A Conceptual Framework and Architectural Considerations for Capability Enhancement in Software Defined Networks

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Abstract—**Software defined networking (SDN) is an emerging networking paradigm which gained a lot of interests from both academia and industry. SDN decomposes the control plane from the data plane and allows for the network logic to run on a software-based controller. This decomposition of network operations offers the simplification of network management and greater ease of configuration through network programmability. In this paper, we first comprehensively discuss the state-of-the-art experiences in this field and their existing challenges. We also categorize the challenges facing SDN and its integration with other technologies such as network function virtualization (NFV), internet of thing (IoT), 5G networks, big data, and optical networks. Then, considering the key issues, we revisit the SDN architecture and propose a comprehensive conceptual framework and some detailed architectural considerations for enhancing the capabilities of SDN networks. The proposed conceptual framework also applies IoT controllers and hypervisors to support IoT applications and virtualized networks respectively. Moreover, we present future research works according to the proposed framework.**

Keywords-Software Defined Networking, Capability Enhancement, Conceptual Framework, Architectural Considerations, and Network function virtualization.

I. INTRODUCTION

Current communication networks are composed of proprietary routers and switches which run their own protocols, and their configuration is handled separately via vendor specific low level commands. This results in complex administration, difficult policy enforcement and limited flexibility [1, 2]. Software defined networking is a new paradigm shift toward ease of management and programmatic control of network devices.

Fig. 1 shows an overall view of the SDN architecture which consists of three planes: application plane, control plane, and data plane. In this architecture, network devices are simple forwarding elements (FE) and form the data plane. FEs are managed by a network controller which comprises the control plane. The network controller is a logically centralized unit that directly configures data plane elements through a standard application programming interface (API) which is referred to as southbound API. A well-known example of this API is OpenFlow [3]. It defines the interaction of multiple control servers with OpenFlow-compliant switches. Open Networking Foundation (ONF) organization standardized OpenFlow protocol for the southbound interface. An overview of OpenFlow can be found in [4]. At the control plane,

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controllers implement the logic of the network in order to achieve the goal of applications in the upper plane. Application plane corresponds to the part where SDN and business applications reside. These applications communicate with the controllers via the northbound API and intend to provide services for users. The separation of planes in SDN simplifies the enforcement of policies, alleviates the update of protocols, and improves the resource allocation.

All of the SDN architectures proposed by standards producing organizations such as ONF [5], IETF [6], and ITU [7] have the three aforementioned planes. However, IETF and ITU have also considered a management plane in their proposed architectures. In the SDN architecture of IETF, the management plane resides between the application and data planes and has interfaces with each of them similar to the control plane. This management plane is responsible for monitoring, maintaining and configuring the network devices in order for them to be operational. The management plane introduced by ONF has interfaces with all of the main planes. This plane performs tasks that cannot be done in any other planes such as network device bootstrapping and policy enforcement on controllers and applications.

SDN has attracted much attention from both academia and industry over the past few years. The general principles of SDN have been well explained in multiple previous surveys. In [1], SDN architecture is described and available products for supporting SDN deployment are compared. Authors in [8] have presented SDN architecture, definition of its layers and current SDN implementations, services and applications. They also review standardization efforts towards SDN. It is worth mentioning that the standardization organizations have created study groups (SG) to work on standardizing mechanism, establishing SDN requirements, and defining protocols. These study groups include the IETF's Forwarding and Control Element Separation (ForCES) working group, study groups of ITU's Telecommunication Standardization Sector (ITU-T) such as SG11 and SG13, the Software-Defined Networking Research Group (SDNRG) at IRTF, working groups (WG) of ONF such as Architecture and Framework WG and Interfaces WG.

In [9], building blocks of an SDN infrastructure is analyzed and existing standards and protocols in each layer is surveyed. The authors in [9] divide the SDN networking problem into eight facets. Then, each layer is analyzed and its properties are explained based on different technologies. In [10], tools that facilitates the deployment and maintenance of SDN are reviewed.

In all the aforementioned works, authors mostly focus on reviewing the SDN basic architecture, protocols, and general principles. Several works also surveyed specific topics in SDN. In [11-13], the literature related to security in SDN is reviewed. Authors in [14] cover related works on hypervisors in virtualized SDN networks. Research works on leveraging SDN in 4G and 5G networks is analyzed and categorized in [15] and [16] respectively. However, these works are limited to scope and do not cover all aspects of SDN.
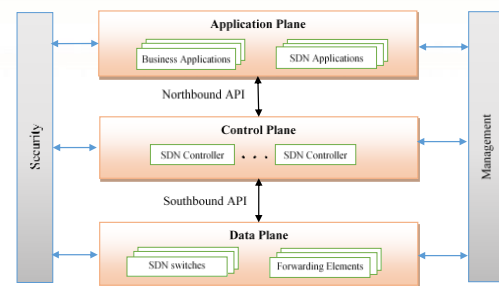

Figure 1. SDN Architecture

In this paper, we target more than one aspect of SDN and present a conceptual framework and architectural considerations that includes building blocks enhancing the SDN capabilities and sustaining its success. Specifically, we first discuss challenges related to the problems including routing, controller placement, traffic engineering, virtualization in SDN, SDN/Network function virtualization (NFV) integration, energy efficiency in SDN, SDN security and management. Moreover, we present experiences related to SDN and its integration with internet of things (IoT), 4th and 5th generation of mobile networks (4G/5G), big data, wireless networks, and optical networks. Then, considering these challenges and key issues, we propose a conceptual framework and architectural considerations for enhancing SDN capabilities. Functional building blocks differentiated by the plane are also determined in the framework.

The rest of the paper is organized as follows: Section II discusses the challenges whose solutions will result in the performance improvement of SDN. In Section III, experiences for energy efficiency of SDN are reviewed. In Section IV, security and management enhancement of SDN are discussed. Section V outlines the challenges and advantages of the integration of SDN with other applications. Section VI presents the proposed conceptual framework and architectural considerations. Finally, Section VII concludes the paper.

II. EXPRIENCES AND CHALLENGES FOR PERFORMANCE IMPROVEMENT

In this section, we present problems whose solutions help improving the SDN performance. The related works on this subject are summarized in Table. I at the end of this section.

A. Routing

In order to provide a connection between a transmitter and a receiver, a route is required to be selected between the communication points. Many routing algorithms are designed for traditional networks. These algorithms do not effectively utilize SDN characteristics such as centralized global view of the network, decoupled control and data plane, simplified network management, and high computational capabilities. In fact, it is essential to redesign the fully distributed routing algorithms to be logically centralized ones.

