Software-Defined Networking: A Comprehensive Survey

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Software-Defined Networking: A Comprehensive Survey

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***Abstract*—The Internet has led to the creation of a digital society, where (almost) everything is connected and is accessible from anywhere. However, despite their widespread adoption, traditional IP networks are complex and very hard to manage. It is both difficult to configure the network according to predefined policies, and to reconfigure it to respond to faults, load and changes. To make matters even more difficult, current networks are also vertically integrated: the control and data planes are bundled together. Software-Defined Networking (SDN) is an emerging paradigm that promises to change this state of affairs, by breaking vertical integration, separating the network's control logic from the underlying routers and switches, promoting (logical) centralization of network control, and introducing the ability to program the network. The separation of concerns introduced between the definition of network policies, their implementation in switching hardware, and the forwarding of traffic, is key to the desired flexibility: by breaking the network control problem into tractable pieces, SDN makes it easier to create and introduce new abstractions in networking, simplifying network management and facilitating network evolution.**

Today, SDN is both a hot research topic and a concept gaining wide acceptance in industry, which justifies the comprehensive survey presented in this paper. We start by introducing the motivation for SDN, explain its main concepts and how it differs from traditional networking. Next, we present the key building blocks of an SDN infrastructure using a bottom-up, layered approach. We provide an in-depth analysis of the hardware infrastructure, southbound and northbounds APIs, network virtualization layers, network operating systems (SDN controllers), network programming languages, and management applications. We also look at cross-layer problems such as debugging and troubleshooting. In an effort to anticipate the future evolution of this new paradigm, we discuss the main ongoing research efforts and challenges of SDN. In particular, we address the design of switches and control platforms – with a focus on aspects such as resiliency, scalability, performance, security and dependability – as well as new opportunities for carrier transport networks and cloud providers. Last but not least, we analyze the position of SDN as a key enabler of a software-defined environment.

***Index Terms*—Software-defined networking, decoupled control and data plane, network virtualization, network operating systems, network hypervisor, programming languages, flow-based network control, survey, scalability and dependability, software-defined environments.**

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I. Introduction

The distributed control and transport network protocols running inside the routers and switches are the key technologies that allow information, in the form of digital packets, to travel around the world. Despite their widespread adoption, traditional IP networks are *complex and hard to manage* [1]. To express the desired high-level network policies, network operators need to configure each individual network device separately using low-level and often vendor-specific commands. In addition to the configuration complexity, network environments have to endure the dynamics of faults and adapt to load changes. Automatic reconfiguration and response mechanisms are virtually non-existent in current IP networks. Enforcing the required policies in such a dynamic environment is therefore highly challenging.

To make it even more complicated, current networks are also *vertically integrated*. The control plane (that decides how to handle network traffic) and the data plane (that forwards traffic according to the decisions made by the control plane) are bundled inside the networking devices, reducing flexibility and hindering innovation and evolution of the networking infrastructure. The transition from IPv4 to IPv6, started more than a decade ago and still largely incomplete, bears witness to this challenge, while in fact IPv6 represented *merely* a protocol update. Due to the inertia of current IP networks, a new routing protocol can take 5 to 10 years to be fully designed, evaluated and deployed. Likewise, a clean-slate approach to change the Internet architecture (e.g., replacing IP), is regarded as a tantalizing task – simply not feasible in practice [2], [3]. Ultimately, this situation has inflated the capital and operational expenses of running an IP network.

Software-Defined Networking (SDN) [4], [5] is an emerging networking paradigm that gives hope to change the limitations of current network infrastructures. First, it breaks the vertical integration by separating the network's control logic (the control plane) from the underlying routers and switches that forward the traffic (the data plane). Second, with the separation of the control and data planes, network switches become simple forwarding devices and the control logic is implemented in a *logically centralized* controller (or

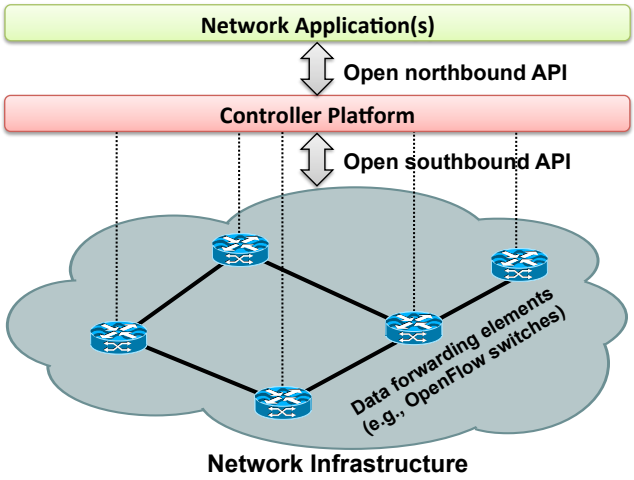

Fig. 1. Simplified view of an SDN architecture.

network operating system[1]), simplifying policy enforcement and network (re)configuration and evolution [6]. A simplified view of this architecture is shown in Figure 1. It is important to emphasize that a logically centralized programmatic model does not postulate a physically centralized system [7]. In fact, the need to guarantee adequate levels of performance, scalability, and reliability would preclude such a solution. Instead, production-level SDN network designs resort to physically distributed control planes [8], [7].

The separation of the control plane and the data plane can be realized by means of a well-defined programming interface between the switches and the SDN controller. The controller exercises direct control over the state in the data-plane elements via this well-defined application programming interface (API), as depicted in Figure 1. The most notable example of such an API is OpenFlow [9], [10]. An OpenFlow switch has one or more tables of packet-handling rules (flow table). Each rule matches a subset of the traffic and performs certain actions (dropping, forwarding, modifying, etc.) on the traffic. Depending on the rules installed by a controller application, an OpenFlow switch can – instructed by the controller – behave like a router, switch, firewall, or perform other roles (e.g., load balancer, traffic shaper, and in general those of a middlebox).

An important consequence of the software-defined networking principles is the *separation of concerns* introduced between the *definition* of network policies, their *implementation* in switching hardware, and the *forwarding* of traffic. This separation is key to the desired flexibility, breaking the network control problem into tractable pieces, and making it easier to create and introduce new abstractions in networking, simplifying network management and facilitating network evolution and innovation.

Although SDN and OpenFlow started as academic experiments [9], they gained significant traction in the industry over the past few years. Most vendors of commercial switches now include support of the OpenFlow API in their equipment. The SDN momentum was strong enough to make Google, Facebook, Yahoo, Microsoft, Verizon, and Deutsche Telekom fund Open Networking Foundation (ONF) [10] with the main goal of promotion and adoption of SDN through open standards development driven by the users (i.e., equipment buyers) rather than the vendors (i.e., equipment manufacturers). As the initial concerns with SDN scalability were addressed [11] – in particular the myth that logical centralization implied a physically centralized controller, an issue we will return to later on – SDN ideas have matured and evolved from an academic exercise to a commercial success. Google, for example, has deployed a software-defined network to interconnect its data centers across the globe. This production network has been in deployment for 3 years, helping the company to improve operational efficiency and significantly reduce costs [8]. VMware's network virtualization platform, NSX [12], is another example. NSX is a commercial solution that delivers a fully functional network in software, provisioned independent of the underlying networking devices, entirely based around SDN principles. As a final example, the world's largest IT companies (from carriers and equipment manufacturers to cloud providers and financial-services companies) have recently joined SDN consortia such as the ONF and the OpenDaylight initiative [13], another indication of the importance of SDN from an industrial perspective.

In this paper, we present a comprehensive literature survey on SDN organized as depicted in Figure 2. We start, in the next two sections, by explaining the context, introducing the motivation for SDN and explaining the main concepts of this new paradigm and how it differs from traditional networking. Our aim in the early part of the survey is also to explain that SDN is not as novel as a technological advance. Indeed, its existence is rooted at the intersection of a series of "old" ideas, technology drivers, and current and future needs. The concepts underlying SDN – the separation of the control and data planes, the flow abstraction upon which forwarding decisions are made, the (logical) centralization of network control, and the ability to program the network – are not novel by themselves [14]. However, the integration of already tested concepts with recent trends in networking – namely the availability of merchant switch silicon and the huge interest in feasible forms of network virtualization – are leading to this paradigm shift in networking.

Section IV comes next and is the core of this survey, presenting an extensive and comprehensive analysis of the building blocks of an SDN infrastructure using a bottom-up, layered approach. The option for a layered approach is grounded on the fact that SDN allows thinking of networking along two fundamental concepts, which are common in other disciplines of computer science: a) separation of concerns (leveraging the concept of abstraction) and b) recursion. Our layered, bottom-up approach divides the networking problem into eight parts: 1) hardware infrastructure, 2) southbound interfaces, 3) network virtualization (hypervisor layer between the forwarding devices and the network operating systems), 4) network operating systems (SDN controllers and control platforms), 5) northbound interfaces (to offer a common programming abstraction to the upper layers, mainly the network applications), 6) virtualization using slicing techniques provided

[1]We will use these two terms interchangeably.

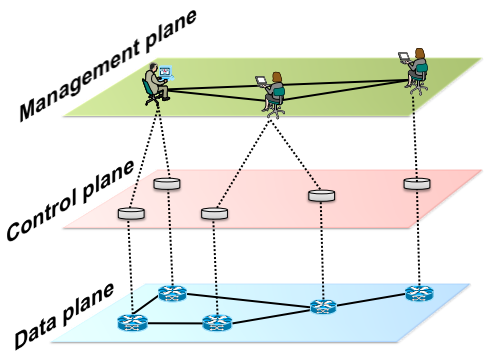

Fig. 3. Layered view of networking functionality.

by special purpose libraries and/or programming languages and compilers, 7) network programming languages, and finally 8) management applications. In addition, we also look at cross-layer problems such as debugging and troubleshooting mechanisms. The discussion in Section V on ongoing research efforts, challenges, future work and opportunities concludes this paper.

II. State of Quo in Networking

Computer networks can be divided in three planes of functionality: the data, control and management planes (see Figure 3). The data plane corresponds to the networking devices, which are responsible for (efficiently) forwarding data. The control plane represents the protocols used to populate the forwarding tables of the data plane elements. The management plane includes the software services, such as SNMP-based tools [15], used to remotely monitor and configure the control functionality. Network policy is defined in the management plane, the control plane enforces the policy, and the data plane executes it by forwarding data accordingly.

In traditional IP networks, the control and data planes are tightly coupled, and embedded in the same networking devices, and the whole structure is highly decentralized. This was considered important for the design of the Internet in the early days: it seemed the best way to guarantee network resilience, which was a crucial design goal. In fact, this approach has been quite effective in terms of network performance, with a rapid increase of line rate and port densities.

However, the outcome is a very complex and relatively static architecture. It is also the fundamental reason why traditional networks are rigid, and complex to manage and control. These two characteristics are largely responsible for a vertically-integrated industry where innovation is difficult.

Network misconfigurations and related errors are extremely common in today's networks. For instance, more than 1000 configuration errors have been observed in BGP routers [16]. A single misconfigured device can be a big headache for network operators and may have extremely severe consequences. Indeed, while rare, a single misconfigured router is able to compromise the correct operation of the whole Internet for hours [17], [18].

To support network management, a small number of vendors offer proprietary solutions of specialized hardware, operating systems, and control programs (network applications). Network operators have to acquire and maintain different management solutions and the corresponding specialized teams. The capital and operational cost of building and maintaining a networking infrastructure is significant, with long return on investment cycles, which hamper innovation and addition of new features and services (for instance access control, load balancing, energy efficiency, traffic engineering). To alleviate the lack of in-path functionalities within the network, a myriad of specialized components and middleboxes, such as firewalls, intrusion detection systems and deep packet inspection engines, proliferate in current networks. A recent survey of 57 enterprise networks shows that the number of middleboxes is already on par with the number of routers in current networks [19]. Despite helping in-path functionalities, the net effect of middleboxes has been increased complexity of network design and its operation.

III. What is Software-Defined Networking?

The term SDN (Software-Defined Networking) was originally coined to represent the ideas and work around OpenFlow at Stanford University [20]. As originally defined, SDN refers to a network architecture where the forwarding state in the data plane is managed by a remote control plane decoupled from the former. The networking industry has on many occasions shifted from this original view of SDN, by referring to anything that involves software as being SDN. We therefore attempt, in this section, to provide a much less ambiguous definition of software-defined networking.

We define an SDN as a network architecture with four pillars:

1) The control and data planes are *decoupled*. Control functionality is removed from network devices that will become simple (packet) forwarding elements.
2) Forwarding decisions are flow-based, instead of destination-based. A flow is broadly defined by a set of packet field values acting as a match (filter) criterion and a set of actions (instructions). The flow abstraction allows unifying the behavior of different types of network devices, including routers, switches, firewalls, and middleboxes. Flow programming enables unprecedented flexibility, limited only to the capabilities of the implemented flow tables [9].
3) Control logic is moved to an external entity, the so-called SDN controller or Network Operating System (NOS). The NOS is a software platform that runs on commodity server technology and provides the essential resources and abstractions to facilitate the programming of forwarding devices based on a logically centralized, abstract network view. Its purpose is therefore similar to that of a traditional operating system.
4) The network is *programmable* through software applications running on top of the NOS that interacts with the underlying data plane devices. This is a fundamental characteristic of SDN, considered as its main value proposition.

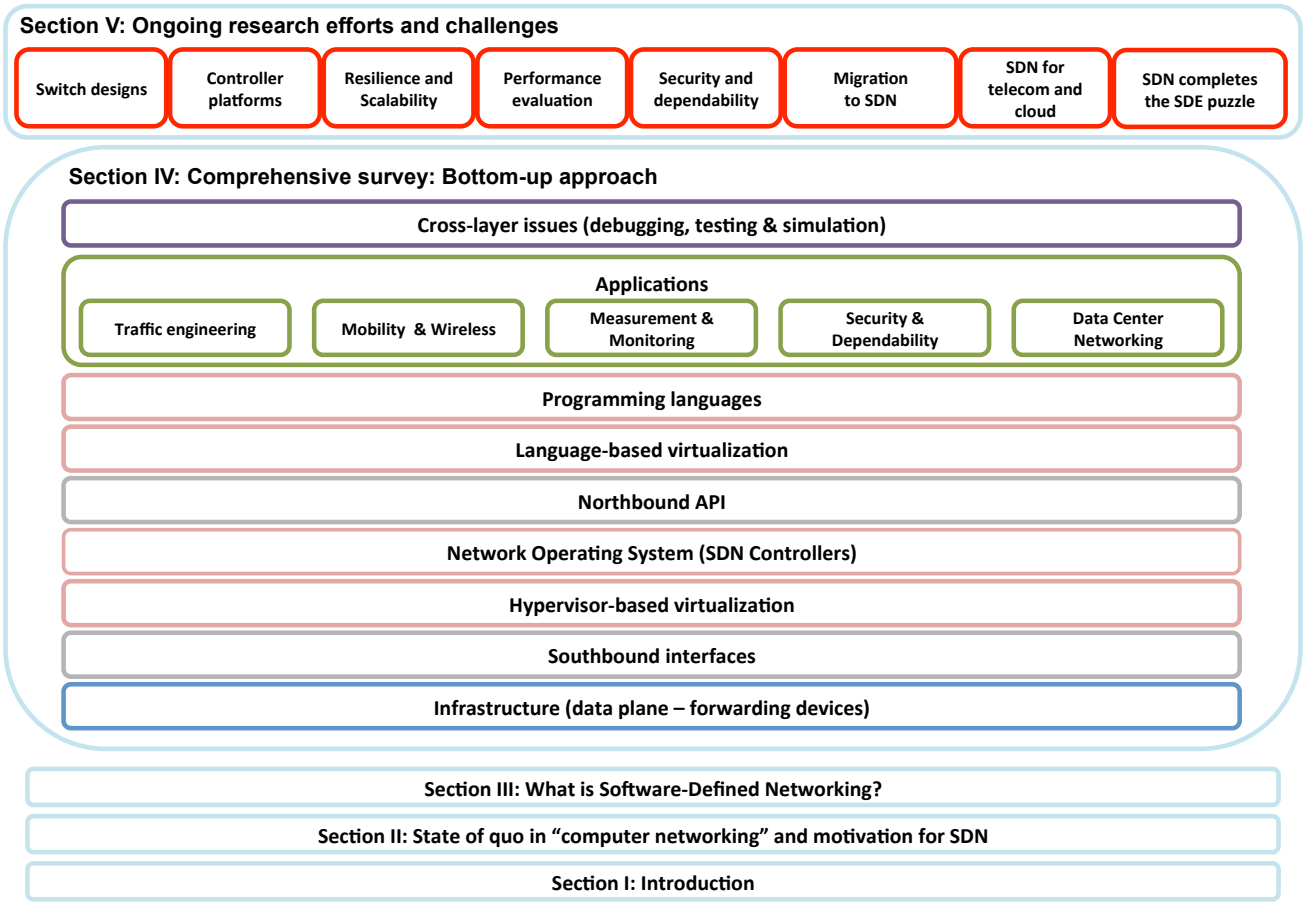

Fig. 2. Condensed overview of this survey on SDN.

Note that the logical centralization of the control logic, in particular, offers several additional benefits. First, it is simpler and less error-prone to modify network policies through high-level languages and software components, compared with low-level device specific configurations. Second, a control program can automatically react to spurious changes of the network state and thus maintain the high-level policies intact. Third, the centralization of the control logic in a controller with global knowledge of the network state simplifies the development of more sophisticated networking functions, services and applications.

Following the SDN concept [5], an SDN can be defined by three fundamental abstractions: (*i*) forwarding, (*ii*) distribution, and (*iii*) specification. In fact, abstractions are essential tools of research in computer science and information technology, being already an ubiquitous feature of many computer architectures and systems [21].

Ideally, the *forwarding abstraction* should allow any forwarding behavior desired by the network application (the control program) while hiding details of the underlying hardware. OpenFlow is a practical realization of one such abstraction, which can be seen as the equivalent to a "device driver" in an operating system.

The *distribution abstraction* should shield SDN applications from the vagaries of distributed state, making the distributed control problem a logically centralized one. Its realization requires a common distribution layer, which in SDN resides in the NOS. This layer has two essential functions. First, it is responsible for installing the control commands on the forwarding devices. Second, it collects status information about the forwarding layer (network devices and links), to offer a global network view to network applications.

The last abstraction is *specification*, which should allow a network application to express the desired network behavior without being responsible for implementing that behavior itself. This can be achieved through virtualization solutions, as well as network programming languages. These approaches map the abstract configurations that the applications express based on a simplified, abstract model of the network, into a physical configuration for the global network view exposed by the SDN controller. Figure 4 depicts the SDN architecture, concepts and building blocks.

As previously mentioned, the strong coupling between control and data planes has made it difficult to add new functionality to traditional networks. The introduction of new features requires the inclusion of expensive and hard-to-configure equipment in the network – load balancers, intrusion detection systems and firewalls are common examples. These middleboxes need to be placed strategically in the network, making it even harder to later change the network topology, configuration and functionality. This can be observed in Figure 5. For instance, an intrusion detection system might need

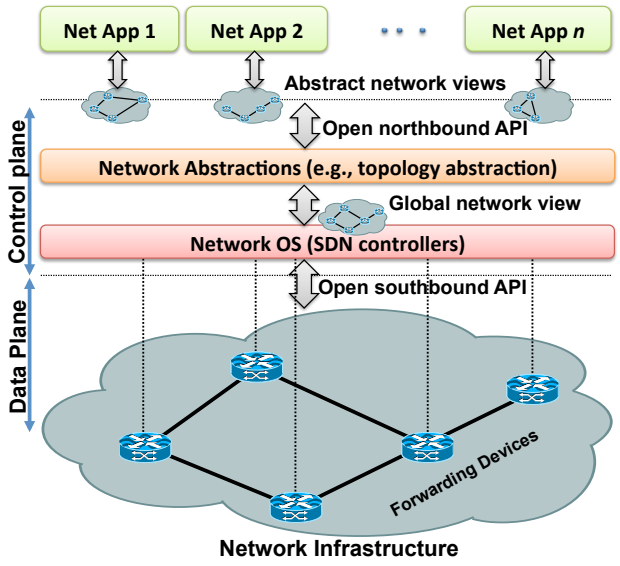

Fig. 4. SDN architecture and its fundamental abstractions.

