEPON), and it is evident that OpenFlow functionality can be integrated on the existing devices through their management planes.

Kerpez *et al.* [63] proposed a software-defined access network (SDAN) architecture, which captures the benefits of SDN and NFV technologies. The proposed scheme provides a common interface to different controllers owned by multiple operators. It supports multicommodity architecture for access networking, where multiple vendors can operate in a single platform. The authors presented different applications of the proposed SDAN architecture such as dynamic bandwidth allocation, service differentiation, network monitoring, and dynamic spectrum management. In another study, Dai *et al.* [64] proposed a software-defined multiple access mechanism to support application-specific requirements of IoT, while enabling run-time adaptive configuration of available access schemes. Nonorthogonal multiple access (NOMA) technology is introduced to interact multiple devices in the network. In contrast to the traditional multiple access technologies, NOMA is capable of allocating resources to more number of users through nonorthogonal allocation strategy. The proposed scheme is useful to address different challenges present in IoT, as mentioned in Section IV-A.

A proxy-based control plane architecture is proposed by Kim *et al.* [65] for wireless networks. In the proposed scheme, two types of controllers are designed—proxy-based SDN controller (PSC) and main SDN controller (MSC). First, PSC provides a control plane for APs deployed in wireless networks, while replacing some of the responsibilities of MSC. Second, the PSCs are controlled by MSCs whenever there is a change in the topology, as mobility is one of the important issues in wireless networks. Thus, the even-driven nature of wireless networks is supported with the proposed scheme, while improving the scalability and reliability of the network.

SDR resource management in cellular networks is proposed by Vassilakis *et al.* [66]. The authors considered different concepts such as network declassification, heterogeneity, and differentiation of control plane in cellular networks. Using the proposed scheme, macro BSs are capable of allocating adequate resources to small-scale BSs, in order to improve efficiency and QoS during hand-offs, while considering the mobility of users/vehicles in the network. Beside the resource management, mobility management is an important issue in IoT network, as most of the devices are mobile in nature. Due to the mobility of end-users, it is expected that the users will connect to multiple access networks. In this aspect, Wu *et al.* [67] proposed a mobility management framework in the SDIoT architecture, while considering ubiquitous flow control in multinetworks. Multiple controllers are placed according to geographical areas of the APs. Accordingly, flow-rules are placed at the APs by their respective controllers. Additionally, best match between the controllers and the APs are also analyzed.

2) Pub-Sub-Based Architecture: Pub-sub architecture provides greater scalability in a dynamic network topology. In such an architecture, message senders publish messages without having details knowledge of the receivers, known as subscribers. On the other hand, the subscribers also express their interests in receiving different messages without knowing about the publishers in detail. This is an important aspects of IoT applications, in which multiple devices are expected to act together without knowing about one another in detail. Hakiri *et al.* [56] proposed a pub-sub SDN architecture to enable scalable and efficient IoT communications, while integrating data distribution services (DDSs). Different access networking devices, such as smart objects and gateways, pub-sub data through a DDS middleware. The proposed pub-sub abstraction layer is independent of specific networking protocol and technology. Therefore, application-specific protocols can be deployed in the network dynamically, thereby improving QoS in the network. The authors discussed different issues in IoT, such as standardization, interoperability, mobility, scalability, and network management, which can be addressed using the proposed scheme.

3) SDN-Based Optical Access Networks: Chitimalla *et al.* [68] proposed a feedback-based software-defined optical network architecture, in which users provide application-specific feedback to network service providers. According to the feedback received from users, adequate decisions are made in order to improve QoS of the network. The proposed scheme also ensures improved service delivery models with improved client-service-level differentiation. Similarly, Wang *et al.* [69] proposed an SDN architecture to control optical access networks, while enabling the global view of the network. In such a scheme, the SDN controller collects network statistics based on per-flow analysis. Accordingly, the controller explores optimum path for data forwarding, while considering the required QoS to the users. The authors evaluated the proposed scheme in GEPON networks, and showed that such approach is useful to minimize energy consumption in the network.