Routing algorithms can be divided into two categories: unicast and multicast. In unicast routing, a route is selected for the communication between a transmitter and a single receiver. In SDN networks,

multiple unicast routing algorithms are proposed considering different objectives [17-20]. In [17], routing algorithms are proposed to decrease latency and improve traffic load balance. Authors in [18] propose a routing algorithm to minimize the number of active OpenFlow switches. A genetic algorithm based routing mechanism with the objective to minimize the cost is presented in [19]. A multi-path routing scheme is presented in [20] to reduce the delay and the packet loss. In [21], a source routing algorithm is proposed for SDN-based wide area networks. In this algorithm, when the controller calculates the path, it sends the path information to the ingress switch. The ingress switch inserts the path in the packet header and forwards it accordingly. In this approach, intermediate nodes do not need to communicate with the controller. Authors in [22] and [23] assume a hybrid SDN network which includes both centralized and distributed controllers and design a routing mechanism for this network. In [24], a genetic algorithm-based routing algorithm is presented for unicast video delivery over software defined networks. The algorithm tries to find a less congested path for re-routing. Authors in [25] consider the traffic demand variations in the SDN routing problem and propose an iterative solver with decreased incurred reconfiguration cost. A stochastic optimization problem is formulated to minimize the network cost while constraining the reconfiguration budget.

Multicast routing is a mechanism for delivering data to a group of receivers. In these communications, a multicast tree including the sender and receivers is often constructed. [26-32] dealt with multicasting problem in SDN networks. In [26], an approximation algorithm is proposed to find a reliable multicast tree with minimum primary and recovery costs. Authors in [28] present a method for multicast tree construction in SDN with the objective to minimize the number of edges and nodes in a tree. A heuristic algorithm based on the combination of the shortest path routing and minimum Steiner tree method is designed in [30].

In SDN, forwarding rules are stored in Ternary Content Addressable Memory (TCAM). This memory is capacity-limited and power-hungry. Considering these characteristics, scalability of routing algorithms becomes a critical designing metric. Scalability issues are more challenging in multicast routing. This is due to the fact that every node in the multicast tree should add an entry to its forwarding table for the communication. In [33], constraints on the capacities of the rule space and the network links are taken into consideration, and a unicast energy-aware routing algorithm is proposed. In [27], an approximation algorithm is designed for the multicast tree routing problem with the node capacity constraints. Segment routing is also considered as a solution for the scalability issues in both multicast [34] and unicast routing [35, 36] in SDN. Segment routing encodes the routing information in the packet header and avoids them to be stored in TCAM memory. However, it can impose network overhead caused by larger packet headers. Addressing scalability issues in routing algorithms while satisfying various quality of service (QoS) requirements of all flows is a challenging problem and should be investigated more thoroughly in future works.

B. Controller Placement

In SDN networks, the centralized controller implements the forwarding rules in flow tables of switches based on network policies. Forwarding switches should be connected to the controller to operate correctly. Otherwise, they run old policies and cannot forward new incoming flows. To prevent the existence of a single point of failure and bottleneck in SDN networks, multiple controllers are required to be deployed. In this case, the optimal number of required controllers should be determined. On the other hand, random placement of theses controllers does not lead to desirable network performance [37]. Hence, finding the optimal place for the deployment of controllers in the network topology is another important problem.

The controller placement problem can be tackled under various objectives which will result in different solutions. Authors in [37] investigate the controller placement problem with the objective to minimize the average and worst case latency between controllers and FEs. Each problem corresponds to a facility location problem and is NP-hard. The authors use exhaustive search method to obtain the optimal solution and claim that this procedure is computationally feasible for realistic networks. In [38], this problem is extended and the limited load capacity of controllers are taken into consideration. A heuristic algorithm is proposed to solve the mentioned optimization problem. An approximation algorithm is presented in [39] which aims at finding the minimum number of controllers subject to bounded maximum and average latency. The same problem -jointly with delay-optimal control traffic path selection- is considered in [40] and a two-step algorithm is presented to solve the two sub-problems. Authors in [41] investigate more contributors of the overall latency in addition to propagation latency such as the transmission latency and the queuing latency. They introduce a clustering-based algorithm to partition the network and select the appropriate location for the controller placement. Authors in [42] consider propagation delay, hop count and link utilization for the controller placement and switch assignment problem and introduce a hybrid analytic hierarchy process and genetic algorithm to solve this problem.

Since the network environment is dynamic due to the changing traffic load and node or link failures, the reliability factor is another important objective in the controller placement problem which is investigated by some researchers [43-46]. The reliability factor is defined in terms of the reliability of the path between the controller and FE or the expected value of the probability of node or link failures. The survivability factor which is defined by the number of paths between the controller and FE is considered as another objective in [47].

Some of the mentioned objectives for the controller placement problem may conflict and a trade-off exists between these metrics. In [48], the trade-off between multiple objectives (maximum latency, average latency, and load imbalance) are investigated and a pareto simulated annealing (PSA)-based algorithm is presented to find the pareto-optimal solutions. A heuristic algorithm is also introduced in [49] for the same problem based on the non-dominated sorting

genetic algorithm (NSGA). Authors in [50] consider control network reliability, load balance among controllers and worst-case latency as objectives and propose a method based on adaptive bacterial foraging optimization (ABFO) algorithm to solve the multi-objective optimization problem.

The placement of controllers affects all aspects of the system from the distribution to fault tolerance. However, a scalable yet effective method for optimal or near-optimal placements of controllers for wide area networks is still required. Moreover, the problem of controller placement in hierarchical controller architecture needs to be explored. The dynamic controller-switch assignment with regard to the changing traffic is also another open problem.

C. Traffic Engineering

Traffic engineering (TE) is an important subject in optimizing the network performance. It can be realized through analysis, prediction and behavior setting of transmitted data. TE has been investigated in MPLS [51], ATM [52] and IP networks [53]. However, the existing solutions cannot be directly applied to SDN networks. The reason is that current solutions are designed for inflexible packet-based network architectures. Authors in [54, 55] surveyed the traffic engineering schemes for SDN. Traffic engineering mechanisms in SDN focus on the following criteria.

- Flow management: When a new flow enters the network, the SDN controller is responsible for selecting the forwarding path according to the network policy. However, new path installation requires a timely procedure. Moreover, when the number of incoming flows are high, the SDN controller can become a bottleneck as well as the switches with high traffic load. Flow management schemes address the load balancing and latency issues. Some of them balance the load across switches by splitting the flow between multiple candidate paths [56]. These methods control the traffic at the data plane. Some other flow management mechanisms aim at balancing the load between multiple controllers [57-61]. However, these methods are either static or low-adaptive. Therefore, there is a lack of solution method to dynamically adjust the load of the controllers and switches based on the dynamic network environment such as traffic characteristics.