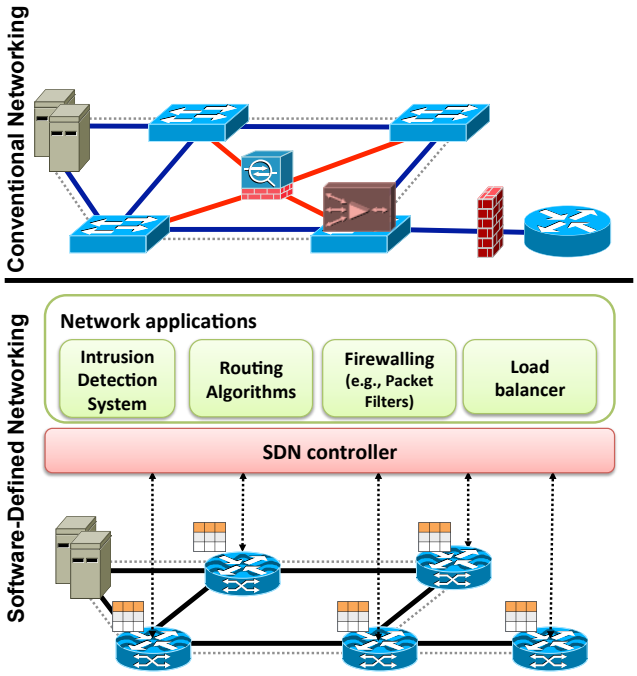

Fig. 5. Traditional networks versus Software-Defined Networks (SDNs). With SDN, management becomes simpler and traditional middleboxes can be removed.

to receive a cloned copy of the traffic of all switching devices of the network through specific physical and or logical links.

In contrast, introducing new functionality in SDN is made simply by adding a new software application to run on top of the NOS. This approach has several advantages:

- It becomes easier to program these applications since the abstractions provided by the control platform and/or the network programming languages can be shared.
- All applications can take advantage of the same network information (the global network view), leading (arguably) to more consistent and effective policy decisions while re-using control plane software modules.
- These applications can take actions (i.e., reconfigure forwarding devices) from any part of the network. There is therefore no need to devise a precise strategy about the location of the new functionality.
- The integration of different applications becomes more straightforward. For instance, load balancing and routing applications can be combined sequentially, with load balancing decisions having precedence over routing policies.

A. Terminology

To identify the different elements of an SDN as unequivocally as possible, we now present the essential terminology used throughout this work.

Fowarding Devices (FD): Hardware- or software-based data plane devices that perform a set of elementary operations. The forwarding devices have well-defined instruction sets (e.g., flow rules) used to take actions on the incoming packets (e.g., forward to specific ports, drop, forward to the controller, rewrite some header). These instructions are defined by southbound interfaces (e.g., OpenFlow [9], ForCES [22], Protocol-Oblivious Forwarding (POF) [23]) and are installed in the forwarding devices by the SDN controllers implementing the southbound protocols.

Data Plane (DP): Forwarding devices are interconnected through wireless radio channels or wired cables. The network infrastructure comprises the interconnected forwarding devices, which represent the data plane.

Southbound Interface (SI): The instruction set of the forwarding devices is defined by the southbound API, which is part of the southbound interface. Furthermore, the SI also defines the communication protocol between forwarding devices and control plane elements. This protocol formalizes the way the control and data plane elements interact.

Control Plane (CP): Forwarding devices are programmed by control plane elements through well-defined SI embodiments. The control plane can therefore be seen as the "network brain". All control logic rests in the applications and controllers, which form the control plane.

Northbound Interface (NI): The network operating system can offer an API to application developers. This API represents a northbound interface, i.e., a common interface for developing applications. Typically, a northbound interface abstracts the low level instruction sets used by southbound interfaces to program forwarding devices.

Management Plane (MP): The management plane is the set of applications that leverage the functions offered by the NI to implement network control and operation logic. This includes applications such as routing, firewalls, load balancers, monitoring, and so on. Essentially, a management application defines the policies, which are ultimately translated to southbound-specific instructions that program the behavior of the forwarding devices.

B. Alternative/Broadening SDN Definitions

Since its inception in 2010 [20], the original OpenFlow-centered SDN term has seen its scope broadened beyond

architectures with a cleanly decoupled control plane interface. The definition of SDN will likely continue to broaden, driven by the industry business-oriented views on SDN – irrespective of the decoupling of the control plane. In this survey, we focus on the original, "canonical" SDN definition based on the aforementioned key pillars and the concept of layered abstractions. However, for the sake of completeness and clarity, we acknowledge alternative SDN definitions [24], including:
Control Plane / Broker SDN: A networking approach that retains existing distributed control planes but offers new APIs that allow applications to interact (bidirectionally) with the network. An SDN controller – often called orchestration platform – acts as a broker between the applications and the network elements. This approach effectively presents control plane data to the application and allows a certain degree of network programmability by means of "plug-ins" between the orchestrator function and network protocols. This API-driven approach corresponds to a hybrid model of SDN, since it enables the broker to manipulate and directly interact with the control planes of devices such as routers and switches. Examples of this view on SDN include recent IETF efforts (e.g., ALTO [25], I2RS [26], ABNO [27]) and the design philosophy behind the OpenDaylight project [13] that goes beyond the OpenFlow split control mode.
Overlay SDN: A networking approach where the (software- or hardware-based) network edge is dynamically programmed to manage tunnels between hypervisors and/or network switches, introducing an overlay network. In this hybrid networking approach, the distributed control plane providing the underlay remains untouched. The centralized control plane provides a logical overlay that utilizes the underlay as a transport network. This flavor of SDN follows a proactive model to install the overlay tunnels. The overlay tunnels usually terminate inside virtual switches within hypervisors or in physical devices acting as gateways to the existing network. This approach is very popular in recent data center network virtualization [28], and are based on a variety of tunneling technologies (e.g., STT, NVGRE, VXLAN, LISP) [29].

In addition, the term SDN is often used to define extensible network management planes (e.g., OpenStack [30]), whitebox switches and open-source dataplanes (e.g., Pica8 Xorplus [31], Quagga [32]), specialized programmable hardware devices (e.g., NetFPGA [33]), virtualized software-based appliances (e.g., Network Function Virtualization - NFV [34]), in spite of lacking a decoupled control and data plane or common interface along its API. Hybrid SDN models will be further discussed in Section V-G.

C. History of Software-Defined Networking

Albeit a fairly recent concept, SDN leverages on networking ideas with a longer history [14]. In particular, it builds on work made on programmable networks, such as active networks [35], and on proposals for control and data plane separation, such as NCP [36] and RCP [37].

In order to present an historical perspective, we summarize in Table I different instances of SDN-related work prior to SDN, splitting it into five categories. Along with the categories we defined, the second and third columns of the table mention past initiatives (pre-SDN, i.e., before the OpenFlow-based initiatives that sprung into the SDN concept), and recent developments that led to the definition of SDN.

Data plane programmability has a long history. Active networks [35] represent one of the early attempts on building new network architectures based on this concept. The main idea behind active networks is for each node to have the capability to perform computations on, or modify the content of, packets. To this end, active networks propose two distinct approaches: programmable switches and capsules. The former does not imply changes in the existing packet or cell format. It assumes that switching devices support the downloading of programs with specific instructions on how to process packets. The second approach, on the other hand, suggests that packets should be replaced by tiny programs, which are encapsulated in transmission frames and executed at each node along their path.

ForCES [22], OpenFlow [9] and POF [23] represent recent approaches for designing and deploying programmable data plane devices. In a manner different from active networks, these new proposals rely essentially on modifying forwarding devices to support flow tables, which can be dynamically configured by remote entities through simple operations such as adding, removing or updating flow rules, i.e., entries on the flow tables.

The earliest initiatives on separating data and control signalling date back to the 80s and 90s. The network control point (NCP) [36] is probably the first attempt to separate control and data plane signalling. NCPs were introduced by AT&T to improve the management and control of its telephone network. This change promoted a faster pace of innovation of the network and provided new means for improving its efficiency, by taking advantage of the global view of the network provided by NCPs. Similarly, other initiatives such as Tempest [46], ForCES [22], RCP [37], and PCE [48] proposed the separation of the control and data planes for improved management in ATM, Ethernet, BGP, and MPLS networks, respectively.

More recently, initiatives such as SANE [51], Ethane [52], OpenFlow [9], NOX [53] and POF [23] proposed the decoupling of the control and data planes for Ethernet networks. Interestingly, these recent solutions do not require significant modifications on the forwarding devices, making them attractive not only for the networking research community, but even more to the networking industry. OpenFlow-based devices [9], for instance, can easily co-exist with traditional Ethernet devices, enabling a progressive adoption (i.e., not requiring a disruptive change to existing networks).

Network virtualization has gained a new traction with the advent of SDN. Nevertheless, network virtualization also has its roots back in the 90s. The Tempest project [46] is one of the first initiatives to introduce network virtualization, by introducing the concept of switchlets in ATM networks. The core idea was to allow multiple switchlets on top of a single ATM switch, enabling multiple independent ATM networks to share the same physical resources. Similarly, MBone [54] was one of the early initiatives that targeted the creation of virtual network topologies on top of legacy networks, or overlay

TABLE I
SUMMARIZED OVERVIEW OF THE HISTORY OF PROGRAMABLE NETWORKS

Category	Pre-SDN initiatives	More recent SDN developments
Data plane programmability	Tennenhouse Wetherall [38], smart packets [39], ANTS [40], SwitchWare [41], Calvert [42], high performance router [43], NetScript [44], IEEE P1520 [45]	ForCES [22], OpenFlow [9], POF [23]
Control and data plane decoupling	NCP [36], Tempest [46], ForCES [22], RCP [37], SoftRouter [47], PCE [48], 4D [49], IRSCP [50]	SANE [51], Ethane [52], OpenFlow [9], NOX [53], POF [23]
Network virtualization	Tempest [46], MBone [54], 6Bone [55], RON [56], Planet Lab [57], Impasse [58], GENI [59], VINI [60]	Open vSwitch [61], Mininet [62], FlowVisor [63], NVP [64]
Network operating systems	Cisco IOS [65], JUNOS [66]. ExtremeXOS [67], SR OS [68]	NOX [53], Onix [7], ONOS [69]
Technology pull initiatives	Open Signaling [70]	ONF [10]

networks. This work was followed by several other projects such as Planet Lab [57], GENI [59] and VINI [60]. It is also worth mentioning FlowVisor [71] as one of the first recent initiatives to promote a hypervisor-like virtualization architecture for network infrastructures, resembling the hypervisor model common for compute and storage. More recently, Koponen et al. proposed a Network Virtualization Platform (NVP [64]) for multi-tenant datacenters using SDN as a base technology.

The concept of a network operating system was reborn with the introduction of OpenFlow-based network operating systems, such as NOX [53], Onix [7] and ONOS [69]. Indeed, network operating systems have been in existence for decades. One of the most widely known and deployed is the Cisco IOS [65], which was originally conceived back in the early 90s. Other network operating systems worth mentioning are JUNOS [66], ExtremeXOS [67] and SR OS [68]. Despite being more specialized network operating systems, targeting network devices such as high-performance core routers, these NOSs abstract the underlying hardware to the network operator, making it easier to control the network infrastructure as well as simplifying the development and deployment of new protocols and management applications.

Finally, it is also worth recalling initiatives that can be seen as "technology pull" drivers. Back in the 90s, a movement towards open signalling [70] started to happen. The main motivation was to promote the wider adoption of the ideas proposed by projects such as NCP [36] and Tempest [46]. The open signalling movement worked towards separating the control and data signalling, by proposing open and programmable interfaces. Curiously, a rather similar movement can be observed with the recent advent of OpenFlow and SDN, with the lead of the Open Networking Foundation (ONF) [10]. This type of movement is crucial to promote open technologies into the market, hopefully leading equipment manufacturers to support open standards and thus fostering interoperability, competition, and innovation.

For a more extensive intellectual history of programmable networks and SDN we forward the reader to the recent paper by Feamster et al. [14].

IV. SOFTWARE-DEFINED NETWORKS: BOTTOM-UP

An SDN architecture can be depicted as a composition of different layers, as shown in Figure 6 (b). Each layer has its own specific functions. While some of them are always present in an SDN deployment, such as the southbound API, network operating systems, northbound API and management applications, others may be present only in particular deployments, such as hypervisor- or language-based virtualization.

Figure 6 presents a tri-fold perspective of SDNs. The SDN layers are represented in the center (b) of the figure, as explained above. Figures 6 (a) and 6 (c) depict a plane-oriented view and a system design perspective, respectively.

The following sections introduce each layer, following a bottom-up approach. For each layer, the core properties and concepts are explained based on the different technologies and solutions. Additionally, debugging and troubleshooting techniques and tools are discussed.

A. Layer I: Infrastructure

An SDN infrastructure, similarly to a traditional network, is composed of a set of networking equipment (switches, routers and middlebox appliances). The main difference resides in the fact that those traditional physical devices are now simple forwarding elements without embedded control or software to take autonomous decisions. The network intelligence is removed from the data plane devices to a logically-centralized control system, i.e., the network operating system and applications, as shown in Figure 6 (c). More importantly, these new networks are built (conceptually) on top of open and standard interfaces (e.g., OpenFlow), a crucial approach for ensuring configuration and communication compatibility and interoperability among different data and control plane devices. In other words, these open interfaces enable controller entities to dynamically program heterogeneous forwarding devices, something difficult in traditional networks, due to the large variety of proprietary and closed interfaces and the distributed nature of the control plane.

In an SDN/OpenFlow architecture, there are two main elements, the controllers and the forwarding devices, as shown in Figure 7. A data plane device is a hardware or software element specialized in packet forwarding, while a controller is a software stack (the "network brain") running on a commodity hardware platform. An OpenFlow-enabled forwarding device is based on a pipeline of flow tables where each entry of a flow table has three parts: (1) a matching rule, (2) actions to be executed on matching packets, and (3) counters

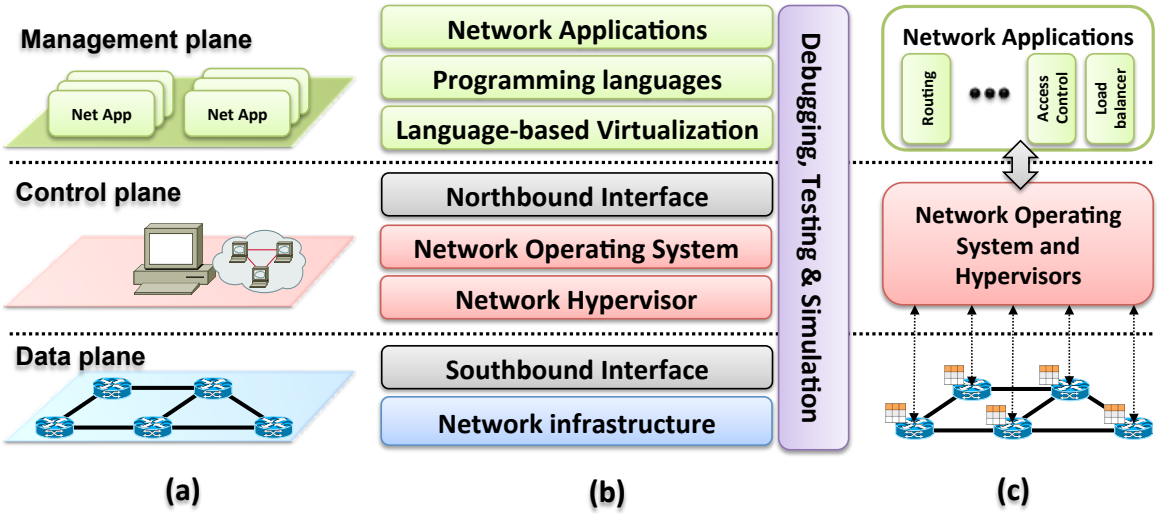

Fig. 6. Software-Defined Networks in (a) planes, (b) layers, and (c) system design architecture

that keep statistics of matching packets. This high-level and simplified model derived from OpenFlow is currently the most widespread design of SDN data plane devices. Nevertheless, other specifications of SDN-enabled forwarding devices are being pursued, including POF [23], [72] and the Negotiable Datapath Models (NDMs) from the ONF Forwarding Abstractions Working Group (FAWG) [73].

Inside an OpenFlow device, a path through a sequence of flow tables defines how packets should be handled. When a new packet arrives, the lookup process starts in the first table and ends either with a match in one of the tables of the pipeline or with a miss (when no rule is found for that packet). A flow rule can be defined by combining different matching fields, as illustrated in Figure 7. If there is no default rule, the packet will be discarded. However, the common case is to install a default rule which tells the switch to send the packet to the controller (or to the normal non-OpenFlow pipeline of the switch). The priority of the rules follows the natural sequence number of the tables and the row order in a flow table. Possible actions include (1) forward the packet to outgoing port(s), (2) encapsulate it and forward it to the controller, (3) drop it, (4) send it to the normal processing pipeline, (5) send it to the next flow table or to special tables, such as group or metering tables introduced in the latest OpenFlow protocol.

As detailed in Table II, each version of the OpenFlow specification introduced new match fields including Ethernet, IPv4/v6, MPLS, TCP/UDP, etc. However, only a subset of those matching fields are mandatory to be compliant to a given protocol version. Similarly, many actions and port types are optional features. Flow match rules can be based on almost arbitrary combinations of bits of the different packet headers using bit masks for each field. Adding new matching fields has been eased with the extensibility capabilities introduced in OpenFlow version 1.2 through an OpenFlow Extensible Match (OXM) based on type-length-value (TLV) structures. To improve the overall protocol extensibility, with OpenFlow version 1.4 TLV structures have been also added to ports, tables, and queues in replacement of the hard-coded counterparts of earlier protocol versions.

Overview of available OpenFlow devices

Several OpenFlow-enabled forwarding devices are available on the market, both as commercial and open source products (see Table III). There are many off-the-shelf, ready to deploy, OpenFlow switches and routers, among other appliances. Most of the switches available on the market have relatively small Ternary Content-Addressable Memory (TCAMs), with up to 8K entries. Nonetheless, this is changing at a fast pace. Some of the latest devices released in the market go far beyond that figure. Gigabit Ethernet switches for common business purposes are already supporting up to 32K L2+L3 or 64K L2/L3 exact match flows [74]. Enterprise class 10GE switches are being delivered with more than 80K Layer 2 flow entries [75]. Other switching devices using high performance chips such as the EZchip NP-4, provide optimized TCAM memory that already supports from 125K up to 1000K flow table entries [76]. This is a clear sign that the size of the flow tables is growing at a pace aiming to meet the needs of future SDN deployments.

Networking hardware manufacturers have produced various kinds of OpenFlow-enabled devices, as is shown in Table III. These devices range from equipment for small businesses (e.g., Gigabit Ethernet switches) to high-class data center equipment (e.g., high-density switch chassis with up to 100GbE connectivity for edge-to-core applications, with tens of Tbps of switching capacity).