4) Flow-Based Information Accessing: Matias *et al.* [70] proposed a per-flow-based access control mechanism, which allocates the resources depending on the service requests from users. Therefore, depending on the flows at the data-plane, adequate services can be authorized simultaneously to users. Additionally, secure access control mechanism is also ensured, as per-flow-based services are delivered. Therefore, traffic load in the network is minimized, as flows are mapped with the respective service delivery models, while avoiding collision and mis-identification. Bull *et al.* [71] proposed a preemptive flow installation mechanism in IoT using SDN. The proposed scheme dynamically learns the application-specific requirements, and deploys the required traffic rules for improving efficiency of the network. Therefore, the devices adapt the required changes in traffic rules prior to the actual packet arrival from devices. As the scheme places the flow-rules at the switches in a proactive manner, packet delivery delay can be minimized significantly.

5) Rule-Caching in Mobile Access Networks: The devices are stationary in nature in the existing solution approaches discussed so far. However, in case of mobile access networks, we need to have adequate rule-caching mechanism to orchestrate optimal performance. Dong *et al.* [72] proposed a novel rule-caching mechanism for software-defined mobile access networks. Two-layer rule space structure is designed in the proposed scheme—*memory manager* and *cache manager*. The memory manager is inserted in the SDN device and is responsible for storing the rules. On the contrary, the cache manager caches the rules defined by the centralized controller and updates the rules before they are stored by the memory manager. Therefore, an efficient rule-caching mechanism is established using the proposed software-defined mobile access networks, in order to improve energy consumption profile of the mobile nodes. Similarly, Li *et al.* [73] formulated an optimization problem for optimal rule placement at the switches, while considering the network dynamics in the presence of mobile devices. Due to the presence of mobile devices, network behavior changes frequently, which, in turn, requires frequent rule modification/placement at the switches. However, optimum rule placement in a highly dynamic network is an NP-hard problem. Therefore, heuristic optimization [74] is used to place flow-rules at the SDN switches to deal with the dynamic behavior of the network.

We summarize the existing SDN-based access networking technologies in Table II, while offering insights into future research directions.

V. SDN-BASED CORE NETWORKING IN IoT

This section provides a brief overview of different challenges and requirements involved in core networking of IoT applications. Further, we present a comparative analysis of the existing SDN-based core networking technologies in a tabular format.

A. Requirements at Core Network

1) Adequate Security Mechanism at Core Network: The security of enterprise network is an important concern. There exists two well-established solution approaches—distributed host-based and centralized security using network intrusion detection system (NIDS) at the core network. However, the existing solution approaches fail in different respects. The NIDS-based schemes require additional infrastructure [77] due to high aggregate data-rates. Additionally, the network operators have very limited global-view of the network. On the other hand, the host-based solution approaches are OS-specific and may lead to solutions converging merely to local optima. Therefore, we need to have adequate security mechanisms at the core network in order to block different malicious activities.

2) Issues With Traditional Classification Approaches: These approaches suffer from searching a particular action taken at a single networking device, as global view of the network is not supported with the traditional networking