- Failure recovery [62-68]: In order to provide reliability, recovery mechanisms are required in case of a node or link failure. Failures happen at both data and control planes. When a node or link failure in the data plane occurs, controller is responsible for performing failure recovery schemes with a centralized view of the network. After detecting the failure, the controller installs new path in the working switches for the packets traversing the failed link or switch. However, considering the delay between the control and data plane, designing fast recovery mechanisms is challenging. Additionally, for the network to continue operating in case of controller failure, it is necessary to deploy backup controllers. In this case, standard coordination protocols between the primary and backup controller are required to be designed.

- Topology update [69-73]: Configuration updates take place very often due to the dynamic nature of networks. This procedure has to be performed such that inconsistency and transient states are prevented in the network. The network update in SDN has its own challenges such as efficient updates considering inherent delay caused by the communication link between controllers and switches. Authors in [74, 75] identify and survey SDN network update problems and solutions.

- Traffic measurement and analysis [76-78]: The network traffic has to be measured and analyzed in order to gain knowledge about the traffic model which can be utilized for anomaly and failure detection, congestion prevention and network performance evaluation. Traffic measurement schemes in SDN networks have to be carefully designed to address the tradeoff between the network overhead and the measurement accuracies. They also should prevent data saturation in the controller and communication bottlenecks. Authors in [76] have surveyed measurement methods in SDN and existing challenges.

D. Virtualization in SDN

In recent years, the virtualization technology has been considered as a promising technique to improve the network performance. Virtualization involves abstracting physical resources to logical entities and sharing them by multiple parties. Through the efficient usage and isolation of resources, lower expenditure and higher flexibility are achieved. Virtualization has been effectively utilized in different areas such as computing [79], wired networks [80], and wireless networks [81]. Software defined networks can also be flexibly shared between multiple tenants through virtualization. Multiple virtualized software defined networks (vSDN) can be established for each tenant upon the same SDN infrastructure. Each vSDN has its own isolated resources which cover control and data plane resources and can operate independent of other tenants. A hypervisor is required to create vSDNs which are controlled by their virtual SDN controllers. The hypervisor can run in a central unit which potentially serves multiple virtual SDN controllers. The architecture of the hypervisor can also be distributed where virtualization functions can logically operate separately from each other. Hypervisors can be implemented in general purpose or special purpose network elements. A comprehensive survey on network virtualization hypervisors for software defined networking is presented in [14]. In addition to research challenges on SDN hypervisors outlined in [14], we present some of the challenges arising from virtualizing the SDN network in the sequel. Designing a network monitoring method for vSDNs is of great importance. A joint virtualization and routing framework subject to QoS requirements [82, 83] is required to be developed. Fault tolerance mechanisms and energy efficient

TABLE I. Summary of the Experiences and Challenges for Performance Improvement Aspects of SDN

Subject	References	Description	Challenges	Plane(s)
Routing	[17-22, 24, 25, 33, 34]	These works focus on unicast routing algorithms.	- Addressing scalability issues in routing algorithms while satisfying various quality of service (QoS) requirements of all flows	Application, Control
	[26-32, 35, 36]	These works focus on multicast routing algorithms.		
Controller Placement	[37, 38, 41]	These works address controller placement problem with the objective to minimize the average and worst case latency between controllers and FEs.	- Designing a scalable yet effective method for optimal or near-optimal placements of controllers for wide area networks - Exploring The problem of controller placement in hierarchical controller architecture - The dynamic controller-switch assignment with regard to the changing traffic	Management, Control
	[39, 40]	These works focus on controller placement problem minimizing the number of controllers subject to bounded maximum and average latency		
	[42]	This work presents controller placement problem considering propagation delay, hop count and link utilization		
	[43-46]	These works focus on controller placement problem maximizing the reliability factor		
	[47]	These works focus on controller placement problem maximizing the survivability factor		
	[48-50]	These works focus address the trade-off between multiple objectives in controller palcement problem		
Traffic Engineering	[56-61]	These schemes address the load balancing and latency issues	- lack of a dynamic solution method to adjust the load of the controllers and switches based on the dynamic network environment such as traffic characteristics	Application, Management
	[62-68]	These schemes focus on recovery mechanisms are required in case of a node or link failure	- considering the delay between the control and data plane, designing fast recovery mechanisms is challenging - standard coordination protocols between the primary and backup controller are required to be designed	
	[69-75]	These schemes present topology update and configuration updates mechanisms	- efficient updates considering inherent delay caused by the communication link between controllers and switches	
	[76-78]	These schemes focus on traffic measurement and analysis techniques	- address the tradeoff between the network overhead and the measurement accuracies. - They also should prevent data saturation in the controller and communication bottlenecks.	
Virtualization in SDN	[14, 82, 83]	These works focus on virtualized SDN networks. They either address hypervisor issues or virtualization framework	- Designing a network monitoring method for vSDNs - Fault tolerance mechanisms and energy efficient approaches for vSDNs	Application, Control and Data
SDN/NFV Integration	[84-94]	These works focus on the integration of SDN and NFV in all networks.	- Real time VNF migration between severs to achieve high throughput - Resource allocation in an SDN/NFV environments - VNF placement with the objective of achieving maximum system capacity - handover management in SDN/NFV based mobile networks.	Application, Control and Data

approaches for vSDNs are also needed to improve their performance.

E. SDN/NFV Integration

Traditionally, network functions are implemented in proprietary dedicated hardware which leads to high capital and operational expenses for service provides. Network function virtualization (NFV) technology is recently proposed to overcome these drawbacks and facilitate the deployment of new services. NFV implements network functions as software instances (called virtualized network functions (VNF)) and virtualizes them to run on commodity servers. This results in better manageability and provisioning as well as the flexible and dynamic resource usage.

The trend of integrating SDN and NFV has gained a lot of interest recently [84, 85]. SDN and NFV are related and complementary concepts. SDN can utilize the potential benefits offered by NFV based infrastructure. NFV can help SDN with virtualizing SDN controller to operate in the cloud [86]. SDN also helps NFV by providing programmable network connectivity between VNFs to achieve optimized traffic engineering and steering. In [95], the architecture of software defined NFV is explored. Furthermore,

SDN/NFV architectures have been proposed for satellite [87], IoT [88], and enterprise networks [89]. It has also been integrated in 4G/5G [90-92] and optical networks [93]. A security architecture for SDN/NFV-enabled environments is introduced in [94].