Software switches are emerging as one of the most promising solutions for data centers and virtualized network infrastructures [99], [100], [101]. Examples of software-based OpenFlow switch implementations include Switch Light [97], ofsoftswitch13 [93], Open vSwitch [94], OpenFlow Reference [95], Pica8 [102], Pantou [98], and XorPlus [31]. Recent reports show that the number of virtual access ports is already larger than physical access ports on data centers [101]. Network virtualization has been one of the drivers behind this trend. Software switches such as Open vSwitch have been

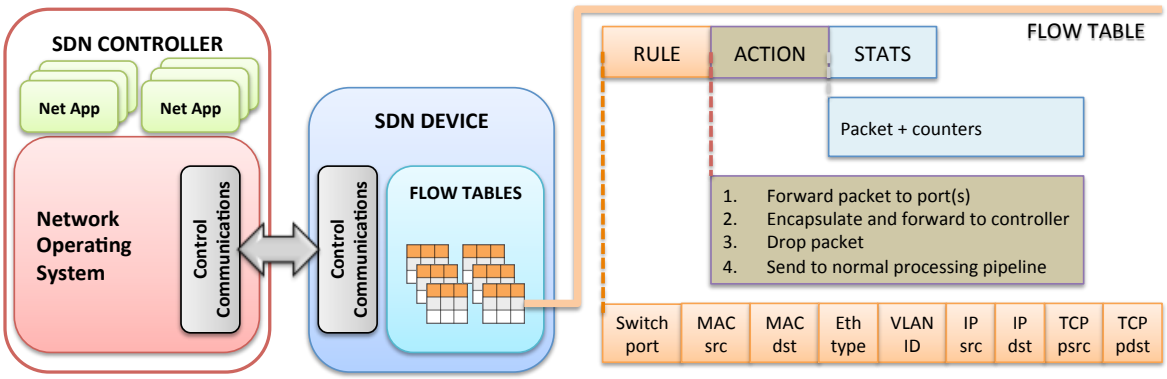

Fig. 7. OpenFlow-enabled SDN devices

TABLE II
DIFFERENT MATCH FIELDS, STATISTICS AND CAPABILITIES HAVE BEEN ADDED ON EACH OPENFLOW PROTOCOL REVISION. THE NUMBER OF REQUIRED (REQ) AND OPTIONAL (OPT) CAPABILITIES HAS GROWN CONSIDERABLY.

OpenFlow Version	Match fields	Statistics	# Matches		# Instructions		# Actions		# Ports	
			Req	Opt	Req	Opt	Req	Opt	Req	Opt
v 1.0	Ingress Port	Per table statistics	18	2	1	0	2	11	6	2
	Ethernet: src, dst, type, VLAN	Per flow statistics								
	IPv4: src, dst, proto, ToS	Per port statistics								
	TCP/UDP: src port, dst port	Per queue statistics								
v 1.1	Metadata, SCTP, VLAN tagging	Group statistics	23	2	0	0	3	28	5	3
	MPLS: label, traffic class	Action bucket statistics								
v 1.2	OpenFlow Extensible Match (OXM)		14	18	2	3	2	49	5	3
	IPv6: src, dst, flow label, ICMPv6									
v 1.3	PBB, IPv6 Extension Headers	Per-flow meter	14	26	2	4	2	56	5	3
		Per-flow meter band								
v 1.4	—	—	**14**	**27**	**2**	**4**	**2**	**57**	**5**	**3**
		Optical port properties								

used for moving network functions to the edge (with the core performing traditional IP forwarding), thus enabling network virtualization [64].

An interesting observation is the number of small, start-up enterprises devoted to SDN, such as Big Switch, Pica8, Cyan, Plexxi, and NoviFlow. This seems to imply that SDN is springing a more competitive and open networking market, one of its original goals. Other effects of this openness triggered by SDN include the emergence of so-called "bare metal switches" or "whitebox switches", where the software and hardware are sold separately and the end-user is free to load an operating system of its choice [103].

B. Layer II: Southbound Interfaces

Southbound interfaces (or southbound APIs) are the connecting bridges between control and forwarding elements, thus being the crucial instrument for clearly separating control and data plane functionality. However, these APIs are still tightly tied to the forwarding elements of the underlying physical or virtual infrastructure.

Typically, a new switch can take two years to be ready for commercialization if built from scratch, with upgrade cycles that can take up to nine months. The software development for a new product can take from six months to one year [104]. The initial investment is high and risky. As a central component of its design the southbound APIs represent one of the major barriers for the introduction and acceptance of any new networking technology. In this light, the emergence of SDN southbound API proposals such as OpenFlow [9] is seen as welcome by many in the industry. These standards promote interoperability, allowing the deployment of vendor-agnostic network devices. This has already been demonstrated by the interoperability between OpenFlow-enabled equipments from different vendors.

As of this writing, OpenFlow is the most widely accepted and deployed open southbound standard for SDN. It provides a common specification to implement OpenFlow-enabled forwarding devices, and for the communication channel between data and control plane devices (e.g., switches and controllers). The OpenFlow protocol provides three information sources for network operating systems. First, event-based messages are sent by forwarding devices to the controller when a link or port change is triggered. Second, flow statistics are generated by the forwarding devices and collected by the controller.

TABLE III
OPENFLOW ENABLED HARDWARE AND SOFTWARE DEVICES

Group	Product	Type	Maker/Developer	Version	Short description
Hardware	8200zl and 5400zl [77]	chassis	Hewlett-Packard	v1.0	Data center class chassis (switch modules).
	Arista 7150 Series [78]	switch	Arista Networks	v1.0	Data centers hybrid Ethernet/OpenFlow switches.
	BlackDiamond X8 [79]	switch	Extreme Networks	v1.0	Cloud-scale hybrid Ethernet/OpenFlow switches.
	CX600 Series [80]	router	Huawei	v1.0	Carrier class MAN routers.
	EX9200 Ethernet [81]	chassis	Juniper	v1.0	Chassis based switches for cloud data centers.
	EZchip NP-4 [82]	chip	EZchip Technologies	v1.1	High performance 100-Gigabit network processors.
	MLX Series [83]	router	Brocade	v1.0	Service providers and enterprise class routers.
	NoviSwitch 1248 [76]	switch	NoviFlow	v1.3	High performance OpenFlow switch.
	NetFPGA [33]	card	NetFPGA	v1.0	1G and 10G OpenFlow implementations.
	RackSwitch G8264 [84]	switch	IBM	v1.0	Data center switches supporting Virtual Fabric and OpenFlow.
	PF5240 and PF5820 [85]	switch	NEC	v1.0	Enterprise class hybrid Ethernet/OpenFlow switches.
	Pica8 3920 [86]	switch	Pica8	v1.0	Hybrid Ethernet/OpenFlow switches.
	Plexxi Switch 1 [87]	switch	Plexxi	v1.0	Optical multiplexing interconnect for data centers.
	V330 Series [88]	switch	Centec Networks	v1.0	Hybrid Ethernet/OpenFlow switches.
	Z-Series [89]	switch	Cyan	v1.0	Family of packet-optical transport platforms.
Software	contrail-vrouter [90]	vrouter	Juniper Networks	v1.0	Data-plane function to interface with a VRF.
	LINC [91], [92]	switch	FlowForwarding	v1.3	Erlang-based soft switch with OF-Config 1.1 support.
	ofsoftswitch13 [93]	switch	Ericsson, CPqD	v1.3	OF 1.3 compatible user-space software switch implementation.
	Open vSwitch [94], [61]	switch	Open Community	v1.0	Switch platform designed for virtualized server environments.
	OpenFlow Reference [95]	switch	Stanford	v1.0	OF Switching capability to a Linux PC with multiple NICs.
	OpenFlowClick [96]	vrouter	Yogesh Mundada	v1.0	OpenFlow switching element for Click software routers.
	Switch Light [97]	switch	Big Switch	v1.0	Thin switching software platform for physical/virtual switches.
	Pantou/OpenWRT [98]	switch	Stanford	v1.0	Turns a wireless router into an OF-enabled switch.
	XorPlus [31]	switch	Pica8	v1.0	Switching software for high performance ASICs.

Third, packet-in messages are sent by forwarding devices to the controller when they do not known what to do with a new incoming flow or because there is an explicit "send to controller" action in the matched entry of the flow table. These information channels are the essential means to provide flow-level information to the network operating system.

Albeit the most visible, OpenFlow is not the only available southbound interface for SDN. There are other API proposals such as ForCES [22], OVSDB [105], POF [23], [72], and OpFlex [106]. ForCES proposes a more flexible approach to traditional network management without changing the current architecture of the network, i.e., without the need of a logically-centralized external controller. The control and data planes are separated but can potentially be kept in the same network element. However, the control part of the network element can be upgraded on-the-fly with third-party firmware.

OVSDB [105] is another type of southbound API, designed to provide advanced management capabilities for Open vSwitches. Beyond OpenFlow's capabilities to configure the behavior of flows in a forwarding device, an Open vSwitch offers other networking functions. For instance, it allows the control elements to create multiple virtual switch instances, set QoS policies on interfaces, attach interfaces to the switches, configure tunnel interfaces on OpenFlow data paths, manage queues, and collect statistics. Therefore, the OVSDB is a complementary protocol to OpenFlow for Open vSwitch.

One of the first direct competitors of OpenFlow is POF [23], [72]. One of the main goals of POF is to enhance the current SDN forwarding plane. With OpenFlow, switches have to understand the protocol headers to extract the required bits to be matched with the flow tables entries. This parsing represents a significant burden for data plane devices, in particular if we consider that OpenFlow version 1.3 already contains more than 40 header fields. Besides this inherent complexity, backward compatibility issues may arise every time new header fields are included in or removed from the protocol. To achieve its goal, POF proposes a generic flow instruction set (FIS) that makes the forwarding plane protocol-oblivious. A forwarding element does not need to know, by itself, anything about the packet format in advance. Forwarding devices are seen as white boxes with only processing and forwarding capabilities. In POF, packet parsing is a controller task that results in a sequence of generic keys and table lookup instructions that are installed in the forwarding elements. The behavior of data plane devices is therefore completely under the control of the SDN controller. Similar to a CPU in a computer sytem, a POF switch is application- and protocol-agnostic.

A very recent soutbound interface proposal is OpFlex [106]. Contrary to OpenFlow (and similar to ForCES), one of the ideas behind OpFlex is to distribute part of the complexity of managing the network back to the forwarding devices, with the aim of improving scalability. Similar to OpenFlow, policies are

logically centralized and abstracted from the underlying implementation. The differences between OpenFlow and OpFlex are a clear illustration of one of the important questions to be answered when devising a southbound interface: where to place each piece of the overall functionality.

C. Layer III: Network Hypervisors

Virtualization is already a consolidated technology in modern computers. The fast developments of the past decade have made virtualization of computing platforms mainstream. Based on recent reports, the number of virtual servers has already exceeded the number of physical servers [107], [64].

Hypervisors enable distinct virtual machines to share the same hardware resources. In a cloud infrastructure-as-a-service (IaaS), each user can have its own virtual resources, from computing to storage. This enabled new revenue and business models where users allocate resources on-demand, from a shared physical infrastructures, at a relatively low cost. At the same time, providers make better use of the capacity of their installed physical infrastructures, creating new revenue streams without significantly increasing their CAPEX and OPEX costs. One of the interesting features of virtualization technologies today is the fact that virtual machines can be easily migrated from one physical server to another and can be created and/or destroyed on-demand, enabling the provisioning of elastic services with flexible and easy management. Unfortunately, virtualization has been only partially realized in practice. Despite the great advances in virtualizing computing and storage elements, the network is still mostly statically configured in a box-by-box manner [28].

The main network requirements can be captured along two dimensions: network topology and address space. Different workloads require different network topologies and services, such as flat L2 or L3 services, or even more complex L4-L7 services for advanced functionality. Currently, it is very difficult for a single physical topology to support the diverse demands of applications and services. Similarly, address space is hard to change in current networks. Nowadays, virtualized workloads have to operate in the same address of the physical infrastructure. Therefore, it is hard to keep the original network configuration for a tenant, virtual machines can not migrate to arbitrary locations, and the addressing scheme is fixed and hard to change. For example, IPv6 cannot be used by the VMs of a tenant if the underlying physical forwarding devices support only IPv4.

To provide complete virtualization the network should provide similar properties to the computing layer [28]. The network infrastructure should be able to support arbitrary network topologies and addressing schemes. Each tenant should have the ability to configure both the computing nodes and the network simultaneously. Host migration should automatically trigger the migration of the corresponding virtual network ports. One might think that long standing virtualization primitives such as VLANs (virtualized L2 domain), NAT (Virtualized IP address space), and MPLS (virtualized path) are enough to provide full and automated network virtualization. However, these technologies are anchored on a box-by-box basis configuration, i.e., there is no single unifying abstraction that can be leveraged to configure (or reconfigure) the network in a global manner. As a consequence, current network provisioning can take months, while computing provisioning takes only minutes [64], [108], [109], [110].

There is hope that this situation will change with SDN and the availability of new tunneling techniques (e.g., VXLAN [111], NVGRE [112]). For instance, solutions such as FlowVisor [113], [63], [114], FlowN [115], NVP [64], OpenVirteX [116] and IBM SDN VE [117], [118] have been recently proposed, evaluated and deployed in real scenarios for on-demand provisioning of virtual networks.

Slicing the network

FlowVisor is one of the early technologies to virtualize a Software-Defined Network. Its basic idea is to allow multiple logical networks share the same OpenFlow networking infrastructure. For this purpose, it provides an abstraction layer that makes it easier to slice a data plane based on off-the-shelf OpenFlow-enabled switches, allowing multiple and diverse networks to co-exist.

Five slicing dimensions are considered in FlowVisor: bandwidth, topology, traffic, device CPU and forwarding tables. Moreover, each network slice supports a controller, i.e., multiple controllers can co-exist on top of the same physical network infrastructure. Each controller is allowed to act only on its own network slice. In general terms, a slice is defined as a particular set of flows on the data plane. From a system design perspective, FlowVisor is a transparent proxy that intercepts OpenFlow messages between switches and controllers. It partitions the link bandwidth and flow tables of each switch. Each slice receives a minimum data rate and each guest controller gets its own virtual flow table in the switches.

Similarly to FlowVisor, OpenVirteX [116] acts as a proxy between the network operating system and the forwarding devices. However, its main goal is to provide virtual SDNs through both topology, address, and control function virtualization. All these properties are necessary in multi-tenant environments where virtual networks need to be managed and migrated according to the computing and storage virtual resources. Virtual network topologies have to be mapped onto the underlying forwarding devices, with virtual addresses allowing tenants to completely manage their address space without depending on the underlying network elements addressing schemes.

AutoSlice [119] is another SDN-based virtualization proposal. Similar to FlowVisor, the idea is to allow multiple controllers to manage their respective virtual SDN. The main difference is that AutoSlice intends to develop a transparent virtualization layer, or SDN hypervisor, to automate the deployment of virtual SDNs in a less cumbersome manner than FlowVisor.

FlowN [115], [120] is based on a slightly different concept. Whereas FlowVisor can be compared to a full virtualization technology, FlowN is analogous to a container-based virtualization, i.e., a lightweight virtualization approach. FlowN was also primarily conceived to address multi-tenancy in the context of cloud platforms. It is designed to be scalable and

allows a unique shared controller platform to be used for managing multiple domains in a cloud environment. Each tenant has full control over its virtual networks and is free to deploy any network abstraction and application on top of the controller platform.

Commercial multi-tenant network hypervisors

None of the aforementioned approaches is designed to address all challenges of multi-tenant data centers. For instance, tenants want to be able to migrate their enterprise solutions to cloud providers without the need to modify the network configuration of their home network. Existing networking technologies and migration strategies have mostly failed to meet both the tenant and the service provider requirements. A multi-tenant environment should be anchored in a network hypervisor capable of abstracting the underlaying forwarding devices and physical network topology from the tenants. Moreover, each tenant should have access to control abstractions and manage its own virtual networks independently and isolated from other tenants.

With the market demand for network virtualization and the recent research on SDN showing promise as an enabling technology, different commercial virtualization platforms based on SDN concepts have started to appear. VMWare has proposed a network virtualization platform (NVP) [64] that provides the necessary abstractions to allow the creation of independent virtual networks for large-scale multi-tenant environments. NVP is a complete network virtualization solution that allows the creation of virtual networks, each with independent service model, topologies, and addressing architectures over the same physical network. With NVP, tenants do not need to know anything about the underlying network topology, configuration or other specific aspects of the forwarding devices. NVP's network hypervisor translates the tenants configurations and requirements into low level instruction sets to be installed on the forwarding devices. For this purpose, the platform uses a cluster of SDN controllers to manipulate the forwarding tables of the Open vSwitches in the host's hypervisor. Forwarding decisions are therefore made exclusively on the network edge. After the decision is made, the packet is tunneled over the physical network to the receiving host hypervisor (the physical network sees nothing but ordinary IP packets).

IBM has also recently proposed SDN VE [117], [118], another commercial and enterprise-class network virtualization platform. SDN VE uses OpenDaylight as one of its building blocks for Software-Defined Environments (SDEs)[2]. This solutions also offers a complete implementation framework for network virtualization. Like NVP, it uses a host-based overlay approach, achieving advanced network abstraction that enables application-level network services in large-scale multi-tenant environments. Interestingly, SDN VE 1.0 is capable of supporting in one single instantiation up to 16,000 virtual networks and 128,000 virtual machines [117], [118].

To summarize, currently there are only a few network hypervisor proposals leveraging the advances of SDN. We antecipate, however, this ecosystem to expand in the near future since network virtualization will most likely play a key role in future virtualized environments, similarly to the expansion we have been witnessing in virtualized computing.

[2]We will return to OpenDaylight and SDE later.

D. Layer IV: Network Operating Systems / Controllers

Traditional operating systems provide abstractions (e.g., high-level programming APIs) for accessing lower-level devices, manage the concurrent access to the underlying resources (e.g., hard drive, network adapter, CPU, memory), and provide security protection mechanisms. These functionalities and resources are key enablers for increased productivity, making the life of system and application developers easier. Their widespread use has significantly contributed to the evolution of various ecosystems (e.g., programming languages) and the development of a myriad of applications.

In contrast, networks have so far been managed and configured using lower level, device-specific instruction sets and mostly closed proprietary network operating systems (e.g., Cisco IOS and Juniper JunOS). Moreover, the idea of operating systems abstracting device-specific characteristics and providing, in a transparent way, common functionalities is still almost absent in networks. For instance, nowadays designers of routing protocols need to deal with complicated distributed algorithms when solving networking problems. Network practitioners have therefore been solving the same problems over and over again.

SDN is promised to facilitate network management and ease the burden of solving networking problems by means of the logically-centralized control offered by a network operating system (NOS) [53]. As with traditional operating systems, the crucial value of a NOS is to provide abstractions, essential services, and common application programming interfaces (APIs) to developers. Generic functionality as network state and network topology information, device discovery, and distribution of network configuration can be provided as services of the NOS. With NOSs, to define network policies a developer no longer needs to care about the low-level details of data distribution among routing elements, for instance. Such systems can arguably create a new environment capable of fostering innovation at a faster pace by reducing the inherent complexity of creating new network protocols and management applications.

A NOS (or controller) is a critical element in an SDN architecture as it is the key supporting piece for the control logic (applications) to generate the network configuration based on the policies defined by the network operator. Similar to a traditional operating system, the control platform abstracts the lower-level details of connecting and interacting with forwarding devices (i.e., of materializing the network policies).

Architecture and design axes

There are very diverse controllers and control platforms with different design and architectural choices [7], [13], [121], [122], [123], [124]. Existing controllers can be categorized based on many aspects. From an architectural point of view, one of the most relevant is if they are centralized or distributed. This is one of the key design axes of SDN control platforms, so we start by discussing this aspect next.