TABLE II
SUMMARY OF SDN-BASED ACCESS NETWORKING IN IOT

Application	**SDN-Based Applications**	**Future Research Directions**
Network access-core integration (as in [52])	Proposed SDN-based optical network architecture for network processing and information routing, while integrating access and core networks together.	• Dynamic resource allocation through programmable networks, while integrating access and core networks to improve flexibility and scalability of the network.
Accessing information (as in [62])	Proposed a scheme which enables OpenFlow at access networking devices with minimal changes. It would help the network operator to monitor/control the access devices efficiently.	• In the proposed scheme, some of the devices may not be enabled with OpenFlow. Therefore, studying different interfacing mechanisms among devices in the semi-OpenFlow-enabled network, so that the devices can communicate with one another efficiently.
Simplifying access network (as in [63], [75])	• Proposed next-generation software-defined access network to simply the access network to make it simple, agile, and elastic. • Access network control and management are virtualized. • It can be used in multi-operator environment appropriately.	• The proposed scheme can be extended further to cope up with the growing development of access networks. • Different pricing and billing policies can be proposed for vendor-specific services, as multiple vendors provide services in a single platform.
Scalable IoT communications (as in [56], [76])	Publish-subscribe architecture is proposed, while integrating SDN and IoT together, which enables scalable IoT communications and also brings flexibility to the network.	• Energy-efficiency and resource management are important aspects in IoT which need to be addressed, while introducing a middleware in the network architecture.
Ethernet optical access network (as in [68], [69])	• A SDN-based Ethernet optical access network is proposed to enable application-specific feedback system from customers for better service delivery. • Energy-efficient optical access network is proposed.	• In the proposed scheme, downstream network flow management is considered. However, in IoT applications, upstream network flow management is also a research challenge. Therefore, novel upstream network flow management scheme can be proposed in addition to the downstream flow.
Wireless access networking (as in [65])	• A proxy-based software-defined wireless access networking scheme is proposed for wireless access points. • The proposed scheme can adaptively change strategies in different situations — network partitions and control bottlenecks.	• In the propose scheme, it is assumed that a PSC is controlled by only one MSC. Therefore, the master-slave architecture can be studied in the presence of multiple MSCs. • Mobility-aware application-specific service differentiation can be studied using the concept of network function virtualization (NFV).
Mobile access network (as in [66])	SDN-based radio resource management scheme is proposed to allocate resources to small-scale base stations to ensure better QoS during hand-offs.	• In the proposed scheme, an approximation-based method is used. Network calculus can be used to capture the randomness of the proposed scheme.
Flow-based network access control (as in [70])	SDN-based per-flow network access control mechanism is proposed to support application-specific requirements.	• Adequate flow-scheduling scheme needs to be implemented so that none of the flows are stalled in the network. Additionally, network delay can also be minimized.
Dynamic flow installation (as in [71])	• Dynamic flow installation technique is proposed. • Devices adapt adequate traffic rules before actual packet arrival, and thus, improves efficiency of the network.	• As mentioned by the authors, the adaptation of traffic rules can be studied in the presence of heterogeneous networks.
Rule-caching in mobile access network (as in [72], [73])	• SDN-based rule caching mechanism is proposed in mobile access network, while considering nodes' mobility in the network. • Heuristic optimization approach is used with low-complexity to minimize the overhead involved in rule-placement.	• Efficient hand-off mechanism needs to be studied to improve the QoS, while the users move from one BS to another BS. • Energy-efficiency is another important aspect which needs to be considered, while replacing the forwarding rules dynamically.

technologies. Therefore, we need an adequate classification mechanism for efficient searching in the network.

3) Adequate Network Traffic Distribution: Due to the presence of heterogeneous devices in IoT, as discussed in Section III, it is evident that different application-specific routing requests should be handled efficiently, while fulfilling users' requirements. Application-specific requests should be redirected as per the requests received within the intermediate