Despite the advantages brought by the integrated SDN/NFV architecture, some challenges should be addressed which includes real time VNF migration between severs to achieve high throughput, resource allocation in an SDN/NFV environments, VNF placement with the objective of achieving maximum system capacity, and handover management in SDN/NFV based mobile networks.

III. EXPRIENCES AND CHALLENGES FOR IMPROVING ENERGY EFFICIENCY

In recent years, the energy consumption of networks has been a serious problem. Based on NewYork Times report in 2012, worldwide energy consumption of datacenters is 30 billion Watts. It is estimated that ICT CO_2 emission will reach 12 percent of the worldwide emissions in 2020 [96]. The energy consumption of the networks limits their growth due to the energy cost and environmental catastrophes. Therefore, the energy consumption of networks should be taken seriously and cannot be ignored.

In recent years, lots of research have been dedicated to the energy efficiency of different wireless networks (e.g. sensor networks [97, 98], mobile networks [99], vehicular adhoc networks [100]) and various network architectures (e.g. Cloud infrastructure [101]). Utilizing the software defined networking paradigm brings several opportunities to reduce the energy consumption of networks. In [102], the potential of using SDN to reduce energy is investigated. SDN allows for the easier control of traffic and therefore leading to better utilization of links. This can result in lower energy consumption.

Some surveys overview the strategies which lead to the energy efficiency of software defined networks [103-105]. Each of these surveys divides the energy efficient methods into multiple categories. While existing categorizations lack full coverage of methods, we here present a comprehensive one as follows:

- *Ternary Content Addressable Memory (TCAM)-based solutions*

  The TCAM memory stores forwarding rules and consumes power when accessed and looked up. TCAM-based techniques [33, 106-108] aim at compacting the required memory of information stored in forwarding switches.

- *Energy efficient rule placement*

  As stated before, forwarding rules are stored in TCAM memory of the switches. This memory is capacity-constrained. Rule placement techniques aim at optimizing the rule space of switches and reduce the number of active links. The inactive links can be turned off to save energy. Therefore, these techniques (e.g. [109]) try to optimally place rules in the forwarding switches with the objective of saving energy while implementing the network policies.

- *Energy efficient controller placement*

  The number and position of controllers in SDN affects the energy consumption of a software defined network. The controller placement problem [110] can be tackled with the objective of energy minimization.

- *Energy efficient virtual machine (VM) placement*

  In an SDN-based cloud datacenter, the ability to migrate VMs between physical hosts can be utilized to reduce the energy consumption. In these approaches [111, 112], while considering QoS constraints, VMs are mapped to some of the physical hosts and others are switched off.

- *Energy efficient traffic engineering*
  - *Energy efficient traffic measurement and monitoring*

    In these approaches, network status information is collected, monitored and analyzed in an energy efficient way. For example, an intelligent energy-efficient selection method is proposed in [113] to choose the switches which the information are to be collected.

  - *Energy efficient traffic management*

    Traffic load of the network varies throughout the day and the peak capacity is not reached all the time. Traffic aware approaches [114-119] tend to switch off unutilized and underutilized network components based the varying traffic load.

  - *Energy efficient load balancing*

    Load balancing schemes can be used for energy minimization. These schemes [120, 121] aim at balancing the load of controllers and links in order to save energy.

  - *Energy efficient traffic scheduling*

    These approaches [122] try to schedule flows across switches to achieve energy saving. They also consider quality of service (QoS) requirements.

- *Specialized energy-efficient techniques in SDN-based networks*

  Several schemes have been proposed for specific SDN-based networks such as software-defined optical networks [123], software-defined wireless networks [124], and software-defined mobile networks [125].

The energy efficient methods are summarized in Table II. Although several works have tried to overcome the energy consumption minimization problem in software defined networks, there are still many challenges left to realize its full potential. In the sequel, we point out some existing important open problems in this area.

Flexible energy efficient traffic management solutions are required to adapt to dynamic traffic while being scalable. Energy efficient rule placement strategies should be designed to consider the QoS requirements of the flows and the maximum number of rules that each switch can save.

TABLE II.   SUMMARY OF THE EXPERIENCES AND CHALLENGES FOR IMPROVING ENERGY EFFICIENCY TECHNIQUES IN SDN

Subject	References	Description	Challenges	Plane(s)
Energy Efficiency	[33, 106-108]	These works aim at compacting the required memory of information stored in forwarding switches.	- Flexible energy efficient traffic management solutions are required to adapt to dynamic traffic while being scalable. - Energy efficient rule placement strategies should be designed to consider the QoS requirements of the flows and the maximum number of rules that each switch can save. - Energy aware virtual function placement schemes need to be proposed for SDN/NFV environments. - The problem of physical resource allocation to virtual networks in virtualized SDN should be tackled in order to maximize energy efficiency. - The trade-off between fairness and energy efficiency should be investigated in SDNs.	Data
	[109]	This work tries to optimally place rules in the forwarding switches with the objective of saving energy		Control, Data
	[110]	This work focuses on energy-efficient controller placement problem		Management
	[111, 112]	These works focus on energy-efficient virtual machine placement in SDN		Control, Application
	[113]	This scheme addresses the energy-efficient traffic measurement.		Management
	[114-119]	These works focus on energy-efficient traffic management.		Data, Control
	[120, 121]	These schemes address the energy-efficient load balancing problem.		Data, Control
	[122]	This work present a flow scheduling method.		Control
	[123-125]	These works present energy efficient methods for SDN-based networks.		Data, Control, Application

Energy aware virtual function placement schemes need to be proposed for SDN/NFV environments. The problem of physical resource allocation to virtual networks in virtualized SDN should be tackled in order to maximize energy efficiency. The trade-off between fairness and energy efficiency should also be investigated in SDNs.

IV.   EXPRIENCES AND CHLLENGES FOR ENHANCING SECURITY AND MANAGEMENT

A.   Security

In SDN networks, the information gained by traffic monitoring can be sent periodically to the central controller. The global and complete view provided by the SDN architecture empowers the controller to analyze this feedback from network and diagnose threats. New security policies can be disseminated through the network with less policy collision risk to prevent an attack. Moreover, security policy updates can be performed more easily.

While the SDN paradigm provides security advantages, new challenges arise due to its programmability and the centralized controller. The centralized controller which handles the logic of the network may be an attractive potential target. It can be made unreachable by the denial-of-service (DoS) attacks leading to disturbance in the network functionality. Furthermore, attacks can be performed to masquerade one plane and reprogram the network. For example, packets with forged IP addresses make the controller to install new rules in switches based on bogus information.