Centralized vs. Distributed

A centralized controller is a single entity that manages all forwarding devices of the network. Naturally, it represents a single point of failure and may have scaling limitations. A single controller may not be enough to manage a network with a large number of data plane elements. Centralized controllers such as NOX-MT [125], Maestro [126], Beacon [127], and Floodlight [128] have been designed as highly concurrent systems, to achieve the throughput required by enterprise class networks and data centers. These controllers are based on multi-threaded designs to explore the parallelism of multi-core computer architectures. As an example, Beacon can deal with more than 12 million flows per second by using large size computing nodes of cloud providers such as Amazon [127]. Other centralized controllers such as Trema [129], Ryu NOS [130], Meridian [131], and ProgrammableFlow [132], [85] target more or less specific environments such as data centers, cloud infrastructures, and carrier grade networks.

Contrary to a centralized design, a distributed network operating system can be scaled up to meet the requirements of potentially any environment, from small to large-scale networks. A distributed controller can be a centralized cluster of nodes or a physically distributed set of elements. While the first alternative can offer high throughput for very dense data centers, the latter can be more resilient to different kinds of logical and physical failures. A cloud provider that spans multiple data centers interconnected by a wide area network may require a hybrid approach, with clusters of controllers inside each data center and distributed controller nodes in the different sites [8].

Onix [7], HyperFlow [133], HP VAN SDN [122], ONOS [69], DISCO [123], and *yanc* [134] are examples of distributed controllers. Most distributed controllers offer weak consistency semantics, which means that data updates on distinct nodes will *eventually* be updated on all controller nodes. This implies that there is a period of time in which distinct nodes may read different values (old value or new value) for a same property. Strong consistency, on the other hand, ensures that all controller nodes will read the most updated property value after a write operation. Despite its impact on system performance, strong consistency offers a simpler interface to application developers. To date, only Onix and ONOS provide different data consistency models (both weak and strong).

Another common property of distributed controllers is fault tolerance. When one node fails, another neighbor node should take over the duties and devices of the failed node. So far, despite some controllers tolerating crash failures, they do not tolerate arbitrary failures, which means that any node with an abnormal behavior will not be replaced by a potentially well behaved one.

A single controller may be enough to manage a small network, however it represents a single point of failure. Similarly, independent controllers can be spread across the network, each of them managing a network segment, reducing the impact of a single controller failure. Yet, if the control plane availability is critical, a cluster of controllers can be used to achieve a higher degree of availability and/or for supporting more devices. Ultimately, a distributed controller can improve the control plane resilience, scalability and reduce the impact of problems caused by network partition, for instance. SDN resiliency as a whole is an open challenge that will be further discussed in Section V-C.

Dissecting SDN Controller Platforms

To provide a better architectural overview and understanding the design a network operating system, Table IV summarizes some of the most relevant architectural and design properties of SDN controllers and control platforms. We have focused on the elements, services and interfaces of a selection of production-level, well-documented controllers and control platforms. Each line in the table represent a component we consider important in a modular and scalable control platform. We observe a highly diversified environment, with different properties and components being used by distinct control platforms. This is not surprising, given an environment with many competitors willing to be at the forefront of SDN development. Note also that not all components are available on all platforms. For instance, east/westbound APIs are not required in centralized controllers such as Beacon. In fact, some platforms have very specific niche markets, such as telecom companies and cloud providers, so the requirements will be different.

Based on the analysis of the different SDN controllers proposed to date (both those presented in Table IV and others, such as NOX [53], Meridian [131], ForCES [22], and FortNOX [135]), we extract several common elements and provide a first attempt to clearly and systematically dissect an SDN control platform in Figure 8.

There are at least three relatively well-defined layers in most of the existing control platforms: (*i*) the application, orchestration and services; (*ii*) the core controller functions, and (iii) the elements for southbound communications. The connection at the upper-level layers is based on northbound interfaces such as REST APIs [136] and programming languages such as FML [137], Frenetic [138] and NetCore [139]. On the lower-level part of a control platform, southbound APIs and protocol plugins interface the forwarding elements. The core of a controller platform can be characterized as a combination its base network service functions and the various interfaces.

Core controller functions

The base network service functions are what we consider the essential functionality all controllers should provide. As an analogy, these functions are like base services of operating systems, such as program execution, I/O operations control, communications, protection, and so on. These services are used by other operating system level services and user applications. In a similar way, functions such as topology, statistics, notifications and device management, together with shortest path forwarding and security mechanisms are essential network control functionalities that network applications may use in building its logic. For instance, the notification manager should be able to receive, process, and forward events (e.g., alarm notifications, security alarms, state changes) [140]. Security mechanisms are another example, as they are critical

TABLE IV
ARCHITECTURE AND DESIGN ELEMENTS OF CONTROL PLATFORMS

Component	OpenDaylight	OpenContrail	HP VAN SDN	Onix	Beacon
Base network services	Topology/Stats/Switch Manager, Host Tracker, Shortest Path Forwarding	Routing, Tenant Isolation	Audit Log, Alerts, Topology, Discovery	Discovery, Multi-consistency Storage, Read State, Register for updates	Topology, device manager, and routing
East/Westbound APIs	—	Control Node (XMPP-like control channel)	Sync API	Distribution I/O module	*Not present*
Integration Plug-ins	OpenStack Neutron	CloudStack, OpenStack	OpenStack	—	—
Management Interfaces	GUI/CLI, REST API	GUI/CLI	REST API Shell / GUI Shell	—	Web
Northbound APIs	REST, RESTCONF, Java APIs	REST APIs (configuration, operational, and analytic)	REST API, GUI Shell	Onix API (general purpose)	API (based on OpenFlow events)
Service abstraction layers	Service Abstraction Layer (SAL)	—	Device Abstraction API	Network Information Base (NIB) Graph with Import/Export Functions	—
Southbound APIs or connectors	OpenFlow, OVSDB, SNMP, PCEP, BGP, NETCONF	—	OpenFlow, L3 Agent, L2 Agent	OpenFlow, OVSDB	OpenFlow

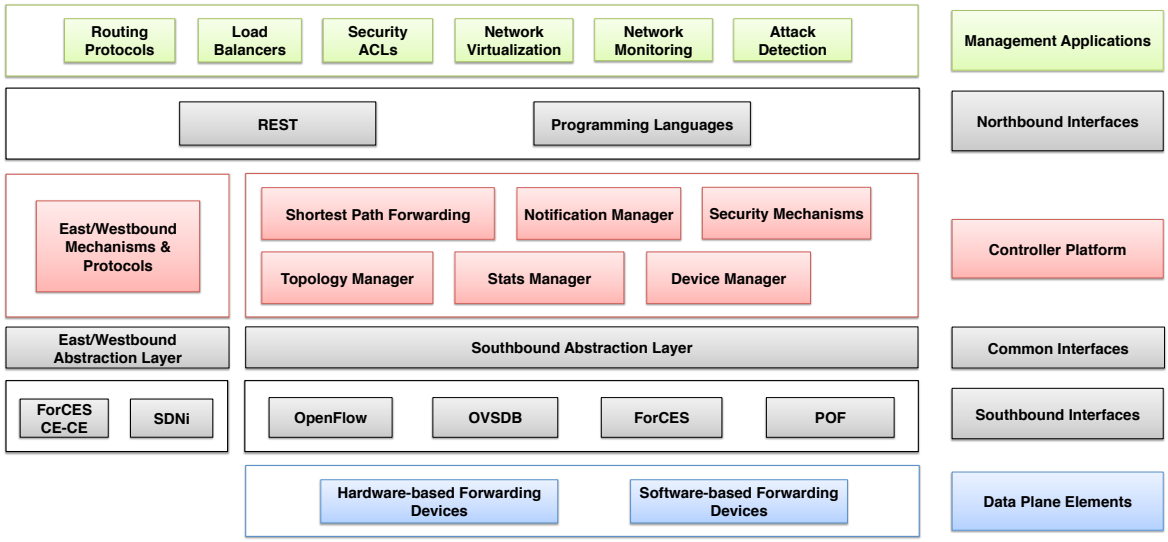

Fig. 8. SDN control platforms: elements, services and interfaces

components to provide basic isolation and security enforcement between services and applications. For instance, rules generated by high priority services should not be overwritten with rules created by applications with a lower priority.

Southbound

On the lower-level of control platforms, the southbound APIs can be seen as a layer of device drivers. They provide a common interface for the upper layers, while allowing a control platform to use different southbound APIs (e.g., OpenFlow, OVSDB, ForCES) and protocol plugins to manage existing or new physical or virtual devices (e.g., SNMP, BGP, NetConf). This is essential both for backward compatibility and heterogeneity, i.e., to allow multiple protocols and device management connectors. Therefore, on the data plane, a mix of physical devices, virtual devices (e.g., Open vSwitch [94], [61], vRouter [141]) and a variety of device interfaces (e.g., OpenFlow, OVSDB, of-config [142], NetConf, and SNMP) can co-exist.

Most controllers support only OpenFlow as a southbound API. Still, a few of them, such as OpenDaylight, Onix and HP VAN SDN Controller, offer a wider range of southbound APIs and/or protocol plugins. Onix supports both the OpenFlow and OVSDB protocols. The HP VAN SDN Controller has other southbound connectors such as L2 and L3 agents. OpenDaylight goes a step beyond by providing a Service Layer Abstraction (SLA) that allows several southbound APIs and protocols to co-exist in the control platform. For instance, its original architecture was designed to support at least seven different protocols and plugins: OpenFlow, OVSDB [105],

NETCONF [143], PCEP [48], SNMP [144], BGP [145] and LISP Flow Mapping [13]. Hence, OpenDaylight is one of the few control platforms being conceived to support a broader integration of technologies in a single control platform.

Eastbound and Westbound

East/westbound APIs, as illustrated in Figure 9, are a special case of interfaces required by distributed controllers. Currently, each controller implements its own east/westbound API. The functions of these interfaces include import/export data between controllers, algorithms for data consistency models, and monitoring/notification capabilities (e.g., check if a controller is up or notify a take over on a set of forwarding devices).

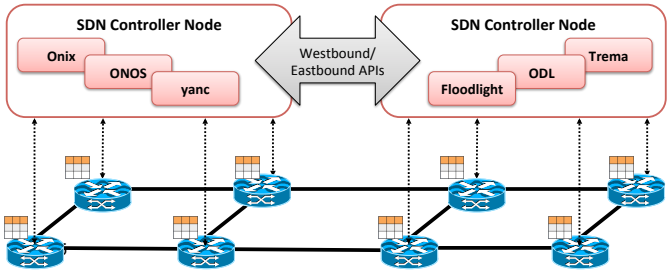

Fig. 9. Distributed controllers: east/westbound APIs.

Similarly to southbound and northbound interfaces, east/westbound APIs are essential components of distributed controllers. To identify and provide common compatibility and interoperability between different controllers, it is necessary to have standard east/westbound interfaces. For instance, SDNi [146] defines common requirements to coordinate flow setup and exchange reachability information across multiple domains. In essence, such protocols can be used in an orchestrated and interoperable way to create more scalable and dependable distributed control platforms. Interoperability can be leveraged to increase the diversity of the control platform element. Indeed, diversity increases the system robustness by reducing the probability of common faults, such as software faults [147].

Other proposals that try to define interfaces between controllers include Onix data import/export functions [7], ForCES CE-CE interface [22], [148], ForCES Intra-NE cold-standby mechanisms for high availability [149], and distributed data stores [150]. An east/westbound API requires advanced data distribution mechanisms such as the Advanced Message Queuing Protocol (AMQP) [151] used by DISCO [123], transactional databases and DHTs [152] (as used in Onix [7]), or advanced algorithms for strong consistency and fault tolerance [150].

In a multi-domain setup, east/westbound APIs may require also more specific communication protocols between SDN domain controllers [153]. Some of the essential functions of such protocols are to *coordinate flow setup* originated by applications, *exchange reachability information* to facilitate inter-SDN routing, *reachability update* to keep the network state consistent, among others.

Northbound

Current controllers offer a quite broad variety of northbound APIs, such as ad-hoc APIs, RESTful APIs [136], multi-level programming interfaces, file systems, among other more specialized APIs such as NVP NBAPI [7], [64] and SDMN API [154]. Section IV-E is devoted to a more detailed discussion on the evolving layer of northbound APIs. A second kind of northbound interfaces are those stemming out of SDN programming languages such as Frenetic [138], Nettle [155], NetCore [139], Procera [156], and Pyretic [157]. Section IV-G gives a more detailed overview of the several existing programming languages for SDN.

Wrapping up remarks and platforms comparison

Table V shows a summary of some of the existing controllers with their respective architectures and characteristics. As can be observed, most controllers are centralized and multi-threaded. Curiously, the northbound API is very diverse. In particular, five controllers (Onix, Floodlight, MuL, Meridian and SDN Unified Controller) pay a bit more attention to this interface, as a statement of its importance. Consistency models and fault tolerance are only present in Onix, HyperFlow, HP VAN SDN, and ONOS. Lastly, when it comes to the OpenFlow standard as southbound API, only Ryu supports its three major versions (v1.0, v1.2 and v1.3).

To conclude, it is important to emphasize that the control platform is one of the critical points for the success of SDN [163]. One of the main issues that needs to be address in this respect is interoperability. This is rather interesting, as it was the very first problem that southbound APIs (such as OpenFlow) tried to solve. For instance, while WiFi and LTE networks [164] need specialized control platforms such as MobileFlow [154] or SoftRAN [165], data center networks have different requirements that can be met with platforms such as Onix [7] or OpenDaylight [13]. For this reason, in environments where diversity of networking infrastructures is a reality, coordination and cooperation between different controllers is crucial. Standardized APIs for multi-controller and multi-domain deployments are therefore seen as an important step to achieve this goal.

E. Layer V: Northbound Interfaces

The North- and Southbound interfaces are two key abstractions of the SDN ecosystem. The southbound interface has already a widely accepted proposal (OpenFlow), but a common northbound interface is still an open issue. At this moment it may still be a bit too early to define a standard northbound interface, as use-cases are still being worked out [166]. Anyway, it is to be expected a common (or a *de facto*) northbound interface to arise as SDN evolves. An abstraction that would allow network applications not to depend on specific implementations is important to explore the full potential of SDN

The northbound interface is mostly a software ecosystem, not a hardware one as is the case of the southbound APIs. In these ecosystems, the implementation is commonly the forefront driver, while standards emerge later and are essentially driven by wide adoption [167]. Nevertheless, an initial and minimal standard for northbound interfaces can still play an important role for the future of SDN. Discussions about

TABLE V
CONTROLLERS CLASSIFICATION

Name	Architecture	Northbound API	Consistency	Faults	License	Prog. language	Version
Beacon [127]	centralized multi-threaded	ad-hoc API	no	no	GPLv2	Java	v1.0
DISCO [123]	distributed	REST	—	yes	—	Java	v1.1
Floodlight [128]	centralized multi-threaded	RESTful API	no	no	Apache	Java	v1.1
HP VAN SDN [122]	distributed	RESTful API	weak	yes	—	Java	v1.0
HyperFlow [133]	distributed	—	weak	yes	—	C++	v1.0
Kandoo [158]	hierarchically distributed	—	no	no	—	C, C++, Python	v1.0
Onix [7]	distributed	NVP NBAPI	weak, strong	yes	commercial	Python, C	v1.0
Maestro [126]	centralized multi-threaded	ad-hoc API	no	no	LGPLv2.1	Java	v1.0
Meridian [131]	centralized multi-threaded	extensible API layer	no	no	—	Java	v1.0
MobileFlow [154]	—	SDMN API	—	—	—	—	v1.2
MuL [159]	centralized multi-threaded	multi-level interface	no	no	GPLv2	C	v1.0
NOX [53]	centralized	ad-hoc API	no	no	GPLv3	C++	v1.0
NOX-MT [125]	centralized multi-threaded	ad-hoc API	no	no	GPLv3	C++	v1.0
NVP Controller [64]	distributed	—	—	—	commercial	—	—
OpenContrail [121]	—	REST API	no	no	Apache 2.0	Python, C++, Java	v1.0
OpenDaylight [13]	distributed	REST, RESTCONF	weak	no	EPL v1.0	Java	v1.{0,3}
ONOS [69]	distributed	RESTful API	weak, strong	yes	—	Java	v1.0
POX [160]	centralized	ad-hoc API	no	no	GPLv3	Python	v1.0
ProgrammableFlow [161]	centralized	—	—	—	—	C	v1.3
Ryu NOS [130]	centralized multi-threaded	ad-hoc API	no	no	Apache 2.0	Python	v1.{0,2,3}
SNAC [162]	centralized	ad-hoc API	no	no	GPL	C++	v1.0
Trema [129]	centralized multi-threaded	ad-hoc API	no	no	GPLv2	C, Ruby	v1.0
Unified Controller [117]	—	REST API	—	—	commercial	—	v1.0
yanc [134]	distributed	file system	—	—	—	—	—

this issue have already begun [166], [167], [168], [169], [170], [171], [172], [173], and a common consensus is that northbound APIs are indeed important but that it is indeed too early to define a single standard right now. The experience from the development of different controllers will certainly be the basis for coming up with a common application level interface.

Open and standard northbound interfaces are crucial to promote application portability and interoperability among the different the control platforms. A northbound API can be compared to the POSIX standard in operating systems, representing an abstraction that guarantees programming language and controller independence. NOSIX [174] is one of the first examples of an effort in this direction. It tries to define portable low-level (e.g., flow model) application interfaces, making southbound APIs such as OpenFlow look like "device drivers". However, NOSIX is not exactly a general purpose northbound interface, but rather a higher-level abstraction for southbound interfaces. Indeed, it could be part of the common abstraction layer in a control platform as the one described in Section IV-D.

Existing controllers such as Floodlight, Trema, NOX, Onix, and OpenDaylight propose and define their own northbound APIs [168], [175]. However, each of them has its own specific definitions. Programming languages such as Frenetic [138], Nettle [155], NetCore [139], Procera [156] and Pyretic [176] also abstract the inner details of the controller functions and data plane behavior from the application developers. Moreover, as we explain in Section IV-G, programming languages can provide a wide range of powerful abstractions and mechanisms such as application composition, transparent data plane fault tolerance, and a variety of basic building blocks to ease software module and application development.

SFNet [177] is another example of a northbound interface. It is a high-level API that translates application requirements into lower level service requests. However, SFNet has a limited scope, targeting queries to request the congestion state of the network and services such as bandwidth reservation and multicast.

Other proposals use different approaches to allow applications to interact with controllers. The *yanc* control platform [134] explores this idea by proposing a general control platform based on Linux and abstractions such as the virtual file system (VFS). This approach simplifies the development of SDN applications as programmers are able to use a traditional concept (files) to communicate with lower level devices and sub-systems.

Eventually, it is unlikely that a single northbound interface emerges as the winner, as the requirements for different network applications are quite different. APIs for security applications are likely to be different from those for routing or financial applications. One possible path of evolution for

northbound APIs are vertically-oriented proposals, before any type of standardization occurs, a challenge the ONF has started to undertake in addition to open-source SDN controller platform developments (e.g., OpenDaylight, Floodlight, OpenStack).

F. Layer VI: Language-based Virtualization

Two essential characteristics of virtualization solutions are the capability of expressing modularity and of allowing different levels of abstractions while still guaranteeing desired properties such as protection. For instance, virtualization techniques can allow different views of a single physical infrastructure. As an example, one virtual "big switch" could represent a combination of several underlying forwarding devices. This intrinsically simplifies the task of application developers as they do not need to think about the sequence of switches where forwarding rules have to be installed, but rather see the network as a simple "big switch". Such kind of abstraction significantly simplify the development and deployment of complex network applications, such as advanced security related services.

Pyretic [176] is an interesting example of a programming language that offers this type of high-level abstraction of network topology. It incorporates this concept of abstraction by introducing network objects. These objects consist of an abstract network topology and the sets of policies applied to it. Network objects simultaneously hide information and offer the required services.