TABLE III
SUMMARY OF SDN-BASED CORE NETWORKING IN IoT

Application	**SDN-Based Scheme**	**Future Research Directions**
Securing enterprise network (as in [78])	• SDN-based hybrid security framework is proposed for enterprise networks. • It is the combination of *host-based* and *network-intrusion* detection systems to capture benefits of the both.	• Network throughput is minimized due to the extra load on the network. Therefore, the proposed scheme can be extended further in which network throughput remains unchanged.
Information-centric networking (as in [79]–[81])	Content-centric networking scheme is proposed in semi-SDN-enabled network, which enhances load-balancing and traffic-monitoring in the network.	• Implementation of node-centric and content-centric networking scheme can be proposed to meet application-specific requirements, while minimizing delay and cost involved in the process.
Packet classification (as in [82])	Global packet classification method is proposed to analyze packet behavior in the SDN-enabled network.	• As mentioned by the authors, compressed self-indexes [83] and Boolean expression minimization [84] can be applied to optimize the packet classification method further.
Device-to-device communication in LTE networks (as in [85])	Proposed device-to-device communication method in SDN-enabled LTE networks to improve QoE of users.	• Different security aspects need to be considered, while allowing devices to communicate with one another.
Routing in mobile core networks (as in [86], [87])	• A routing protocol is proposed for software-defined mobile core networks. • Resource redirection and flow routing are jointly optimized for efficient service delivery.	• Dynamic load balancing scheme can be proposed depending on the application-specific requirements. • Minimization of network delay and operation cost can also be minimized.

nodes, while minimizing the associated cost, network load, and delay.

We limit our discussion on the core technologies present from the aspects of SDIoT. We believe that the existing technologies are useful to meet the requirements of IoT core networks. Additionally, there are existing survey papers which focused on the core network technologies [1], [3]. In Table III, we summarize the existing SDN-based core networking schemes, which are suitable to address the challenges mentioned above, with some future research directions.

VI. SDN-BASED DATA CENTER NETWORKING

In this section, we present the challenges and requirements for efficient data center networking from the perspective of IoT application requirements, while presenting a comparative analysis of the existing SDN-based data center networking schemes in a tabular format.

A. Requirements at Data Center Network

1) Efficient Flow Handling: Typically, there are two types of flows in a network—*long-lived* flows and *short-lived* flows. The *long-lived* and the *short-lived* flows are known as *elephant-* and *mice-flows*, respectively. Therefore, it is necessary to handle both flows efficiently without disrupting one another. However, existing traffic engineering approaches can cause congestion to the short-lived flows if they are not handled in an efficient manner [88].

2) Traffic-Aware VM Deployments: Virtual machines (VMs) play an important role in data center networks to serve users' requests. The VMs are hosted by different data centers to serve the requests. We discussed in Section V-A that application-specific requests should be distributed in an efficient manner within intermediate nodes to minimize the associated cost and network load. Eventually, the requests are fetched to VMs, and the VMs execute the requests and reply back to the users. Therefore, the VMs must be deployed dynamically in such a way that they are adequate to serve the requests, while minimizing the associated cost.

3) Energy-Efficient Data Center Networking: Data centers are one of the most power-hungry consumers [33], in which most of the power consumption is due to the lack of efficient mechanisms and under-utilization of resources. Therefore, the minimization of energy consumption at data centers is a key factor to promote the concept of green technology. Consequently, adequate techniques need to be proposed for energy-efficient data center networking.

4) Over- and Under-Subscription of Services: Another important issue is over- and under-subscription of services. Typically, customers prefer to subscribe more resources in advance to meet real-time requirements, as real-time resource subscription is more costly [89]. Therefore, some of the data center may be over- and under-utilized due to the more and less number of requests, respectively, in real-time from customers. Consequently, a dynamic request mapping technique is required to distribute the requests among data centers.

5) Seamless Mobility of VMs: Typically, VMs are hosted by particular data centers, and they cannot be migrated from one data center to another without disrupting the ongoing services. However, providing seamless connectivity is a key aspect of