Several researchers review and exploit the opportunities brought by SDN for enhancing the network security [126-129]. Several others aim at surveying SDN related security issues and threats and presenting open problems [11, 12, 130-133]. A comparison between security benefits provided by SDN and security threats of SDN is provided in [134]. Some research are conducted to explore the security issues in specialized software defined networks. For instance, security problems of software-defined mobile networks are presented in [135]. Authors in [136] focus on how to prevent Distributed DoS (DDoS) attacks in SDN-based clouds and present the related works on this issue. However, there are still many unaddressed security problems in SDN which may restrict the SDN evolution and limit its adoption to private infrastructures. In addition to common SDN security challenges, its integration with other technologies brings up specific security issues. For example, virtualized SDN are facing confidentiality, availability and integrity issues.

B.   Management

In order to implement high-level network policies, network operators need to configure each device separately with low level specific commands which is a complicated task. Moreover, the limited visibility of network decreases its performance. This makes the management of traditional networks very challenging. In contrast, software defined networking brings several benefits to the network management and offers complementary capabilities to classical management methods. SDN enables us to configure the network in high-level language, simplifies the update of network status, and provides a global view of the network for better troubleshooting and network diagnoses. Authors in [137] discuss how SDN can improve management and configuration tasks across a variety of different types of networks.

According to [138], management functions of SDN are categorized as bootstrap and configuration, availability and resilience, network programmability,

TABLE III.   SUMMARY OF THE EXPERIENCES AND CHALLENGES FOR ENHANCING SECURITY AND MANAGEMENT IN SDN

Subject	References	Description	Challenges	Plane(s)
Security	[126-129]	These works eploit the opportuinities brought by SDN to network security	- Common SDN security challenges such as DoS attack in control plane, Unauthorized controller access, flooding attacks in data plane, lack of access control in application plane - Challenges in integration of SDN with other technologies such as confidentiality, availability and integrity issues in virtualized SDN	Security
	[11, 12, 130-133]	These works review SDN security issues		
	[134]	This work provide a comparison between security benefits and threats of SDN		
	[135, 136]	These works provide solutions for specialized SDN networks		
Management	[137]	This work discuss how SDN improves network management	- A standard protocol capable of implementing all management requirements need to be proposed. - The demarcation line between the management plane and the control plane needs to be determined. - Functionalities of SDN controllers have to be monitored and managed to prevent low resource utilization and controller failures - Cooperative management should be performed to prevent conflicting behaviors. - Specific management functions such as virtual network bootstrapping and configuration are required for virtualized SDN and integrated NFV/SDN environments - The ability of management modules to update, reprogram, and add functionalities to the controller needs to be investigated	Management
	[137, 138]	These works categorize management functions of SDN		
	[138, 139]	These works present management proposals for SDN		

performance and scalability, isolation and security, flexibility and decoupling, network planning, monitoring [140] and visualization. It is of paramount importance to propose a standard protocol capable of implementing all management requirements. In [137], a network control framework is proposed that interacts with the SDN controller to implement the network management functions. Their work is restricted in the control domains and needs to be extended for all management functions. In [138], existing management proposals for SDN is reviewed. However, current management proposals for SDN such as OF-config protocol [139] partially address some of the requirements. Another approach besides defining a management plane is to enrich the control plane with management functions. However, the capabilities of the southbound API protocols are limited and implementing various management functions will be challenging. Therefore, the demarcation line between the management plane and the control plane needs to be determined.

Management requirements and issues that have received less attention are highlighted in the sequel. SDN controllers play an important role in this paradigm. In order to deliver services and provide seamless communications, their functionalities have to be monitored and managed to prevent low resource utilization and controller failures [141]. Moreover, in case of multiple controllers, cooperative management should be performed to prevent conflicting behaviors.

Specific management functions such as virtual network bootstrapping and configuration are required for virtualized SDN and integrated NFV/SDN environments. Moreover, the ability of management modules to update, reprogram, and add functionalities to the controller needs to be investigated. Related works and challenges of management and security are summarized in Table III.

V.   EXPRIENCES AND CHALLENGES ON THE INTEGRATION OF SDN WITH DIFFERENT APPLICATIONS

In this section, we review the integration of SDN in other networks and services such as IoT, 4G/5G mobile networks, big data, wireless networks, and optical networks. Related works and challenges of these integrations are summarized in Table IV.

A. Software Defined Internet of Things (SD-IoT)

Internet of things is an emerging architecture for the future internet. In IoT, a high number of heterogeneous devices are connected to provide integrated services. IoT is the result of technology evolution from machine to machine (M2M) interactions [142]. M2M solutions have been present for decades. M2M refers to a technology that enables smart devices to communicate through a wired or wireless network without human intervention.

The growing number of devices in IoT and M2M leads to the production of huge amount of data which has to be controlled, organized and analyzed. Since SDN architecture offers ease of control, network

programmability, and simplified network management, it facilitates the deployment of IoT and is considered as a key enabler of IoT. Authors in [143-146] propose SDN-based architectures for IoT. The proposed architecture in [143] consist of three main layer. The physical layer is classified to a sensor network cluster and a database pool cluster. Control layer includes several software defined controllers such as IoT controller, SDN controller, SDStore controller and SDSec controller. Finally, the application layer consists of user applications. The interactions between these layers are discussed in the paper. The IoT controller in this architecture is responsible for managing the device heterogeneity. It obtains the information from the communicating objects and calculates the forwarding rules despite their non-compatible protocols. The SDN controller then implements the rules given by IoT controller in the forwarding devices. Authors in [146] also focus on device heterogeneity and propose a SDN-Docker based architecture for IoT. In [147], a hybrid SDN architecture including both legacy and SDN routers is introduced for the next generation IoT. However, some issues such as the flow management, topology update and security is not investigated in the paper. In [148], a software defined energy harvesting IoT is presented. In this architecture, an energy plane is also defined to optimize the control of energy flows. In this plane, energy in the nodes battery can be replenished and uploaded to the mobile charger. This work can be extended by considering the co-existence of data flows and energy flows.

Software defined networking paradigm can also be applied to M2M networks for performance improvement. In [149], a software defined networking scheme is proposed for M2M services in order to achieve more flexible network control. Using SDN, a traffic-aware load balancing technique for M2M networks is presented in [150]. In this technique, flow tables are only updated when network loading parameters exceed some predefined QoS thresholds.