Another form of language-based virtualization is static slicing. This a scheme where the network is sliced by a compiler, based on application layer definitions. The output of the compiler is a monolithic control program that has already slicing definitions and configuration commands for the network. In such a case, there is no need for a hypervisor to dynamically manage the network slices. Static slicing can be valuable for deployments with specific requirements, in particular those where higher performance and simple isolation guarantees are preferrable to dynamic slicing.

One example of static slicing approach it the Splendid isolation [178]. In this solution the network slices are made of 3 components: (a) *topology*, consisting of switches, ports, and links; (b) *mapping* of slice-level switches, ports and links on the network infrastructure; (c) *predicates on packets*, where each port of the slice's edge switches has an associated predicate. The topology is a simple graph of the sliced nodes, ports and links. Mapping will translate the abstract topology elements into the corresponding physical ones. The predicates are used to indicate whether a packet is permitted or not to enter a specific slice. Different applications can be associated to each slice. The compiler takes the combination of slices (topology, mapping, and predicates) and respective programs to generate a global configuration for the entire network. It also ensures that properties such as isolation are enforced among slices, i.e., no packets of a slice A can traverse to a slice B unless explicitly allowed.

Other solutions, such as libNetVirt [179], try to integrate heterogeneous technologies for creating static network slices. libNetVirt is a library designed to provide a flexible way to create and manage virtual networks in different computing environments. Its main idea is similar to the OpenStack Quantum project [180]. While Quantum is designed for OpenStack (cloud environments), libNetVirt is a more general purpose library which can be used in different environments. Additionally, it goes one step beyond OpenStack Quantum by enabling QoS capabilities in virtual networks [179]. The libNetVirt library has two layers: (1) a generic network interface; and (2) technology specific device drivers (e.g., VPN, MPLS, OpenFlow). On top of the layers are the management applications and virtual network descriptions. The OpenFlow driver uses a NOX controller to manage the underlying infrastructure, using OpenFlow rule-based flow tables to create isolated virtual networks. By supporting different technologies, it can be used as a bridging component in heterogeneous networks.

Table VI summarizes the hypervisor and non-hypervisor based virtualization technologies. As can be observed, only libNetVirt supports heterogeneous technologies, not restricting its application to OpenFlow-enabled networks. FlowVisor, AutoSlice and OpenVirteX allow multiple controllers, one per network slice. FlowN provides a container-based approach where multiple applications from different users can co-exist on a single controller. FlowVisor allows QoS provisioning guarantees by using VLAN PCP bits for priority queues. SDN VE and NVP also provide their own provisioning methods for guaranteeing QoS.

G. Layer VII: Programming languages

Programming languages have been proliferating for decades. Both academia and industry have evolved from low-level hardware-specific machine languages, such as assembly for x86 architectures, to high-level and powerful programming languages such as Java and Python. The advancements towards more portable and reusable code has driven a significant shift on the computer industry [181], [182].

Similarly, programmability in networks is starting to move from low level machine languages such as OpenFlow ("assembly") to high-level programming languages [138], [137], [155], [139], [156], [157], [64]. Assembly-like machine languages, such as OpenFlow [9] and POF [23], [72], essentially mimic the behavior of forwarding devices, forcing developers to spend too much time on low-level details rather than on the problem solve. Raw OpenFlow programs have to deal with hardware behavior details such as overlapping rules, the priority ordering of rules, and data-plane inconsistencies that arise from in-flight packets whose flow rules are under installation [138], [139], [183]. The use of these low-level languages makes it difficult to reuse software, to create modular and extensive code, and leads to a more error-prone development process [157], [184], [185].

Abstractions provided by high level programming languages can significantly help address many of the challenges of these lower-level instruction sets [138], [137], [155], [139], [156], [157]. In SDNs, high-level programming languages can be designed and used to:

1) create higher level abstractions for simplifying the task of programming forwarding devices;

TABLE VI
VIRTUALIZATION SOLUTIONS

Solution	Multiple controllers	Slicing	QoS "guarantees"	Multi-technology
AutoSlice [119]	yes, one per slice	VLAN tags	no	no, OF only
FlowVisor [113], [114]	yes, one per slice	virtual flow tables per slice	yes (VLAN PCP bits)	no, OF only
FlowN [115], [120]	no (contained applications)	VLAN tags	*unknown*	no, OF only
IBM SDN VE [117]	yes, a cluster of controllers	logical datapaths	yes (priority-based)	yes (VXLAN, OVS, OpenFlow)
libNetVirt [179]	no, one single controller	VLAN tags	no	yes (e.g., VPN, MPLS, OpenFlow)
NVP's Hypervisor [64]	yes, a cluster of controller	logical datapaths	yes	no, OVS only
OpenVirteX [116]	yes, one per slice	virtual flow tables per slice	*unknown*	no, OF only
Pyretic [176]	no, one single controller	compiler time OF rules	no	no, OF only
Splendid Isolation [178]	no, one single controller	compiler time VLANs	no	no, OF only

2) enable more productive and problem-focused environments for network software programmers, speeding up development and innovation;
3) promote software modularization and code reusability in the network control plane;
4) foster the development of network virtualization.

Several challenges can be better addressed by programming languages in SDNs. For instance, in pure OpenFlow-based SDNs, it is hard to ensure that multiple tasks of a single application (e.g., routing, monitoring, access control) do not interfere with each other. For example, rules generated for one task should not override the functionality of another task [138], [183]. Another example is when multiple applications run on a single controller [157], [183], [135], [186], [187]. Typically, each application generates rules based on its own needs and policies without further knowledge about the rules generated by other applications. As a consequence, conflicting rules can be generated and installed in forwarding devices, which can create problems for network operation. Programming languages and runtime systems can help to solve these problems that would be otherwise hard to prevent.

Important software design techniques such as code modularity and reusability are very hard to achieve using low-level programming models [157]. Applications thus built are monolithic and consist of building blocks that can not be reused in other applications. The end result is a very time consuming and error prone development process.

Another interesting feature that programming language abstractions provide is the capability of creating and writing programs for virtual network topologies [176], [178]. This concept is similar to object-oriented programming, where objects abstract both data and specific functions for application developers, making it easier to focus on solving a particular problem without worrying about data structures and their management. For instance, in an SDN context, instead of generating and installing rules in each forwarding device, one can think of creating simplified virtual network topologies that represent the entire network, or a subset of it. For example, the application developer should be able to abstract the network as an atomic big switch, rather than a combination of several underlying physical devices. The programming languages or runtime systems should be responsible for generating and installing the lower-level instructions required at each forwarding device to enforce the user policy across the network. With such kind of abstractions, developing a routing application becomes a straightforward process. Similarly, a single physical switch could be represented as a set of virtual switches, each of them belonging to a different virtual network. These two examples of abstract network topologies would be much harder to implement with low-level instruction sets. In contrast, a programming language or runtime system can more easily provide abstractions for virtual network topologies, as has already been demonstrated by languages such as Pyretic [176].

High-level SDN programming languages

Low-level instruction sets suffer from several problems. To address some of these challenges, higher-level programming languages have been proposed, with diverse goals, such as:

- Avoiding low-level and device-specific configurations and dependencies spread across the network, as happens in traditional network configuration approaches;
- Providing abstractions that allow different management tasks to be accomplished through easy to understand and maintain network policies;
- Decoupling of multiple tasks (e.g., routing, access control, traffic engineering);
- Implementing higher-level programming interfaces to avoid low-level instruction sets;
- Solving forwarding rules problems, e.g., conflicting or incomplete rules that can prevent a switch event to be triggered, in an automated way;
- Addressing different race condition issues which are inherent to distributed systems;
- Enhancing conflict-resolution techniques on environments with distributed decision makers;
- Provide native fault-tolerance capabilities on data plane path setup;
- Reducing the latency in the processing of new flows;
- Easing the creation of stateful applications (e.g., stateful firewall).

Programming languages can also provide specialized abstractions to cope with other management requirements, such as monitoring [156], [138], [188]. For instance, the runtime system of a programming language can do all the "laundry

work" of installing rules, polling the counters, receiving the responses, combining the results as needed, and composing monitoring queries in conjunction with other policies. Consequently, application developers can take advantage of the simplicity and power of higher level query instructions to easily implement monitoring modules or applications.

Another aspect of paramount importance is the portability of the programming language, necessary so that developers do not need to re-implement applications for different control platforms. The portability of a programming language can be considered as a significant added value to the control plane ecosystem. Mechanisms such as decoupled back-ends could be key architectural ingredients to enable platform portability. Similarly to the Java virtual machine, a portable northbound interface will easily allow applications to run on different controllers without requiring any modification. As an example, the Pyretic language requires only a standard socket interface and a simple OpenFlow client on the target controller platform [157].

Several programming languages have been proposed for SDNs, as summarized in Table VII. The great majority propose abstractions for OpenFlow-enabled networks. The predominant programming paradigm is the declarative one, with a single exception, Pyretic, which is an imperative language. Most declarative languages are functional, while but there are instances of the logic and reactive types. The purpose – i.e., the specific problems they intend to solve – and the expressiveness power vary from language to language, while the end goal is almost always the same: to provide higher-level abstractions to facilitate the development of network control logic.

Programming languages such as FML [137], Nettle [155], and Procera [156] are functional and reactive. Policies and applications written in these languages are based on reactive actions triggered by events (e.g., a new host connected to the network, or the current network load). Such languages allow users to declaratively express different network configuration rules such as access control lists (ACLs), virtual LANs (VLANs), and many others. Rules are essentially expressed as allow-or-deny policies, which are applied to the forwarding elements to ensure the desired network behavior.

Other SDN programming languages such as Frenetic [138], Hierarchical Flow Tables (HFT) [183], NetCore [139], and Pyretic [157], were designed with the simultaneous goal of efficiently expressing packet-forwarding policies and dealing with overlapping rules of different applications, offering advanced operators for parallel and sequential composition of software modules. To avoid overlapping conflicts, Frenetic disambiguates rules with overlapping patterns by assigning different integer priorities, while HFT uses hierarchical policies with enhanced conflict-resolution operators.

See-every-packet abstractions and race-free semantics also represent interesting features provided by programming languages (such as Frenetic [138]). The former ensures that *all* control packets will be available for analysis, sooner or later, while the latter provides the mechanisms for suppressing unimportant packets. As an example, packets that arise from a network race condition, such as due to a concurrent flow rule installation on switches, can be simply discarded by the runtime system.

Advanced operators for parallel and sequential composition help bind (through internal workflow operators) the key characteristics of programming languages such as Pyretic [157]. Parallel composition makes it possible to operate multiple policies on the same set of packets, while sequential composition facilitates the definition of a sequential workflow of policies to be processed on a set of packets. Sequential policy processing allows multiple modules (e.g., access control and routing) to operate in a cooperative way. By using sequential composition complex applications can be built out of a combination of different modules (in a similar way as pipes can be used to build sophisticated Unix applications).

Further advanced features are provided by other SDN programming languages. FatTire [189] is an example of a declarative language that heavily relies on regular expressions to allow programmers to describe network paths with fault-tolerance requirements. For instance, each flow can have its own alternative paths for dealing with failure of the primary paths. Interestingly, this feature is provided in a very programmer-friendly way, with the application programmer having only to use regular expressions with special characters, such as an asterisk. In the particular case of FatTire, an asterisk will produce the same behavior as a traditional regular expression, but translated into alternative traversing paths.

Programming languages such as FlowLog [184] and Flog [185] bring different features, such as model checking, dynamic verification and stateful middleboxes. For instance, using a programming language such as Flog, it is possible to build a stateful firewall application with only five lines of code [185].

Merlin [191] is one of the first examples of unified framework for controlling different network components, such as forwarding devices, middleboxes, and end-hosts. An important advantage is backward-compatibility with existing systems. To achieve this goal, Merlin generates specific code for each type of component. Taking a policy definition as input, Merlin's compiler determines forwarding paths, transformation placement, and bandwidth allocation. The compiled outputs are sets of component-specific low-level instructions to be installed in the devices. Merlin's policy language also allows operators to delegate the control of a sub-network to tenants, while ensuring isolation. This delegated control is expressed by means of policies that can be further refined by each tenant owner, allowing them to customize policies for their particular needs.

Other recent initiatives (e.g., systems programming languages [192]) target problems such as detecting anomalies to improve the security of network protocols (e.g., OpenFlow), and optimizing horizontal scalability for achieving high throughput in applications running on multicore architectures [190].

Most of the value of SDN will come from the network managements applications built on top of the infrastructure. Advances in high-level programming languages are a fundamental component to the success of a prolific SDN application development ecosystem. To this end, efforts are undergoing to shape forthcoming standard interfaces (cf. [193]) and towards

TABLE VII
PROGRAMMING LANGUAGES

Name	Programming paradigm	Short description/purpose
FatTire [189]	declarative (functional)	Uses regular expressions to allow programmers to describe network paths and respective fault-tolerance requirements.
Flog [185]	declarative (logic), event-driven	Combines ideas of FML and Frenetic, providing an event-driven and forward-chaining logic programming language.
FlowLog [184]	declarative (functional)	Provides a finite-state language to allow different analysis, such as model-checking.
FML [137]	declarative (dataflow, reactive)	High level policy description language (e.g., access control).
Frenetic [138]	declarative (functional)	Language designed to avoid race conditions through well defined high level programming abstractions.
HFT [183]	declarative (logic, functional)	Enables hierarchical policies description with conflict-resolution operators, well suited for decentralized decision makers.
Maple [190]	declarative (functional)	Provides a highly-efficient multi-core scheduler that can scale efficiently to controllers with 40+ cores.
Merlin [191]	declarative (logic)	Provides mechanisms for delegating management of sub-policies to tenants without violating global constraints.
nlog [64]	declarative (functional)	Provides mechanisms for data log queries over a number of tables. Produces immutable tuples for reliable detection and propagation of updates.
Nettle [155]	declarative (functional, reactive)	Based on functional reactive programming principles in order to allow programmers to deal with streams instead of events.
NetCore [139]	declarative (functional)	High level programming language that provides means for expressing packet-forwarding policies in a high level.
Procera [156]	declarative (functional, reactive)	Incorporates a set of high level abstractions to make it easier to describe reactive and temporal behaviors.
Pyretic [157]	imperative	Specifies network policies at a high level of abstraction, offering transparent composition and topology mapping.

the realization of integrated development environments (e.g., NetIDE [194]) with the goal of fostering the development of a myriad of SDN applications. We discuss these next.

H. Layer VIII: Management applications

Management applications can be seen as the "network brains". They implement the control-logic that will be translated into commands to be installed in the data plane, dictating the behavior of the forwarding devices. Taking a simple application as routing as an example. The logic of this application is to define the path through which packets will flow from a point A to a point B. To achieve this goal a routing application has to, based on the topology input, decide on the path to use and instruct the controller to install the respective forwarding rules in all forwarding devices on the chosen path, from A to B.

Software-defined networks can be deployed on any traditional network environment, from home and enterprise networks to data centers and Internet exchange points. Such variety of environments has led to a wide array of management applications. Existing network management applications perform traditional functionality such as routing, load balancing, and security policy enforcement, but also explore novel approaches, such as reducing power consumption . Other examples include fail-over and reliability functionalities to the data plane, end-to-end QoS enforcement, network virtualization, mobility management in wireless networks, among many others.

Despite the wide variety of use cases, most SDN applications can be grouped in one of five categories: traffic engineering, mobility and wireless, measurement and monitoring, security and dependability and data center networking. Table VIII summarizes several applications categorized as such, stating their main purpose, controller where it was implemented/evaluated, and southbound API used.

Traffic engineering

Several traffic engineering applications have been proposed, including ElasticTree [198], Hedera [199], OpenFlow-based server load balancing [239], Plug-n-Serve [202] and Aster*x [197], In-packet Bloom filter [200], SIMPLE [206], QNOX [203], QoS framework [204], ALTO [195], and Vi-Aggre SDN [207]. The main goals of most applications is to engineer traffic with the aim of minimizing power consumption, maximizing aggregate network utilization, providing optimized load balancing, and other generic traffic optimization techniques.

Load balancing was one of the first applications envisioned for SDN/OpenFlow. Different algorithms and techniques have been proposed for this purpose [239], [197], [202]. One particular concern is the scalability of these solutions. A technique to allow this type of applications to scale is to use wildcard-based rules to perform proactive load balancing [239]. Wildcards can be utilized for aggregating clients requests based on the ranges of IP prefixes, for instance, allowing the distribution and directing of large groups of client requests without requiring controller intervention for every new flow In tandem, operation in reactive mode may still be used when traffic

TABLE VIII
MANAGEMENT APPLICATIONS AND SERVICES

Group	Solution/Application	Main purpose	Controller	Southbound API
Traffic engineering	ALTO VPN [195]	on-demand VPNs	NMS [196], [25]	SNMP
	Aster*x [197]	load balancing	NOX	OpenFlow
	ElasticTree [198]	energy aware routing	NOX	OpenFlow
	Hedera [199]	scheduling / optimization	—	OpenFlow
	In-packet Bloom filter [200]	load balancing	NOX	OpenFlow
	OpenQoS [201]	dynamic QoS routing for multimedia apps	Floodlight	OpenFlow
	Plug-n-Serve [202]	load balancing	NOX	OpenFlow
	QNOX [203]	QoS enforcement	NOX	Generalized OpenFlow
	QoS framework [204]	QoS enforcement	NOX	OF with QoS extensions
	QoSFlow [205]	multiple packet schedulers to improve QoS	—	OpenFlow
	SIMPLE [206]	middlebox-specific "traffic steering"	Extended POX	OpenFlow
	ViAggre SDN [207]	divide and spread forwarding tables	NOX	OpenFlow
Mobility & Wireless	CROWD [208]	overlapping of LTE and WLAN cells	—	OpenFlow
	CloudMAC [209]	outsourced processing of WLAN MACs	—	OpenFlow
	FAMS [210]	flexible VLAN system based on OpenFlow	ProgrammableFlow	OpenFlow
	MobileFlow [154]	flow-based model for mobile networks	MobileFlow	SDMN API
	Odin [211]	smooth hand-off and load balancing	Floodlight	OpenFlow
	OpenRAN [212]	vertical programmability and virtualization	—	—
	OpenRoads [213]	control of the data path using OpenFlow	FlowVisor	OpenFlow
	SoftRAN [165]	load balancing and interference management	—	Femto API [214], [215]
Measurement & Monitoring	BISmark [6]	active and passive measurements	Procera framework	OpenFlow
	FleXam [216]	flexible sampling extension for OpenFlow	—	—
	FlowSense [217]	measure link utilization in OF networks	—	OpenFlow
	measurement model [218]	model for OF switch measurement tasks	—	OpenFlow
	OpenSketch [219]	separated measurement data plane	OpenSketch	"OpenSketch sketches"
	OpenTM [188]	traffic matrix estimation tool	NOX	OpenFlow
	PaFloMon [220]	passive monitoring tools defined by users	FlowVisor	OpenFlow
Security & Dependability	Active security [221]	integrated security using network feedback control	Floodlight	OpenFlow
	AVANT-GUARD [222]	DoS security specific extensions to OF	POX	OpenFlow
	CloudWatcher [223]	framework for monitoring clouds	NOX	OpenFlow
	DDoS detection [224]	attacks detection and mitigation	NOX	OpenFlow
	Elastic IP and Security Group [225]	an SDN based implementation of Amazon's Elastic IP and Security Groups	NOX	OpenFlow
	Ethane [52]	flow-rule enforcement (match/action)	Ethane controller	first instance of OpenFlow
	FortNOX [135]	security flow rules prioritization	NOX	OpenFlow
	FRESCO [186]	framework for security services composition	NOX	OpenFlow
	LiveSec [226]	security policy enforcement	NOX	OpenFlow
	NetFuse [227]	protection against OF traffic overload	—	OpenFlow
	OF-RHM [228]	random host mutation (defense)	NOX	OpenFlow
	OpenSAFE [229]	direct spanned net traffic in arbitrary ways	NOX	OpenFlow
	Reliable multicasting [230]	reduce packet loss when failures occur	Trema	OpenFlow
	SANE [51]	security policy enforcement	SANE controller	SANE header (pre-OpenFlow)
	VAVE [231]	source address validation with a global view	NOX	OpenFlow
Data Center Networking	Big Data Apps [232]	optimize network utilization	—	OpenFlow
	CloudNaaS [233]	networking primitives for cloud applications	NOX	OpenFlow
	FlowComb [234]	predicts application workloads	NOX	OpenFlow
	FlowDiff [235]	detects operational problems	FlowVisor	OpenFlow
	LIME [236]	live network migration	Floodlight	OpenFlow
	NetGraph [237]	graph queries for network management	—	OpenFlow, SNMP
	OpenTCP [238]	dynamic and programmable TCP adaptation	—	—

bursts are detected. The controller application needs to monitor the network traffic and use some sort of threshold in the flow counters to redistribute clients among the servers when bottlenecks are likely to happen.