TABLE IV
SUMMARY OF SDN-BASED DATA CENTER NETWORKING IN IoT

Application	SDN-Based Applications	Future Research Directions
Traffic engineering in data center (as in [88], [90]–[92])	• Proposed an SDN-based traffic engineering scheme to improve scalability and load balancing at data center. • Traffic-aware VM deployment and inter-data center communication technology are studied to serve users' requests in an efficient manner.	• Prioritized flow-scheduling scheme can be proposed to schedule the flows, while considering the time-to-live (TTL) of the flows. • Efficient VM migration and inter VM communication scheme can be proposed to meet the application-specific requirements dynamically.
Online resource sharing (as in [93])	• Proposed software-defined data center networking to share resources to make it available online to authorized users. • Simulated annealing heuristic is used to schedule the resources available online based on user requirements.	• VM migration and inter VM communication methods can be proposed to meet real-time application-specific requirements. • Security concerns should be incorporated, while sharing contents online.
Energy-efficient networking (as in [94], [95])	SDN-based routing scheme is proposed at data center network to minimize energy consumed by network flow-scheduling.	• In the proposed schemes, lower flow-sizes get higher priority compared to higher flow-sizes. Therefore, higher flow-sizes may not be served within their deadline if there is very large number of lower flow-sizes.
Virtual network service (as in [89], [96])	• Dynamic virtual networks are created across multiple data centers for efficient network operations. • It enables load balancing at data center, while re-configuring mapping of virtual links.	• As mentioned by the authors, virtual network service migration can be considered, while migrating virtual links. • In mobile environment, novel migration technique is required for providing uninterrupted network services.
Routing at data center (as in [97])	• SDN-based system is presented to enable multicast routing in data center. • The proposed multicasting scheme is capable of minimizing the size of routing tree for any given topology.	• Cooperative game-theoretic concepts can be used for such group-based communications, where data centers can form the groups based on their utility values.
VM-migration (as in [98])	• Seamless VM-mobility through multiple data centers is proposed, while leveraging software-defined networking concept. • The proposed scheme is location independent and thereby, VM migration can be handled efficiently without disrupting ongoing services.	• Dynamic mapping of virtual links must be ensured, while migrating the virtual machines from one data center to another. • The available link capacity may not be adequate although a data center is capable of hosting the newly migrated VMs. Therefore, efficient VM migration technique needs to be proposed, while considering available link-capacity.
Network virtualization (as in [99])	• Network function is virtualized dynamically depending on traffic flows and application-specific requirements.	• The proposed scheme can be extended for random network topology. • Migration of virtual network functions (VNF) can also be studied.
SDN-based IoT cloud (as in [100], [101])	• Proposed an SDN-based IoT cloud framework to manage IoT infrastructures in a unified manner. • Application-specific run-time customization can be supported, while separating the control logic from hardware devices.	• Improved resource utilization and run-time governance schemes need to be proposed. • Fine-grained policies must be ensured to deal with security and privacy issues, while allowing providing services from multi-tenant clouds.
SDN-based federated multi-cloud framework (as in [102], [103])	• Resource provisioning at federated cloud environment is studied. • The proposed framework is useful to manage and schedule resources dynamically to meet application-specific requirements.	• Inter-cloud VM-migration can be studied. • Efficient data transfer and traffic engineering can also be studied in federated cloud environment.
Cloud-based SDWNs (as in [104])	• Game-theoretic cooperative and competitive resource management scheme is proposed. • Using SDN facilities, cloud service providers distribute resources among themselves.	The proposed scheme can be studied in a distributed manner for ad-hoc networks such as VANETs and MANETs.

IoT, which needs to be assured, while serving requests by creating VMs. Therefore, seamless mobility of VMs across data centers is required for improving QoS in the data center networks.

We also limit our discussion on the data center technologies present from the aspects of SDIoT. We believe that the existing technologies from the aspects of data center networking are useful to meet the requirements of IoT. Additionally, there are existing papers which focused on the data center network technologies [1], [3]. We summarize the existing SDN-based data center networking schemes in the context of IoT applications in Table IV.