The integration of network virtualization in SD-IoT also helps defining new services and reducing CAPEX and OPEX costs. A review of these architectures can be found in [151]. Many IoT devices wirelessly connect to the internet to offer diverse services. Mobile networks are one of the infrastructures that provide such connections. However, with this flood of data traffic generated by devices into the network, a new networking mechanism is required. SDN has a potential to use its visibility and therefore better utilize resources and manage the traffic. Therefore, a software-defined wireless networking architecture is proposed for IoT in [152].

Despite all the advantages offered by SDN in IoT, some research challenges arise. The security issues of SD-IoT considering device heterogeneity and trust problems are required to be addressed. Solutions have to be provided to limit the control traffic in the network and the size of flow tables in SDN switches imposing by the high number of IoT devices. Energy efficient routing algorithms for SD-IoT are required. Intelligent methods to provide simultaneous QoS requirements of various IoT applications have to be developed.

B. Software Defined 4G/5G Mobile Networks

In recent years, mobile networks are facing with increasing traffic demand. Data traffic is expected to grow tenfold between 2013 and 2019 [153]. The rising popularity of smart phones and tablets is the main reason of this mobile data traffic growth. Operators need to increase their capacity and coverage to satisfy users' demands [154]. Since the spectral efficiency of current inflexible communication networks are reaching its theoretical limit, a new flexible architecture is required for mobile networks to further their capacity. To overcome the shortcomings of the traditional architecture, software defined mobile networks are proposed. Authors in [155] surveyed the existing architectures for software defined mobile networks. A review of SDN and virtualization-based LTE network solutions is also presented in [15]. In [156], the potentials and limitations of the SDN-based LTE network is investigated. The SDN paradigm is also known as a promising solution to realize the fifth generation (5G) mobile networks [157]. A framework for integrating SDN with 5G networks is presented in [16].

In general, mobile networks consist of two parts which are the radio access and the core network. Several studies from academia and industry have considered integrating each part with SDN. We briefly discuss how SDN combines with mobile networks as follows.

- *The radio access network*

Traditional radio access networks include a set of macro base stations which can use different technologies (e.g. LTE, UMTS, etc.) to establish and maintain wireless communications with users. However, it is proposed to overlay macrocells with low power base stations to increase the capacity of network. Low power nodes are classified as pico, femto and relay nodes. Although utilizing low power nodes leads to reduced costs and higher capacity gains, the dense deployment of these nodes also results in more frequent handovers and increased interference [158]. To deal with these issues, complex resource management techniques are used. Moreover, coordinated decisions should be made across neighboring low power nodes in dense networks. Distributed algorithms face scalability issues in coordination. SDN can greatly benefit mobile networks in this regard. In software defined radio access networks, base stations become simple radio devices and are managed by the SDN controller. Since the SDN controller has a global view of the network, resource allocation optimizations can be performed more efficiently. Moreover, updates in resource management methods can be easily deployed. The delay challenge between the base stations and SDN controller can be alleviated through refactoring the control functionalities and handling the local decisions at base stations. Authors in [159] have proposed a software-defined based architecture, called SoftRAN, for the radio access network. In [160], an SDN-based radio access network architecture with virtualization is presented.

- *The core network*

The core network consists of multiple gateways and servers. These network entities are proprietary hardware which are expensive and suffer from the lack of control interfaces. In this regard, SDN decouples the control and data plane and provides the programmability of core network elements. Authors in [161] have proposed SoftCell which is a software defined architecture for the LTE core network. In [162], common procedures that often take place in the LTE core network are detailed for an SDN-based architecture. The function placement problem is addressed in [163] for NFV/SDN-based LTE core network.

Integrating SDN with mobile networks is still in its infancy and promises to be a fruitful area of future research. The optimal resource allocation in software defined mobile networks is a hot topic. The SDN controller scalability issues need to be addressed considering high volume of traffic flows. Moreover, methods to decrease the control flow (signaling) latency have to be designed.

C. Big Data and SDN

Big data refers to a high volume of data which also has high variety and velocity [164]. Due to the rise of IoT applications, social networking, online transactions, mobile phones and their applications, the generation of big data is growing. The challenges for big data include the ability to store a huge amount of data in a cloud data center and the ability to transfer them on a networking infrastructure.

SDN can help improving the performance of big data applications. In this regard, software defined data centers can provide better manageability and processing of big data due to their centralized view of the network and efficient resource allocation. In [165], an SDN-based data center network is proposed for big data applications. In this architecture, the SDN controller has interfaces with the master node of big data application such as Hadoop [166]. The master node is responsible for managing the storage and processing of data. Then, an integrated network control architecture is presented which programs the network at run-time by optical switches.

Furthermore, using SDN paradigm in the underlying infrastructure offers programmable delivery of the huge amount of data. In [167], a software-defined hybrid optical and electrical network architecture is proposed to accelerate the cast-based delivery of big data. The authors of [168] design a traffic management system that optimizes bulk transfers on wide-area networks. A survey on the integration of SDN and big data is presented in [169]. In [170], an SDN-based big data management scheme is introduced. A fast data forwarding method is also proposed in the paper based on Bloom filter.

There are still many issues that need to be addressed in this field of research which have implications on SDN. Big data applications have a dynamic nature and their QoS requirements should be satisfied. The design of an efficient method for frequent update of the entries of flow tables is important for big data applications.

Since all the processing of big data is performed in SDN controllers, its scalability issues require further investigation. The problem of delivery of big data over SDN-based wireless networks is also overlooked.

D. Software Defined Wireless Networks

The SDN networking paradigm have been extensively used in wired networks. Since it simplifies the network management and configuration, researchers and developers are motivated to apply this architecture in wireless networks as well. Examples of the adoption of SDN in wireless networks are: Software-defined wireless local area network (SD-WLAN) [171], Software-defined wireless sensor network (SD-WSN) [172-174], Software-defined wireless mesh network (SD-WMN) [175-177], Software-defined mobile adhoc network (SD-MONET) [178], and Software defined vehicular adhoc network (SD-VANET) [179-182].

In an SDN-based architecture, the control plane is decoupled from data plane. Software defined wireless networks will have a similar structure. However, this becomes challenging in infrastructure-less wireless networks such as SD-MONETs and SD-VANETs. Nodes in such architectures can be both receivers and routers. Therefore, their SDN-based architectures and protocols should be designed accordingly. Moreover, nodes are mobile and the condition of wireless channels varies during time. Hence, the environment is highly dynamic in wireless networks. This results in high communication overhead and latency between the data and control plane. Also, the acquisition of a global view of the dynamic network in the controller for resource allocation imposes excessive control traffic overhead. The mechanisms and protocols should be carefully designed to fit the requirements of wireless networks. A review of recent works on leveraging SDN in wireless sensor, mesh and home networks is presented in [183].