SDN load-balancing also simplifies the placement of network services in the network [202]. Every time a new server is installed, the load-balancing service can take the appropriate actions to seamlessly distribute the traffic among the available servers, taking into consideration both the network load and the available computing capacity of the respective servers. This simplifies network management and provides more flexibility to network operators.

Existing southbound interfaces can be used for actively monitoring the data plane load. This information can be leveraged to optimize the energy consumption of the network [198]. By using specialized optimization algorithms and diversified configuration options, it is possible to meet the infrastructure goals of latency, performance, and fault tolerance, for instance, while reducing power consumption. With the use of simple techniques, such as shutting down links and devices intelligently in response to traffic load dynamics, data center operators can save up to 50% of the network energy in normal traffic conditions [198].

One of the important goals of data center networks is to avoid or mitigate the effect of network bottlenecks on the operation of the computing services offered. Linear bisection bandwidth is a technique that can be adopted for traffic patterns that stress the network by exploring path diversity in a data center topology. Such technique has been proposed in an SDN setting, allowing the maximization of aggregated network utilization with minimal scheduling overhead [199].

SDN can also be used to provide a fully automated system for controlling the configuration of routers. This can be particularly useful in scenarios that apply virtual aggregation [240] . This technique allows network operators to reduce the data replicated on routing tables, which is one of the causes of routing tables' growth [241]. A specialized routing application [207] can calculate, divide and configure the routing tables of the different routing devices through a southbound API such as OpenFlow.

Traffic optimization is another interesting application for large scale service providers, where dynamic scale-out is required. For instance, the dynamic and scalable provisioning of VPNs in cloud infrastructures, using protocolols such as ALTO [25], can be simplified through an SDN-based approach [195].

Other applications that perform routing and traffic engineering include application-aware networking for video streaming [242] and improved QoS by employing multiple packet schedulers [205] and other techniques [204], [203], [201], [243].

Mobility & wireless

The current distributed control plane of wireless networks is suboptimal for managing the limited spectrum, allocating radio resources, implementing handover mechanisms, managing interference, and performing efficient load-balancing between cells. SDN-based approaches represent an opportunity for making it easier to deploy and manage different types of wireless networks, such as WLANs and cellular networks [211], [213], [208], [165], [244], [245]. Traditionally hard-to-implement but desired features are indeed becoming a reality with the SDN-based wireless networks. These include seamless mobility through efficient hand-overs [211], [246], [244], load balancing [211], [165], creation of on-demand virtual access points (VAPs) [211], [209], downlink scheduling (e.g., an OpenFlow switch can do a rate shaping or time division) [209], dynamic spectrum usage [209], enhanced inter-cell interference coordination [209], [244], device to device offloading (i.e., decide in when and how LTE transmissions should be offloaded to users adopting the D2D paradigm [247]) [208], per client and/or base station resource block allocations (i.e., time and frequency slots in LTE/OFDMA networks, which are known as resource blocks) [165], [208], [245], control and assign transmission and power parameters in devices or in a group basis (e.g., algorithms to optimize the transmission and power parameters of transmission and power parameters of WLAN devices, define and assign transmission power values to each resource block, at each base station, in LTE/OFDMA networks) [208], [165], simplified administration [211], [213], [165], easy management of heterogenous network technologies [213], [165], [248], interoperability between different networks [248], [245], shared wireless infrastructures [248], seamless subscriber mobility and cellular networks [244], QoS and access control policies made feasible and easier [244], [245], and easy deployment of new applications [211], [165], [248].

One of the first steps towards realizing these features in wireless networks is to provide programmable and flexible stack layers for wireless networks [249], [165]. One of the first examples is OpenRadio [249], which proposes a software abstraction layer for decoupling the wireless protocol definition from the hardware, allowing shared MAC layers across different protocols using commodity multi-core platforms. OpenRadio can be seen as the "OpenFlow for wireless networks". Similarly, SoftRAN [165] proposes to rethink the radio access layer of current LTE infrastructures. Its main goal is to allow operators to improve and optimize algorithms for better hand-overs, fine-grained control of transmit powers, resource block allocation, among other management tasks.

Light virtual access points (LVAPs) is another interesting way of improving the management capabilities of wireless networks, as proposed by Odin [211]. Differently from OpenRadio, it works with existing wireless hardware and does not impose any change on IEEE 802.11 standards. An LVAP is implemented as a unique BSSID associated with a specific client, which means that there is a one-to-one mapping between LVAPs and clients. This empowers infrastructure operators to provide seamless mobility, load balancing and hidden terminal mitigation. For instance, when a user moves from one access point (AP) to another, the network mobility management application can automatically and proactively act and move the client LVAP from AP to the other. In this way, a wireless client will not even notice that it started to use a different AP because there is no perceptive hand-off delay, as it would be the case in traditional wireless networks.

Very dense heterogeneous wireless networks have also been a target for SDN. These DenseNets have limitations due to constraints such as radio access network bottlenecks, control overhead, and high operational costs [208]. A dynamic two-tier SDN controller hierarchy can be adapted to address some of these constraints [208]. Local controllers can be used to take fast and fine-grained decisions, while regional (or "global") controllers can have a broader, coarser-grained scope, i.e., that take slower but more global decisions. In such a way, designing a single integrated architecture that encompasses LTE (macro/pico/femto) and WiFi cells, while challenging, seems feasible.

Measurement & monitoring

Measurement and monitoring solutions can be divided in two classes. First, applications that provide new functionality for other networking services. Second, proposals that target to improve features of OpenFlow-based SDNs, such as to reduce control plane overload due to the collection of statistics.

An example of the first class of applications is improving the visibility of broadband performance [250], [6]. An SDN-based broadband home connection can simplify the addition of new functions in measurement systems such as BISmark [250], allowing the system to react to changing conditions in the home network [6]. As an example, a home gateway can perform reactive traffic shaping considering the current measurement results of the home network.

The second class of solutions typically involve different kinds of sampling and estimation techniques to be applied, in order to reduce the burden of the control plane with respect to the collection of data plane statistics. Different techniques have been applied to achieve this goal, such as stochastic and deterministic packet sampling techniques [251], traffic matrix estimation [188], and fine-grained monitoring of wildcard rules [252]. Point-to-point traffic matrix estimation, in particular, can help in network design and operational tasks such as load balancing, anomaly detection, capacity planning and network provisioning. With information on the set of active flows in the network, routing information (e.g., from the routing application), flow paths, and flow counters in the switches it is possible to construct a traffic matrix using diverse aggregation levels for sources and destinations [188].

Other initiatives of this second class propose a stronger decoupling between basic primitives (e.g., matching and counting) and heavier traffic analysis functions such as the detection of anomaly conditions attacks [253]. A stronger separation favors portability and flexibility. For instance, a functionality to detect abnormal flows should not be constrained by the basic primitives or the specific hardware implementation. Put another way, developers should be empowered with streaming abstractions and higher level programming capabilities.

In that vein, some data and control plane abstractions have been specifically designed for measurement purposes. OpenSketch [219] is a special-purpose southbound API designed to provide flexibility for network measurements. For instance, by allowing multiple measurement tasks to execute concurrently without impairing accuracy. The internal design of an OpenSketch switch can be thought of as a pipeline with three stages (hashing, classification, and counting). Input packets first pass through a hashing function. Then, they are classified according to a matching rule. Finally, the match rule identifies a counting index, which is used to calculate the counter location in the counting stage. While a TCAM with few entries is enough for the classification stage, the flexible counters are stored in SRAM. This makes the OpenSketch's operation efficient (fast matching) and cost-effective (cheaper SRAMs to store counters).

Security & Dependability

An already diverse set of security and dependability proposals is emerging in the context of SDNs. Most take advantage of SDN for improving services required to secure systems and networks, such as policy enforcement (e.g., access control, firewalling) [51], [226], [231], [225], DoS attacks detection and mitigation [224], random host mutation (stabler2012) (i.e., randomly and frequently mutate the IP addresses of end-hosts to break the attackers' assumption about static IPs, which is the common case) [228], monitoring of cloud infrastructures for fine-grained security inspections (i.e., automatically analyze and detour suspected traffic to be further inspected by specialized network security appliances, such as deep packet inspection systems) [223], traffic anomaly detection [251], [224], and so forth [51], [226], [224], [228], [223], [225], [231], [251]. Others address OpenFlow-based networks issues, such as flow rule prioritization, security services composition, and protection against traffic overload [135], [186], [222], [227].

There are essentially two approaches, one involves using SDNs to improve network security, and another for improving the security of the SDN *itself*. The focus has been, thus far, in the latter.

Using SDN to improve the security of current networks. Probably the first instance of SDN was an application for security policies enforcement [51]. An SDN allows the enforcement to be done on the first entry point to the network (e.g., the Ethernet switch to which the user is connected to). Alternatively, in a hybrid environment, security policy enforcement can be made on a wider network perimeter through programmable devices (without the need to migrate the entire infrastructure to OpenFlow) [226]. With either application, malicious actions are blocked before entering the critical regions of the network.

SDN has been successfully applied for other purposes, namely for the detection (and reaction) against DDoS flooding attacks [224], and active security [221]. OpenFlow forwarding devices make it easier to collect a variety of information from the network, in a timely manner, which is very handy for algorithms specialized in detecting DDoS flooding attacks

The capabilities offered by software-defined networks in increasing the ability to collect statistics data from the network and of allowing applications to actively program the forwarding devices, are powerful for proactive and smart security policy enforcement techniques such as Active security [221]. This novel security methodology proposes a novel feedback loop to improve the control of defense mechanisms of a networked infrastructure, and is centered around five core capabilities: protect, sense, adjust, collect, counter. In this perspective,

active security provides a centralized programming interface that simplifies the integration of mechanisms for detecting attacks, by a) collecting data from different sources (to identify attacks), b) converging to a consistent configuration for the security appliances, and c) enforcing countermeasures to block or minimize the effect of attacks.

Improving the security of SDN itself. There are already some research efforts on identifying the critical security threats of SDNs and in augmenting its security and dependability [135], [186], [254]. Early approaches try to apply simple techniques, such as classifying applications and using rule prioritization, to ensure that rules generated by security applications will not be overwritten by lower priority applications [135]. Other proposals try to go a step further by providing a framework for developing security-related applications in SDNs [186]. However, there is still a long way to go in the development of secure and dependable SDN infrastructures [254]. An in-deep overview of SDN security issues and challenges can be found in Section V-F.

Data Center Networking

From small enterprises to large scale cloud providers, most of the existing IT systems and services are strongly dependent on highly scalable and efficient data centers. Yet, these infrastructures still pose significant challenges regarding computing, storage and networking. Concerning the latter, data centers should be designed and deployed in such a way as to offer high and flexible cross-section bandwidth and low-latency, QoS based on the application requirements, high levels of resilience, intelligent resource utilization to reduce energy consumption and improve overall efficiency, agility in provisioning network resources, for example by means of network virtualization and orchestration with computing and storage, and so forth [255], [256], [257]. Not surprisingly, many of these issues remain open due to the complexity and inflexibility of traditional network architectures.

The emergence of software-defined networks has been expected to change the current state of affairs. Early research efforts have indeed showed that data center networking can significantly benefit from SDN in solving different problems such as live network migration [236], improved network management [236], [235], eminent failure avoidance [236], [235], rapid deployment from development to production networks [236], troubleshooting [236], [237], and optimization of network utilization [237], [232], [234], [235]. SDN can also offer networking primitives for cloud applications, solutions to predict network transfers of applications [232], [234], mechanisms for fast reaction to operation problems, network-aware VM placement [237], [233], QoS support [237], [233], realtime network monitoring and problem detection [237], [234], [235], security policy enforcement services and mechanisms [237], [233], and enable programmatic adaptation of transport protocols [232], [238].

SDN can help infrastructure providers to expose more networking primitives to their customers, by allowing virtual network isolation, custom addressing, and the placement of middleboxes and virtual desktop cloud applications [233], [258]. To fully explore the potential of virtual networks in clouds, an essential features is virtual network migration. Similarly to traditional virtual machine migration, a virtual network may need to be migrated when its virtual machines move from one place to another. Integrating live migration of virtual machines and virtual networks is one of the forefront challenges [236]. To achieve this goal it is necessary to dynamically reconfigure all affected networking devices (physical or virtual). This as shown to be possible with SDN platforms, such as NVP [64].

Another potential application of SDN in data centers is in detecting abnormal behaviors of the network operation [235]. By using different behavioral models and collecting the necessary information from elements involved in the operation of a data center (infrastructure, operators, applications), it is possible to continuously build signatures for applications by passively capturing control traffic. Then, the signature history can be used to identify differences in behavior. Every time a difference is detected, operators can reactively or proactively take corrective measures. This can help to isolate abnormal components and avoid further damage to the infrastructure.

Towards SDN App Stores

As can be observed in Table VIII, most SDN applications rely on NOX and OpenFlow. NOX was the first controller available for general use, making it a natural choice for most use-cases so far. As indicated by the sheer number of security-related applications, security is probably one of the killer applications for SDNs. Curiously, while most use cases rely on OpenFlow, new solutions such as SoftRAN are considering different APIs, as is the case of the Femto API [214], [215]. This diversity of applications and APIs will most probably keep growing in SDN.

There are other kinds of management applications that do not easily fit in our taxonomy, such as Avior [259], OESS [260], and SDN App Store [261], [262]. Avior and OESS are graphical interfaces and sets of software tools that make it easier to configure and manage controllers (e.g., Floodlight) and OpenFlow-enabled switches, respectively. By leveraging their graphical functions it is possible to program OpenFlow enabled devices without coding in a particular programming language.

The SDN App Store [261], [262], owned by HP, is probably the first SDN application market store. Customers using HP's OpenFlow controller have access to the online SDN App Store and are able to select applications to be dynamically downloaded and installed in the controller. The idea is similar to the Android Market or the Apple Store, making is easier for developers to provide new applications and for customers to obtain them.

I. Cross-layer issues

In this section we look at cross-layer problems such as debugging and troubleshooting, testing, verification, simulation and emulation.

Debugging and troubleshooting

Debugging and troubleshooting have been important subjects in computing infrastructures, parallel and distributed

systems, embedded systems, and desktop applications [263], [264], [265], [266], [267], [268], [269]. The two predominant strategies applied to debug and troubleshoot are runtime debugging (e.g., `gdb`-like tools) and post-mortem analysis (e.g., tracing, replay and visualization). Despite the constant evolution and the emergence of new techniques to improve debugging and troubleshooting, there are still several open avenues and research questions [264].

Debugging and troubleshooting in networking is at a very primitive stage. In traditional networks, engineers and developers have to use tools such as `ping`, `traceroute`, `tcpdump`, `nmap`, `netflow`, and SNMP statistics for debugging and troubleshooting. Debugging a complex network with such primitive tools is very hard. Even when one considers frameworks such as XTrace [268], Netreplay [270] and NetCheck [271], which improve debugging capabilities in networks, it is still difficult to troubleshoot networking infrastructures. For instance, these frameworks require a huge effort in terms of network instrumentation. The additional complexity introduced by different types of devices, technologies and vendor specific components and features make matters worse. As a consequence, these solutions may find it hard to be widely implemented and deployed in current networks.

Software-defined networks' capability of programming the network offers some hope in this respect. Its software-based control and the use of open standards for control communication can potentially make debug and troubleshoot easier. The flexibility and programmability introduced by SDN is indeed opening new avenues for developing better tools to debug, troubleshoot, verify and test networks [272], [273], [274], [275], [276], [277], [278], [279], [278].

Early debugging tools for OpenFlow-enabled networks, such as `ndb` [272], OFRewind [273] and NetSight [280], make it easier to discover the source of network problems such as faulty device firmware [272], inconsistent or non-existing flow rules [272], [273], lack of reachability [272], [273], and faulty routing [272], [273]. Similarly to the well-known `gdb` software debugger, `ndb` provides basic debugging actions such as *breakpoint*, *watch*, *backtrace*, *single-step*, and *continue*. These primitives help application developers to debug networks in a similar way to traditional software. By using `ndb`'s postcards (i.e., a unique packet identifier composed of a truncated copy of the packet's header, the matching flow entry, the switch, and the output port), for instance, a programmer is able to quickly identify and isolate a buggy OpenFlow switch with hardware or software problems. If the switch is presenting abnormal behavior such as corrupting parts of the packet header, by analyzing the problematic flow sequences with a debugging tool one can find (in a matter of few seconds) where the packets of a flow are being corrupted, and take the necessary actions to solve the problem.

The OFRewind [273] tool works differently. The idea is to record and replay network events, in particular control messages. These usually account for less than 1% of the data traffic and are responsible for 95%-99% of the bugs [279]. This tool allows operators to perform fine-grained tracing of network behavior, being able to decide which subsets of the network will be recorded and, afterwards, select specific parts of the traces to be replayed. These replays provide valuable information to find the root cause of the network misbehavior.

Despite the availability of these debugging and verification tools, it is still difficult to answer questions such as: What is happening to my packets that are flowing from point A to point B? What path do they follow? What header modifications do they undergo on the way? To answer some of these questions one could recur to the *history* of the packets. A packet's history corresponds to the paths it uses to traverse the network, and the header modifications in each hop of the path. NetSight [280] is a platform whose primary goal is to allow applications that use the history of the packets to be built, in order to find out problems in a network. This platform is composed of three essential elements: (1) NetSight, with its dedicate servers that receive and process the postcards for building the packet history, (2) the NetSigh-SwitchAssist, which can be used in switches to reduce the processing burden on the dedicated servers, and (3) the NetSight-HostAssist to generate and process postcards on end hosts (e.g., in the hypervisor on a virtualized infrastructure).

`netwatch` [280], `netshark` [280] and `nprof` [280] are three examples of tools built over NetSight. The first is a live network invariant monitor. For instance, an alarm can be trigged every time a packet violates any invariant (e.g., no loops). The second, `netshark`, enables users to define and execute filters on the entire history of packets. With this tool, a network operator can view a complete list of properties of packets at each hop, such as input port, output port, and packet header values. Finally, `nprof` can be used to profile sets of network links to provide data for analyzing traffic patterns and routing decisions that might be contributing to link load.

Testing and verification

Verification and testing tools can complement debugging and troubleshooting. Recent research [277], [279], [276], [274], [278], [281], [282] has shown that verification techniques can be applied to detect and avoid problems in SDN, such as forwarding loops and black holes. Verification can be done at different layers (at the controllers, management applications, or network devices).

Tools such as NICE [274] generate sets of diverse streams of packets to test as many as possible events, exposing corner cases such as race conditions. Similarly, OFLOPS [275] provides a set of features and functions that allow the development and execution of a rich set of tests on OpenFlow-enabled devices. Its ultimate goal is to measure the processing capacity and bottlenecks of control applications and forwarding devices. With this tool, users are able to observe and evaluate forwarding table consistency, flow setup latency, flow space granularity, packet modification types, and traffic monitoring capabilities (e.g., counters).