VII. Open Research Issues

As discussed in Sections I–VI, there would be massive connectivity issues among multiple devices present in IoT. To fulfill such massive requirements, researchers investing in designing solutions to find out a clear road-map for SDN-based IoT networks. In this paper, we presented the existing works which have the potential to address the challenges present in IoT edge, access, core, and data center networks from the perspective of SDN. We noted that there are several limitations in SDN-based solution approaches, while integrating them with the IoT network. Consequently, we discuss different open research issues from different aspects—*mobility*, *policy enforcement*, *hardware platform*, and *practical deployments*—based on the detailed synthesis of existing solution approaches, as discussed in Sections III–VI.

A. Issues With Mobility

Typically, an IoT environment consists of heterogeneous devices, which are both static and mobile in nature. Moreover, mobility pattern of one device may be different from others. Therefore, the network operators also need to incorporate the mobility issues, while updating forwarding rules at the devices. However, research on updating forwarding rules in the presence of mobile devices is absent in most of the existing SDN-based solution approaches. Additionally, billions of devices are expected to be connected through the power of IoT. Therefore, handling requests from billions of devices in an efficient and reliable manner is a challenging issue, while dynamically changing the forwarding rules in real-time with consideration of devices' mobility. Consequently, several issues such as optimal rule-placement, traffic flow optimization, controller placement problem, and dynamic resource allocation are need to be addressed, while considering both static and mobile behavior of an IoT environment.

B. Adequate Policy Enforcement

Adequate policy enforcement in the entire network is a challenging issue, although a few solution approaches are proposed in [105] and [106]. It is expected that multiple SDN controllers can work together in a distributed manner. Therefore, SDN policy and specification for each controller may be different, which, in turn, creates concurrency policy enforcement issues. Consequently, concurrent policy enforcement may result concurrency issues at the data plane of network switches. Therefore, adequate policy enforcement schemes need to be designed to deal with such issues.

C. Independent Platform

Using SDN technology, in-built control logic can be pulled out from network devices, and it can be reconfigured according to requirements. As a result, current hardware devices need to be managed in an efficient manner, so that they can be configured seamlessly without depending on vendor-specific hardware and protocols. However, it is difficult to support the traditional networking devices with the existing SDN technologies. Therefore, we need to have SDN-based solution approaches, which support the traditional networking devices in an abstracted manner, while considering specific hardware related issues.

D. From Theoretical Aspects to Practical Deployments

Many solution approaches are proposed in the literature, as discussed in Sections III–IV from theoretical aspects. However, there is a research lacuna between theoretical aspects and practical deployments. Different issues such as deployment policies, issues with multiple vendor-specific services, and integration of multiple devices require well-investigation before the actual deployment of the proposed schemes. Therefore, different open challenging issues such as clear market policy and how the existing devices can be supported with the new technologies need to be addressed before going for the actual deployment.

VIII. Conclusion

In this paper, we provided a detailed overview of existing SDN-based technologies in the context of IoT applications, in order to offer seamless, cost-effective, and reliable service delivery to users. Different networking aspects of IoT are discussed—*edge networking* and *access networking*. We also identified some important technical issues and presented several future research directions to address those. Additionally, we presented some of the challenges and requirements of *core* and *data center* networking from the aspects of IoT network, while presenting a comparative analysis of the existing schemes. This survey reveals that the use of SDN-based solution approaches in IoT applications is potentially useful to fulfill the requirements in establishing an IoT environment, while considering the fact that there are several challenges to support the massive connections present in the network.

In case of *edge networking*, we discussed existing SDN-based approaches which are useful to address different challenges and requirements of WSN. On the other hand, in *access networking*, we discussed the existing SDN-based solution approaches that ensure efficient edge networking in IoT such as data collection from sensors/actuators, data aggregation and de-aggregation, and admission control. On the issues of *access networking*, different access networking schemes are discussed, while leveraging the global-view of the network using SDN. Finally, we also presented an overview of the challenges presents in IoT core and data center networks, while highlighting different SDN-based approaches which are useful to address the challenges.

In sum, the integration of SDN schemes in IoT is envisioned to be useful for evolving scalable, energy-efficient, and cost-effective IoT architecture.

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