In addition to the challenges noted above, each of the mentioned software defined wireless networks has their own specific issues. For instance, in wireless sensor networks, nodes are low-powered and memory-constrained. Although using SDN structure in WSNs leads to high reduction in energy consumption, it remains to determine the amount of processing that has to be performed in the controller in order to address the trade-off between energy and delay. Authors in [172] surveyed the proposed architectures for SD-WSN and discussed the challenges arising from this paradigm.

E. Software Defined Optical Networks

Optical networks play important roles in modern networks due to high offered capacity. These networks often provide underlay communications between IP networks or constitute the backbone of telecommunication networks. To adapt to dynamic traffic patterns of today's applications and satisfy their various requirements, a flexible resource allocation is required even at optical layer. Using SDN architecture helps reaching this goal by enabling optimized network configuration. The software defined optical network (SD-ON) allows for the separation of the control plane from proprietary optical element

TABLE IV. SUMMARY OF THE EXPERIENCES AND CHALLENGES ON THE INTEGRATION OF SDN WITH DIFFERENT APPLICATIONS

Subject	References	Description	Challenges	Plane(s)
Software-defined internet of things	[143-148]	These works present SDN-based architectures for IoT	- The security issues of SD-IoT considering device heterogeneity and trust problems are required to be addressed. - Solutions have to be provided to limit the control traffic in the network and the size of flow tables in SDN switches imposing by the high number of IoT devices. - Energy efficient routing algorithms for SD-IoT are required. - Intelligent methods to provide simultaneous QoS requirements of various IoT applications have to be developed.	Application, Control, Data, Management, Security
	[149, 150]	These works focu on SDN-based M2M networks		
	[152]	This work proposes a software-defined wireless networking architecture		
Software defined 4G/5G mobile networks	[159, 160]	SDN-based radio access network	- The optimal resource allocation in software defined mobile networks is a hot topic. - The SDN controller scalability issues need to be addressed considering high volume of traffic flows. - Methods to decrease the control flow (signaling) latency has to be designed.	Application, Control, Data, Management, Security
	[161-163]	A software defined architecture for the LTE core network		
Big data and SDN	[165, 167-170]	These papers propose SDN-based approaches and architectures for big data application	- Satisfying the QoS requirements of big data applications is a challenging issue. - An efficient method for frequent update of the entries of flow tables needs to be designed - Scalability issues of SDN controllers in big data applications require further investigation. - The problem of delivery of big data over SDN-based wireless networks is also overlooked.	Application, Control, Data, Management, Security
Software defined wireless networks	[171]	Software-defined wireless local area networks (SD-WLAN)	- SDN-based architectures and protocols should be designed for infrastructure-less wireless networks. - Methods need to be designed to reduce communication overhead and latency between the data and control plane in highly dynamic environment of wireless networks. - The acquisition of a global view of the dynamic network in the controller for resource allocation is challenging. - The amount of processing that has to be performed in the controller in order to address the trade-off between energy and delay needs to be determined in SD-WSNs	Application, Control, Data, Management, Security
	[172-174]	These works focus on software-defined wireless sensor networks (SD-WSN)		
	[175-177]	These works focus on software-defined wireless mesh networks (SD-WMN)		
	[178]	These works focus on software-defined mobile adhoc networks (SD-MONET)		
	[179-182]	These works focus on software defined vehicular adhoc networks (SD-VANET)		
Software defined optical networks	[184-186]	These research focus on SD-ON application plane	- The level of abstraction for the controller needs to be explored - The extension of the OpenFlow protocol to control the optical transmissions and switching elements should be designed	Application, Control, Data, Management, Security
	[187-189]	These research focus on SD-ON control plane		
	[190-193]	These resaerch focus on SD-ON data plane		

SD-ONs consist of data, control, and application planes. Data plane includes optical transceivers which are configurable by the SDN controller and can transmit and receive optical signals. These software defined elements change the modulation format of optical signals by digital signal processing (DSP) methods. Multiple works are dedicated to deign optical infrastructure which can be flexibly controlled by the SDN controller [184-186]. Research on the control plane focus on how to manage optical network elements [187-189]. In the application plane, applications communicate with the control plane to implement services such as security [190], quality of service provisioning [191], failure recovery [192] and energy consumption minimization [193]. Authors in [194] comprehensively review the research works on each layer and interface, and provide future directions in each one. In addition to the open problems mentioned in [194], further research should explore the level of abstraction for the controller and the extension of the OpenFlow protocol to control the optical transmissions and switching elements.

VI. PROPOSED FRAMEWORK AND CONSIDERATIONS FOR ENHANCING THE CAPABILITIES OF SDN

In this section, we propose a framework for SDN networks considering the challenges discussed in the previous sections. Fig. 2 shows a conceptual framework in which the most important design goals of SDN are

presented. The design goals include management, security, energy efficiency and performance which should be considered by network and service providers. These also should be achieved in the integration of SDN with other networks and services along with their specific challenges.

To ensure each of the design goals in Fig. 2, the challenges in each part should be alleviated. It should be noted that the specific challenges of each one are investigated in Tables I-IV.

Fig. 3 depicts our proposed architectural considerations for SDN. We revisit the SDN architecture and present a detailed one considering different applications, networks and services. In the framework, the data plane is composed of programmable elements without embedded control. These elements can include base stations and gateways in mobile networks, sensors and actuators in IoT network, virtualized network elements, optical network infrastructure, and wireless nodes in wireless networks. The data plane elements have flow tables which are configured by the controllers through the southbound interface. The SDN hypervisor abstracts the physical SDN network into multiple logically isolated virtual SDN networks, each having its own controller (vSDN controller).

As mentioned in Section II.B, the control plane can consist of multiple physically distributed but logically centralized controllers. The controllers can be deployed in different domains. The east-west interfaces use a system of notification and messaging to allow communication between the controllers and provide consistency among them.

In software defined IoT networks, an IoT controller is required over the SDN controller to locate the objects, select the best identification mapping approach, and calculate the route between the IoT agents for communication. Then, IoT controller pushes the rules to SDN controller in order to implement them in the forwarding elements.

The application plane can include both network and user applications. SDN applications range from load balancing, routing, flow management, failure recovery to IoT and big data applications.