FlowChecker [276], OFTEN [278], and VeriFlow [277] are three examples of tools to verify correctness properties violations on the system. While the former two do offline analysis, the latter is capable of online checking of network invariants. Verification constraints include security and reachability issues, configuration updates on the network, loops,

black holes, etc.

Other formal modeling techniques, such as Alloy, can be applied to SDNs to identify unexpected behavior [281]. For instance, a protocol specification can be weak when it underspecifies some aspects of the protocol or due to a very specific sequence of events. In such situations, model checking techniques such as Alloy can help to find and correct unexpected behaviors.

One of the challenges in testing and verification is to verify forwarding tables in very large networks to find routing errors, which can cause traffic losses and security breaches, as quickly as possible. In large scale networks, it is not possible to assume that the network snapshot, at any point, is consistent, due to the frequent changes in routing state. Therefore, solutions such as HSA [283], Anteater [284], NetPlumber [285] and VeriFlow [277] are not suited for this kind of environment. Another important issue is related on how fast the verification process is done, especially in modern data centers that have very tight timing requirements. Libra [282] represents one of the first attempts to address these particular challenges of large scale networks. This tool provides the means for capturing stable and consistent snapshots of large scale network deployments, while also applying long prefix matching techniques to increase the scalability of the system. By using MapReduce computations, Libra is capable of verifying the correctness of a network with up to 10k nodes within one minute.

Simulation and emulation

Simulation and emulation software is of particular importance for fast prototyping and testing without the need for expensive physical devices. Mininet [62] is the first system that provides a quick and easy way to prototype and evaluate SDN protocols and applications. One of the key properties of Mininet is its use of software-based OpenFlow switches in virtualized containers, providing the exact same semantics of hardware-based OpenFlow switches. This means that controllers or applications developed and tested in the emulated environment can be (in theory) deployed in an OpenFlow-enabled network without any modification. Users can easily emulate an OpenFlow network with hundreds of nodes and dozens of switches by using a single personal computer. Mininet-HiFi [286] is an evolution of Mininet that enhances the container-based (lightweight) virtualization with mechanisms to enforce performance isolation, resource provisioning, and accurate monitoring for performance fidelity. One of the main goals of Mininet-HiFi is to enable repeatable and realistic network experiments.

Mininet CE [287] and SDN Cloud DC [288] are extensions to Mininet for enabling large scale simulations. Mininet CE combines groups of Mininet instances into one cluster of simulator instances to model global scale networks. SDN Cloud DC enhances Mininet and POX to emulate an SDN-based intra-DC network by implementing new software modules such as data center topology discovery and network traffic generation.

The capability of simulating OpenFlow devices has been added to the popular ns-3 simulator [289]. Another example of large scale simulation is *fs-sdn*, which extends the *fs* simulation engine [290] by incorporating a controller and switching components with OpenFlow support. Its main goal is to provide a more realistic and scalable simulation platform as compared to Mininet. STS [291] is a simulator designed to allow developers to specify and apply a variety of test cases, while allowing them to interactively examine the state of the network.

V. Ongoing Research Efforts and Challenges

The research efforts we have surveyed so far seek to overcome the challenges of realizing the vision and fulfilling the potential of SDN. While Section IV provided a perspective structured across the layers of the "SDN stack", this section highlights research we consider of particular importance for unleashing the full potential of SDN, and that therefore deserves a specific coverage in this survey.

A. Switch Designs

Currently available OpenFlow switches are very diverse and exhibit notable differences in terms of feature set (e.g., flow table size, optional actions), performance (e.g., fast vs. slow path, control channel latency/throughput), interpretation and adherence to the protocol specification (e.g., `BARRIER` command), and architecture (e.g., hardware vs. software designs).

Heterogenous Implementations

Implementation choices have a fundamental impact on the behavior, accuracy, and performance of switches, ranging from differences in flow counter behavior [295] to a number of other performance metrics [275]. One approach to accommodate such heterogeneity is through NOSIX, a portable API that separates the application expectations from the switch heterogeneity [174]. To do so, NOSIX provides a pipeline of multiple virtual flow tables and switch drivers. Virtual flow tables are intended to meet the expectations of applications and are ultimately translated by the drivers into actual switch flow tables. Towards taming the complexity of multiple OpenFlow protocol versions with different sets of required and optional capabilities – a roadblock for SDN practitioners –, tinyNBI [296] has been proposed as a simple API providing a unifying set of core abstractions of five OpenFlow protocol versions (from 1.0 to 1.4). Ongoing efforts to introduce a new Hardware Abstraction Layer (HAL) for non-OpenFlow capable devices [297] include the development of open source artifacts like ROFL (Revised OpenFlow Library) and the xDPd (eXtensible DataPath daemon), a framework for creating new OpenFlow datapath implementations based on a diverse set of hardware and software platforms. A related open source effort to develop a common library to implement OpenFlow 1.0 and 1.3 protocol endpoints (switch agents and controllers) is libfluid [298], winner of the OpenFlow driver competition organized by the ONF.

Within the ONF, the Forwarding Abstraction Working Group (FAWG) is pursuing another solution to the heterogeneity problem, through Table Type Patterns (TTPs) [73]. A TTP is a standards-based and negotiated switch-level behavioral abstraction. It consists of the relationships between tables forming a graph structure, the types of tables in the graph,

TABLE IX
DEBUGGING, VERIFICATION AND SIMULATION

Group	Solution	Main purpose	Short description
Debugging	`ndb` [272]	*gdb* alike debugging for networks	It provides basic debugging primitives that help developers to debug their networks.
	NetSight [280]	multi purpose packet history	Allows operators to build flexible debugging, monitoring and profiling applications.
	OFRewind [273]	tracing and replay	OFRewind allows operators to do a fine-grained tracing of the network behavior. Operators can decide which subsets of the network will be recorded.
Verification	Cbench [292]	evaluate OpenFlow controllers	The Cbench framework can be used to emulate OpenFlow switches which are configured to generate workload to the controller.
	FLOVER [187]	model checking for security policies	FLOVER provides a provably correct and automatic method for verifying security properties with respect to a set of flow rules committed by an OF controller.
	FlowChecker [276]	flow table configuration verification	A tool used to verify generic properties of global behaviors based on flow tables.
	NetPlumber [285]	real time policy checking	NetPlumber uses a set of policies and invariants to do real time checking. It leverages header space analysis and keeps a dependency graph between rules.
	NICE [274]	remove bugs in controllers	Its main goal is to test controller programs without requiring any type of modification or extra work for application programmers.
	OFCBenchmark [293]	evaluate OpenFlow controllers	creates independent virtual switches, making is possible to emulate different scenarios. Each switch has its how configuration and statistics.
	OFTEN [278]	catch correctness property violations	A framework designed to check SDN systems, analyzing controller and switch interaction, looking for correctness condition violation.
	OFLOPS [275]	evaluate OpenFlow switches	A framework with a rich set of tests for OpenFlow protocol, enabling to measure capabilities of both switch and applications.
	VeriFlow [277]	online invariant verification	It provides real time verification capabilities, while the network state is still evolving.
Simulation	*fs-sdn* [294]	fast simulation	Like Mininet, it provides a simulation environment, but with speed and scalability advantages.
	Mininet [62]	fast prototyping	It emulates and OpenFlow network using Open vSwitches to provide the exact same semantics of hardware devices.
	Mininet CE [287]	global network modeling	It is a combination of tools to create a Mininet cluster for large scale simulation of network topologies and architectures.
	Mininet-HiFi [286]	fast prototyping for reproducibility	An evolution of Mininet to enable repeatable and high fidelity network experiments.
	ns-3 [289]	network simulation	The latest version of ns-3 simulator provides support to OpenFlow, enabling to create programmable network devices.
	SDN Cloud DC [288]	cloud data center emulation	The SDN Cloud DC solution allows users to evaluate the performance of their controllers at scale.
	STS [291]	troubleshooting	It simulates a network, allows to generate tricky test cases, and allows interactively examine the state of the network.

a set of the parameterized table properties for each table in the graph, the legal `flow-mod` and `table-mod` commands for each flow table, and the metadata mask that can be passed between each table pair in the graph.

Flow Table Capacity

Flow matching rules are stored in flow tables inside network devices. One practical challenge is to provide switches with large and efficient flow tables to store the rules [299]. TCAMs are a common choice to hold flow tables. While flexible and efficient in terms of matching capabilities, TCAMs are costly and usually small (from 4K to 32K entries). Some TCAM chips today integrate 18 M-bit (configured as 500k entries $*$ 36 bit per entry) into a single chip working at 133 Mhz [300], i.e., capable of 133M lookups per second. However, these chips are expensive and have a high-power consumption [301], representing a major power drain in a switching device [302]. These are some of the reasons why currently available OpenFlow devices have TCAMs with roughly 8K entries, where the actual capacity in terms of OpenFlow table size has a non-trivial relationship to the type of flow entries being used [303], [304]. OpenFlow version 1.1 introduced multiple tables, thereby adding extra flexibility and scalability. Indeed, OpenFlow 1.0 implied state explosion due to its flat table model [73]. However, supporting multiple tables in hardware is challenging and limited – yet another motivation for the ongoing ONF FAWG work on TTPs [73].

Performance

Commercial OpenFlow switches today support only around 200 control events (e.g., `packet-in`, `flow-mod`) per second [305]. This is clearly a limiting factor that shall be addressed in the switch design process – support of OpenFlow in existing product lines has been more a retrofitting activity than a clean feature planning and implementation activity. Deployment experiences [306] have pointed to a series of

challenges stemming from the limited embedded CPU power of current commercial OpenFlow switches. One approach to handle the problem consists of adding more powerful CPUs into the switches, as proposed in [307]. Others have proposed to rethink the distribution of control actions between external controllers and the OpenFlow agent inside the switch [295]. Our current understanding indicates that an effective way forward is a native design of SDN switches consistent with the evolution of the southbound API standardization activities [308], [73].

Evolving Switch Designs

New SDN switch designs are expected to appear in a myriad of hardware combinations to efficiently work together with TCAMs, such as SRAM, RLDRAM, DRAM, GPU, FPGA, NPs, CPUs, among other specialized network processors [309], [310], [311], [312], [313], [314]. These early works suggest the need for additional efforts into new hardware architectures for future SDN switching devices. For instance, some proposals target technologies such as GPUs that have demonstrated 20 Gbps with flow tables of up to 1M exact match entries and up to 1K wildcard entries [311]. Alternatives to TCAM-based designs include new hardware architectures and components, as well as new and more scalable forwarding planes, such as the one proposed by the Rain Man firmware [315]. Other design solutions, such as parallel lookup models [316], can also be applied to SDN to reduce costs in switching and routing devices. Recent proposals on cache-like OpenFlow switch arrangements [317] shed some light on overcoming the practical limitations of flow table sizes with clever switching designs. Additionally, counters represent another practical challenge in SDN hardware implementations. Many counters already exists, and they could lead to significant control plane monitoring overhead [295]. Software-defined counters (SDC) [307] have been proposed to provide both scalability and flexibility.

Hardware Enhancements & Support

As in any software/hardware innovation cycle, a number of advancements can be expected from the hardware perspective to improve SDN capabilities and performance [318], [319], [299], [320], [310], [321]. Microchip companies such as Intel are already shipping processors with flexible SDN capabilities to the market [318]. Recent advances in Intel general-purpose CPU technology include a data-plane development kit (DPDK) [322] that allows high-level programming of how data packets shall be processed directly within network interface cards. Prototype implementations of an Intel DPDK accelerated switch shows the potential to deliver high-performance SDN software switches without giving up the flexibility of programmable data planes [314]. This trend is likely to continue since high-speed and specialized hardware is needed to boost SDN performance and scalability for large, real-world networks. Hardware-programmable technologies such as FPGA are widely used to reduce time and costs of hardware-based feature implementations. NetFPGA, for instance, has been a pioneering technology used to implement OpenFlow 1.0 switches [310], providing a commodity cost-effective prototyping solution. Another line of work on SDN data planes proposes to augment switches with FPGA to (remotely) define the queue management and scheduling behaviour of packet switches [323].

Native SDN Switch Designs

Most of the SDN switch (re)design efforts so far follow an evolutionary approach, to retrofit OpenFlow-specific programmable features into existing hardware layouts, following common wisdom on switch/router designs and consolidated technologies (e.g., SRAM, TCAM). One departure from this approach is the ongoing work on *forwarding metamorphosis* [308], a reconfigurable match table model inspired from RISC-like pipelined architecture applied to switching chips. This work illustrates the feasibility of realizing a minimal set of action primitives for flexible header processing in hardware, at almost no additional cost or power. Also in line with the core SDN goals of highly flexible and programmable (hardware-based) dataplanes, Protocol-Oblivious Forwarding (POF) [72] aims at overcoming some of the limitations of OpenFlow (e.g., expressiveness, support of user-defined protocols, memory efficiency), through generic flow instruction sets. Open-source prototypes are available [23] as well as evaluation results showing the line-speed capabilities using a network processing unit (NPU)-based [324] proof of concept implementation.

Pretty much as TTPs allow controllers to compile the right set of low-lever instructions known to be supported by the switches, a new breed of switch referred to as P4 (programmable, protocol-independent packet processor) [325] suggests an evolution path for OpenFlow, based on a high-level compiler. The proposed flexibility would allow the functionality of programmable switches (i.e., pipeline, header parsing, field matching) to be not only specified by the controller but also changed in the field. In this model, programmers are able to decide how the forwarding plane processes packets without caring about implementation details due to a compiler that transforms an imperative program into a control flow graph that can be mapped to different specific target switches.

B. Controller Platforms

In the SDN model, the controller platform is a critical pillar of the architecture, and, as such, efforts are being devoted to turn SDN controllers into high-performance, scalable, distributed, modular, and high-available pieces of programming-friendly software.

Performance

As the SDN community learns from the development and operational experiences with OpenFlow controllers (e.g., Beacon [124]), further advancements are expected in terms of raw performance of controller implementations [326], including the exploitation of hierarchical designs and optimized buffer sizing [326]. A more detailed discussion on performance evaluation will be presented in Section V-E.

Modularity

As in software engineering in general, lack of modularity results in controller implementations that are hard to build, maintain, and extend – and ultimately become resistant to further innovations, resembling traditional “hardware-defined”

networks. As surveyed in Section IV-G, SDN programming abstractions (e.g., Pyretic [157]) introduce modularity in SDN applications and simplify their development altogether. Further research efforts (e.g., Corybantic [327]) try to achieve modularity in SDN control programs. Other contributions towards achieving modular controllers can be expected from other areas of computer science (e.g., principles from Operating System [134]) and best practices of modern cloud-scale software applications.

High Availability

In production, SDN controllers need to sustain healthy operation under the pressure of different objectives from the applications they host. Many advances are called for in order to deal with potential risk vectors of controller-based solutions [254]. Certainly, many solutions will leverage on results from the distributed systems and security communities made over the last decade. Recent efforts are evolving towards consistent, fault-tolerant data stores [150].

Interoperability and application portability

Similarly to forwarding device vendor agnosticism that stems from standard southbound interfaces, it is important to foster interoperability between controllers. Early initiatives towards more interoperable control platforms include portable programming languages such as Pyretic [157] and east/westbound interfaces among controllers, such as SDNi [146], ForCES CE-CE interface [22], [148], and ForCES Intra-NE mechanisms [149]. However, these efforts are yet far from fully realizing controller interoperability and application portability.

C. Resilience

Achieving resilient communication is a top purpose of networking. As such, SDNs are expected to yield the same levels of availability as legacy and new alternative technologies. Split control architectures as SDN are commonly questioned [328] about their actual capability of being resilient to faults that may compromise the control-to-data plane communications and thus result in "brainless" networks. Indeed, the malfunctioning of particular SDN elements should not result in the loss of availability. The relocation of SDN control plane functionality, from inside the boxes to remote, logically centralized loci, becomes a challenge when considering critical control plane functions such as those related to link failure detection or fast reaction decisions. The resilience of an OpenFlow network depends on fault-tolerance in the data plane (as in traditional networks) but also on the high availability of the (logically) centralized control plane functions. Hence, the resilience of SDN is challenging due to the multiple possible failures of the different pieces of the architecture.

As noted in [329], there is a lack of sufficient research and experience in building and operating fault-tolerant SDNs. Google B4 [8] may be one of the few examples that have proven that SDN can be resilient at scale. A number of related efforts [330], [331], [332], [189], [333], [334], [335], [336] have started to tackle the concerns around control plane split architectures. The distributed controller architectures surveyed in Section IV-D are examples of approaches towards resilient SDN controller platforms with different tradeoffs in terms of consistency, durability and scalability.

On a detailed discussion on whether the CAP theorem [337] applies to networks, by Panda et al. [332], the authors argue that the trade-offs in building consistent, available and partition-tolerant distributed databases (i.e., CAP theorem) may apply to SDN. The CAP theorem demonstrated that it is impossible for datastore systems to simultaneously achieve strong consistency, availability and partition tolerance. While availability and partition tolerance problems are similar in both distributed databases and networks, the problem of consistency in SDN relates to the consistent application of policies.

Taking the example of an OpenFlow network, when a switch detects that a link failure (`port-down` event), a notification is sent to the controller, which then takes the required actions (re-route computation, pre-computed back-up path lookups) and installs updated flow entries in the required switches to redirect the affected traffic. Such reactive strategies imply (1) high restoration time due to the necessary interaction with the controller; and (2) additional load on the control channel. One experimental work on OpenFlow for carrier-grade networks investigated the restoration process and measured a restoration times in the order of 100 ms [331]. The delay introduced by the controller may, in some cases, be prohibitive. In order to meet carrier grade requirements (i.e., 50 ms recovery time), protection schemes are required to mitigate the effects of a separated control plane. Suitable protection mechanisms (e.g., installation of pre-established backup paths in the switches) are possible in the most recent versions of the OpenFlow protocol, by means of OpenFlow group table entries using "fast-failover" actions.

An OpenFlow fault management approach [330] similar to MPLS global path protection could be a viable solution, provided that OpenFlow switches are extended with end-to-end path monitoring capabilities in the spirit of Bidirectional Forwarding Detection (BFD). Such protection schemes are a critical design choice for larger scale networks and may also required considerable additional flow space.

Another related line of work is SlickFlow [335], leveraging the idea of using packet header space to carry alternative path information to implement resilient source routing in OpenFlow networks. Under the presence of failures along a primary path, packets can be rerouted to alternative paths by the switches themselves without involving the controller. Another recent proposal that uses in-packet information is INFLEX [336], an SDN-based architecture for cross-layer network resilience which provides on-demand path fail-over by having end-points tag packets with virtual routing plane information that can be used by egress routers to re-route by changing tags upon failure detection.

Language-based solutions to the data plane fault-tolerance problem have also been proposed [189]. In this work the authors propose a language that compiles regular expressions into OpenFlow rules to express what network paths packets may take and what degree of (link level) fault tolerance is required. Such abstractions around fault tolerance allow developers to build fault recovery capabilities into applications

without huge coding efforts.

D. Scalability

Scalability has been one of the major concerns of SDNs from the outset. This is a problem that needs to addressed in any system – e.g., in traditional networks – and is obviously also a matter of much discussion in the context of SDN [11].

Most of the scalability concerns in SDNs are related to the decoupling of the control and data planes. Of particular relevance are reactive network configurations where the first packet of a new flow is sent by the first forwarding element to the controller. The additional control plane traffic increases network load and makes the control plane a potential bottleneck. Additionally, as the flow tables of switches are configured in real-time by an outside entity, there is also the extra latency introduced by the flow setup process. In large-scale networks controllers will need to be able to process millions of flows per second [338] without compromising the quality of its service. Therefore, these overheads on the control plane and on flow setup latency are (arguably) two of the major scaling concerns in SDN.