Management and security planes should have interfaces with all planes to implement policies. Security plane also need to prevent interfaces from possible attacks. The functional blocks of these planes are depicted in Fig. 3.
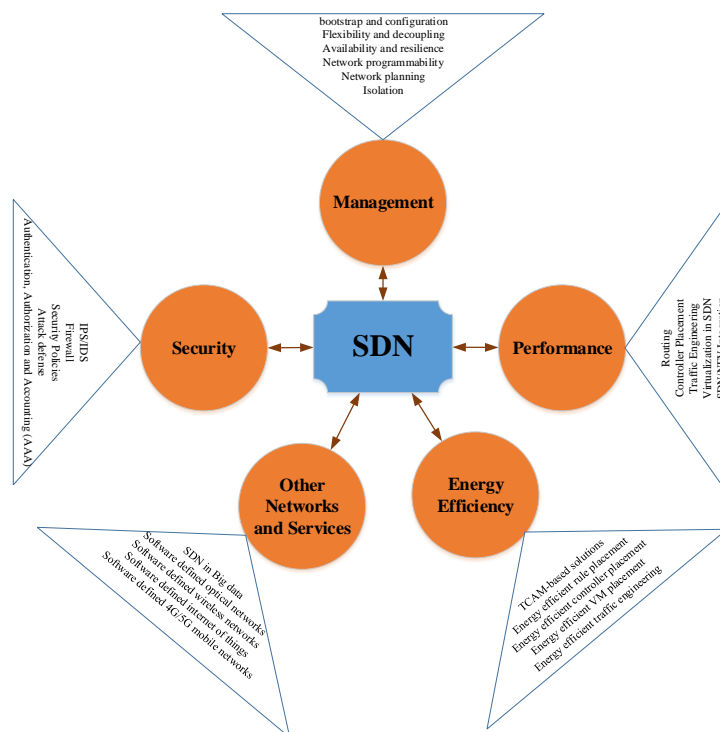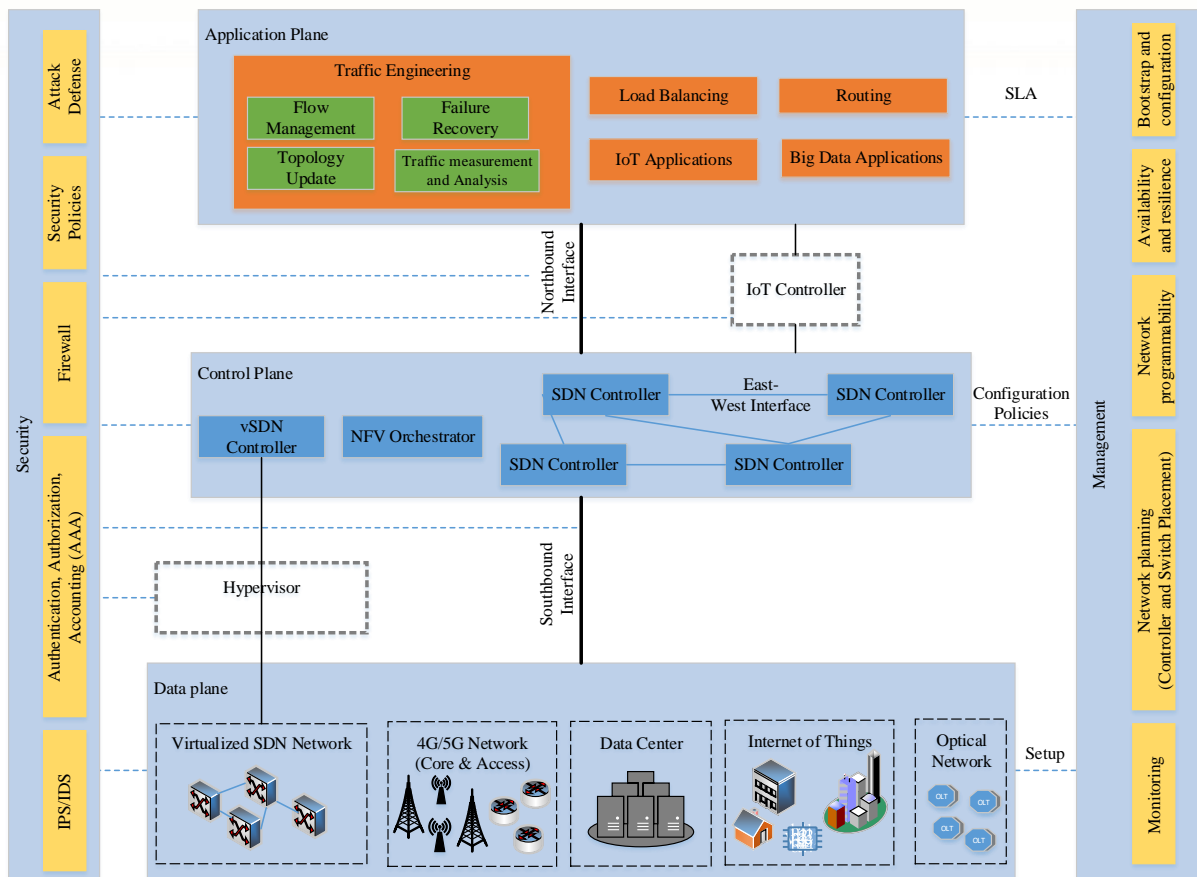

Figure 2.   Proposed conceptual framework for SDN

Figure 3.   Architectural considerations for SDN

VII.   Conclusion

In this paper, we first overviewed the most recent experiences in software defined networking. We discussed the challenges that affect the improvement of SDN operation. These challenges of the problems including routing, controller placement, traffic engineering, SDN virtualization and the integration of SDN and NFV were reviewed. Next, the key issues of energy-efficient methods in SDN were presented. Furthermore, we explored current activities that have been undertaken in security and management areas of SDN networks. Finally, we investigated the services and networks which utilize the SDN architecture. In this regard, open questions resulting from the integration of SDN in emerging technologies such as IoT, big data and 5G networks were discussed. The extension of SDN toward optical networks was also elaborated.

Based on the overviewed challenges, we proposed a comprehensive conceptual framework together with some detailed architectural considerations for SDN networks that considers various networks, services and applications. According to the proposed architectures, the important future directions include scalability issues of SDN controller, support for QoS requirements of big data applications and heterogeneous IoT devices, limiting the control traffic overhead in SDN-based networks, realization of virtualized SDN, mobility management in software-defined wireless networks, and support for efficient multicast communications. Moreover, security mechanisms and dynamic energy-efficient methods considering fairness are required to be designed.

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