As a result, several efforts have been devoted to tackle the SDN scaling concerns, including DevoFlow [295], Software-Defined Counters (SDCs) [307], DIFANE [339], Onix [7], HyperFlow [133], Kandoo [158], Maestro [126], NOX-MT [125], and Maple [190]. Also related to scalability, the notion of elasticity in SDN controllers is also being pursued [334]. Elastic approaches include dynamically changing the number of controllers and their locations under different conditions [340].

Most of the research efforts addressing scaling limitations of SDN can be classified in three categories: data plane, control plane, and hybrid. While targeting the data plane, proposals such as DevoFlow [295] and Software-Defined Counters (SDC) [307] actually reduce the overhead of the control plane by delegating some work to the forwarding devices. For instance, instead of requesting a decision from the controller for every flow, switches can selectively identify the flows (e.g., elephant flows) that may need higher-level decisions from the control plane applications. Another example is to introduce more powerful general purpose CPUs in the forwarding devices to enable SDCs. A general purpose CPU and software-defined counters offer new possibilities for reducing the control plane overhead by allowing software-based implementations of functions for data aggregation and compression, for instance.

Maestro [126], NOX-MT [125], Kandoo [158], Beacon [124], and Maple [190] are examples of the effort on designing and deploying high performance controllers, i.e., trying to increase the performance of the control plane. These controllers mainly explore well-known techniques from networking, computer architectures and high performance computing, such as buffering, pipelining and parallelism, to increase the throughput of the control platform.

The hybrid category is comprised of solutions that try to split the control logic functions between specialized data plane devices and controllers. In this category, DIFANE [339] proposes authoritative (intermediate) switches to keep all traffic in the data plane, targeting a more scalable and efficient control plane. Authoritative switches are responsible for installing rules on the remaining switches, while the controller is still responsible for generating all the rules required by the logic of applications. By dividing the controller work with these special switches, the overall system scales better.

Table X provides a non-exhaustive list of proposals addressing scalability issues of SDN. We characterize these issues by application domain (control or data plane), their purpose, the throughput in terms of number of flows per second (when the results of the experiments are reported), and the strategies used. As can be observed, the vast majority are control plane solutions that try to increase scalability by using distributed and multi-core architectures.

Some figures are relatively impressive, with some solutions achieving up to 20M flows/s. However, we should caution the reader that current evaluations consider only simple applications and count basically the number of `packet-in` and `packet-out` messages to measure throughput. The actual performance of controllers will be affected by other factors, such as the number and complexity of the applications running on the controller and security mechanisms implemented. For example, a routing algorithm consumes more computing resources and needs more time to execute than a simple learning switch application Also, current evaluations are done using plain TCP connections. The performance is very likely to change when basic security mechanisms are put in place, such as TLS, or more advanced mechanisms to avoid eavesdropping, man-in-the-middle and DoS attacks on the control plane.

Another important issue concerning scalability is data distribution among controller replicas in distributed architectures. Distributed control platforms rely on data distribution mechanisms to achieve their goals. For instance, controllers such as Onix, HyperFlow, and ONOS need mechanisms to keep a consistent state in the distributed control platform. Recently, experimental evaluations have shown that high performance distributed and fault-tolerant data stores can be used to tackle such challenges [150]. Nevertheless, further work is necessary to properly understand state distribution trade-offs [342].

E. Performance evaluation

As introduced in Section IV-A, there are already several OpenFlow implementations from hardware and software vendors being deployed in different types of networks, from small enterprise to large-scale data centers. Therefore, a growing number of experiments over SDN-enabled networks is expected in the near future. This will naturally create new challenges, as questions regarding SDN performance and scalability have not yet been properly investigated. Understanding the performance and limitation of the SDN concept is a requirement for its implementation in production networks. There are very few performance evaluation studies of OpenFlow and SDN architecture. Although simulation studies and experimentation are among the most widely used performance evaluation techniques, analytical modeling has its own benefits too. A closed-form description of a networking architecture

TABLE X
SUMMARY AND CHARACTERIZATION OF SCALABILITY PROPOSALS FOR SDNS.

Solution	Domain	Proposes	Main purpose	Flows/s	Resorts to
DevoFlow [295]	data plane	thresholds for counters, type of flow detection	reduce the control plane overhead	—	Reduce the control traffic generated by counters statistics monitoring.
HyperFlow [133]	control plane	a distributed controller	distribute the control plane	—	Application on top of NOX to provide control message distribution among controllers.
Kandoo [158]	control plane	a hierarchical controller	distribute the control plane hierarchically	—	Use two levels of controller (local and root) to reduce control traffic.
Onix [7]	control plane	a distributed control platform	robust and scalable control platform	—	Provide a programmable and flexible distributed NIB for application programmers.
SDCs [307]	data plane	Software-Defined Counters	reduce the control plane overhead	—	Remove counters from the ASIC to a general purpose CPU, improving programmability.
DIFANE [339]	control and data plane	authoritative specialized switches	improve data plane performance	500K	Maintain flows in the data plane reducing controller work.
Floodlight [127]	control plane	a multi-threaded controller	Improve controller performance	1.2M	High performance flow processing capabilities.
NOX-MT [125]	control plane	a multi-threaded controller	improve controller performance	1.8M	High performance flow processing capabilities.
Maestro cluster [341]	control plane	coordination framework	create clusters of controllers	1.8M	A coordination framework to create high-performance clusters of controllers.
NOX cluster [341]	control plane	coordination framework	create clusters of controllers	3.2M	A coordination framework to create high-performance clusters of controllers.
Maestro [126]	control plane	a multi-threaded controller	improve controller performance	4.8M	High performance flow processing capabilities.
NOX [127]	control plane	a multi-threaded controller	improve controller performance	5.3M	High performance flow processing capabilities.
Beacon cluster [341]	control plane	coordination framework	create clusters of controllers	6.2M	A coordination framework to create high-performance clusters of controllers.
Beacon [127]	control plane	a multi-threaded controller	improve controller performance	12.8M	High performance flow processing capabilities using pipeline threads and shared queues.
Maple [190]	control plane	programming language	scaling algorithmic policies	20M	Algorithmic policies and user- and OS-level threads on multicore systems (e.g., 40+ cores).

paves the way for network designers to have a quick (and approximate) estimate of the performance of their design, without the need to spend considerable time for simulation studies or expensive experimental setup [306].

Some work has investigated ways to improve the performance of switching capabilities in SDN. These mainly consist of observing the performance of OpenFlow-enabled networks regarding different aspects, such as lookup performance [343], hardware acceleration [312], the influence of types of rules and packet sizes [321], performance bottlenecks of current OpenFlow implementations [295], how reactive settings impact the performance on data center networks [344], and the impact of configuration on OpenFlow switches [292].

Design choices can have a significant impact on the lookup performance of OpenFlow switching in Linux operating system using standard commodity network interface cards [343]. Just by using commodity network hardware the packet switching throughput can be improved by up to 25% when compared to one based on soft OpenFlow switching [343]. Similarly, hardware acceleration based on network processors can also be applied to perform OpenFlow switching. In such cases, early reports indicate that performance, in terms of packet delay, can be improved by 20% when compared to conventional designs [312].

By utilizing Intel's DPDK library [322], it has been shown that is possible to provide flexible traffic steering capability at the hypervisor level (e.g., KVM) without the performance limitations imposed by traditional hardware switching techniques [345], such as SR-IOV [346]. This is particularly relevant since most of the current enterprise deployments of SDN are in virtualized data center infrastructures, as in VMware's NVP solution [64].

Current OpenFlow switch implementations can lead to performance bottlenecks with respect to the CPU load [295]. Yet, modifications on the protocol specification can help reduce the occurrence of these bottlenecks. Further investigations provide measurements regarding the performance of the OpenFlow switch for different types of rules and packet sizes [321].

In data centers, a reactive setting of flow rules can lead to an unacceptable performance when only eight switches are handled by one OpenFlow controller [344]. This means that large-scale SDN deployments should probably not rely on a purely reactive "modus operandi", but rather on a combination of proactive and reactive flow setup.

To foster the evaluation of different performance aspects of OpenFlow devices, frameworks such as OFlops [275], Cbench [125], and OFCBenchmark [293] have been proposed. They provide a set of tools to analyze the performance of

OpenFlow switches. Cbench [125], [292] is a benchmark tool developed to evaluate the performance of OpenFlow controllers. By taking advantage of the Cbench, it is possible to identify performance improvements for OpenFlow controllers based on different environment and system configurations, such as the number of forwarding devices, network topology, overall network workload, type of equipments, forwarding complexity, and overhead of the applications being executed on top of controllers [125]. Therefore, such tools can help system designers make better decisions regarding the performance of devices and the network, while also allowing end-users to measure the device performance and better decide which one is best suited for the target network infrastructure.

Surprisingly, despite being designed to evaluate the performance of controllers, Cbench is currently a single-threaded tool. Therefore, multiple instances have to be started to utilize multiple CPUs. It also only establishes one controller connection for all emulated switches. Unfortunately, this means little can be derived from the results in terms of controller performance and behavior or estimation of different bounds at the moment. For instance, aggregated statistics are gathered for all switches but not for each individual switch. As a result, it is not possible to identify whether all responses of the controller are for a single switch, or whether the capacity of the controller is actually shared among the switches. Flexible OpenFlow controller benchmarks are available though. OFCBenchmark [293] is one of the recent developments. It creates a set of message-generating virtual switches, which can be configured independently from each other to emulate a specific scenario and to maintain their own statistics.

Another interesting question to pose when evaluating the performance of SDN architectures is what is the required number of controllers for a given network topology and where to place the controllers [347]. By analyzing the performance of controllers in different network topologies, it is possible to conclude that one controller is often enough to keep the latency at a reasonable rate [347]. Moreover, as observed in the same experiments, in the general case adding k controllers to the network can reduce the latency by a factor of k. However, there are cases, such as large scale networks and WANs, where more controllers should be deployed to achieve high reliability and low control plane latency.

Recent studies also show that the SDN control plane cannot be fully physically centralized due to responsiveness, reliability and scalability metrics [342]. Therefore, distributed controllers are the natural choice for creating a logically centralized control plane, while being capable of coping with the demands of large scale networks. However, distributed controllers bring additional challenges, such as the consistency of the global network view, which can significantly affect the performance of the network if not carefully engineered. Taking two applications as examples, one that ignores inconsistencies and another that takes inconsistency into consideration, it is possible to observe that optimality is significantly affected when inconsistencies are not considered and that the robustness of an application is increased when the controller is aware of the network state distribution [342].

Most of these initiatives towards identifying the limitations and bottlenecks of SDN architectures can take a lot of time and effort to produce consistent outputs due to the practical development and experimentation requirements. As mentioned before, analytic models can quickly provide performance indicators and potential scalability bottlenecks for an OpenFlow switch-controller system before detailed data is available. While simulation can provide detailed insight into a certain configuration, the analytical model greatly simplifies a conceptual deployment decision. For instance, a Network calculus-based model can be used to evaluate the performance of an SDN switch and the interaction of SDN switches and controllers [348]. The proposed SDN switch model captured the closed form of the packet delay and buffer length inside the SDN switch according to the parameters of a cumulative arrival process. Using recent measurements, the authors have reproduced the packet processing delay of two variants of OpenFlow switches and computed the buffer requirements of an OpenFlow controller. Analytic models based on queuing theory for the forwarding speed and blocking probability of current OpenFlow switches can also be used to estimate the performance of the network [343].

F. Security and dependability

Cyber-attacks against financial institutions, energy facilities, government units and research institutions are becoming one of the top concerns of governments and agencies around the globe [349], [350], [351], [352], [353], [354]. Different incidents, such as Stuxnet [353], have already shown the persistence of threat vectors [355]. Put another way, these attacks are capable of damaging a nation's wide infrastructure, which represent a significant and concerning issue. As expected, one of the most common means of executing those attacks is through the network, either the Internet or the local area network. It can be used as a simple transport infrastructure for the attack or as a potentialized weapon to amplify the impact of the attack. For instance, high capacity networks can be used to launch large-scale attacks, even though the attacker has only a low capacity network connection at his premises.

Due to the danger of cyber-attacks and the current landscape of digital threats, security and dependability are top priorities in SDN. While research and experimentation on software-defined networks is being conducted by some commercial players (e.g., Google, Yahoo!, Rackspace, Microsoft), commercial adoption is still in its early stage. Industry experts believe that security and dependability are issues that need to be addressed and further investigated in SDN [254], [356], [357].

Additionally, from the dependability perspective, availability of Internet routers is nowadays a major concern with the widespread of clouds and their strong expectations about the network [358]. It is therefore crucial to achieve high levels of availability on SDN control platforms once they become pillars of networked applications. Accordingly, the dependability of software-defined networks cannot be overlooked when we think about enterprise class deployments.

Different threat vectors have already been identified in SDN architectures [254], as well as several security issues

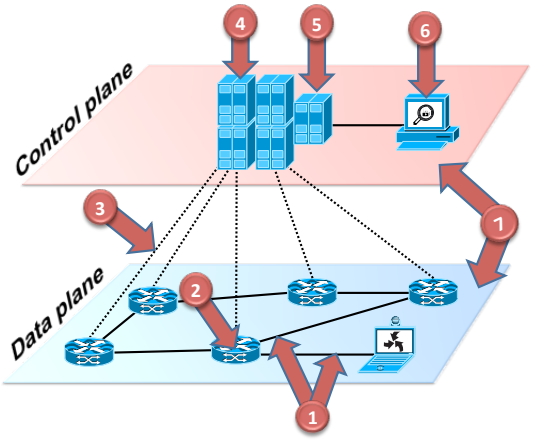

Fig. 10. Main threat vectors of SDN architectures

TABLE XI
SDN SPECIFIC VS. NON-SPECIFIC THREATS

Threat vectors	Specific to SDN?	Consequences in software-defined networks
Vector 1	no	Open door for DDoS attacks.
Vector 2	no	Potential attack inflation.
Vector 3	yes	Exploiting logically centralized controllers.
Vector 4	yes	Compromised controller may compromise the entire network.
Vector 5	yes	Development and deployment of malicious applications on controllers.
Vector 6	no	Potential attack inflation.
Vector 7	no	Negative impact on fast recovery and fault diagnosis.

and weaknesses in OpenFlow-based networks [359], [360], [361], [135], [362]. While some threat vectors are common to existing networks, others are more specific to SDN, such as attacks on control plane communication and logically-centralized controllers. It is worth mentioning that most threats vectors are independent of the technology or the protocol (e.g., OpenFlow, POF, ForCES), because they represent threats on conceptual and architectural layers of SDN itself.

As shown in Figure 10 and Table XI, there are at least seven identified threats vector in SDN architectures. The first threat vector consists of forged or faked traffic flows in the data plane, which can be used to attack forwarding devices and controllers. The second allows an attacker to exploit vulnerabilities of forwarding devices and consequently wreak havoc with the network. Threat vectors three, four and five are the most dangerous ones, since they can compromise the network operation. Attacks on the control plane, controllers and applications can easily grant an attacker the control of the network. For instance, a faulty or malicious controller or application could be used to reprogram the entire network for data theft purposes, e.g., in a data center. The sixth threat vector is linked to attacks on and vulnerabilities in administrative stations. A compromised critical computer, directly connected to the control network, will empower the attacker with resources to launch more easily an attack to the controller, for instance. Last, threat vector number seven represents the lack of trusted resources for forensics and remediation, which can compromise investigations (e.g., forensics analysis) and preclude fast and secure recovery modes for bringing the network back into a safe operation condition.

As can be observed in Table XI, threat vectors 3 to 5 are specific to SDN as they stem from the separation of the control and data planes and the consequent introduction of a new entity in these networks — the logically centralized controller. The other vectors were already present in traditional networks. However, the impact of these threats could be larger than today — or at least it may be expressed differently — and as a consequence it may need to be dealt with differently.

OpenFlow networks are subject to a variety of security and dependability problems such as spoofing [359], tampering [359], repudiation [359], information disclosure [359], denial of service [359], [361], [362], and elevation of privileges [359]. The lack of isolation, protection, access control and stronger security recommendations [360], [361], [135], [362] are some of the reasons for these vulnerabilities. We will explore these next.

OpenFlow security assessment

By applying the STRIDE methodology [363], it is possible to identify different attacks to OpenFlow-enabled networks. Table XII summarizes these attacks (based on [359]). For instance, information disclosure can be achieved through side channel attacks targeting the flow rule setup process. When reactive flow setup is in place, obtaining information about network operation is relatively easy. An attacker that measures the delay experienced by the first packet of a flow and the subsequent can easily infer that the target network is a reactive SDN, and proceed with a specialized attack. This attack – known as fingerprinting [361] – may be the first step to launch a DoS attack intended to exhaust the resources of the network, for example. If the SDN is proactive, guessing its forwarding rule policies is harder, but still feasible [359]. Interestingly, all reported threats and attacks affect all versions (1.0 to 1.3.1) of the OpenFlow specification. It is also worth emphasizing that some attacks, such as spoofing, are not specific to SDN. However, these attacks can have a larger impact in SDNs. For instance, by spoofing the address of the network controller, the attacker (using a fake controller) could take over the control of the entire network. A smart attack could persist for only a few seconds, i.e., just the time needed to install special rules on all forwarding devices for its malicious purposes (e.g., traffic cloning). Such attack could be very hard to detect.

Taking counters falsification as another example, an attacker can try to guess installed flow rules and, subsequently, forge packets to artificially increase the counter. Such attack would be specially critical for billing and load balancing systems, for instance. A customer could be charged for more traffic than she in fact used, while a load balancing algorithm may take non-optimal decisions due to forged counters.

Other conceptual and technical security concerns in OpenFlow networks include the lack of strong security recommendations for developers, the lack of TLS and access control

TABLE XII
ATTACKS TO OPENFLOW NETWORKS.

Attack	Security Property	Examples
Spoofing	Authentication	MAC and IP address spoofing, forged ARP and IPv6 router advertisement
Tampering	Integrity	Counter falsification, rule installation, modification affecting data plane.
Repudiation	Non-repudiation	Rule installation, modification for source address forgery.
Information disclosure	Confidentiality	Side channel attacks to figure out flow rule setup.
Denial of service	Availability	Flow requests overload of the controller.
Elevation of privilege	Authorization	Controller take-over exploiting implementation flaws.

support on most switch and controller implementations [360], the belief that TCP is enough because links are "physically secure" [362], [360], the fact that many switches have listener mode activated by default (allowing the establishment of malicious TCP connections, for instance) [362] or that flow table verification capabilities are harder to implement when TLS is not in use [360], [187]. In addition, it is worth mentioning the high denial of service risk posed to centralized controllers [361], [187], the vulnerabilities in the controllers themselves [187], [254], and the risk of resource depletion attacks [361], [362]. For instance, it has been shown that an attacker can easily compromise control plane communications through DoS attacks and launch a resource depletion attack on control platforms by exploiting a single application such as a learning switch [362], [361].

Countermeasures for OpenFlow based SDNs

Several countermeasures can be put in place to mitigate the security threats in SDNs. Table XIII summarizes a number of countermeasures that can be applied to different elements of an SDN/OpenFlow-enabled network. Some of these measures, namely rate limiting, event filtering, packet dropping, shorter timeouts, and flow aggregation, are already recommended in more recent versions of the OpenFlow specification (version 1.3.1 and later). However, most of them are not yet supported or implemented in SDN deployments.

Traditional techniques such as access control, attack detection mechanisms, event filtering (e.g., controller decides which asynchronous messages he is not going to accept), firewalls, and intrusion detection systems, can be used to mitigated the impact of or avoid attacks. They can be implemented in different devices, such as controllers, forwarding devices, middleboxes, and so forth. Middleboxes can be a good option for enforcing security policies in an enterprise because they are (in general) more robust and special purpose (high performance) devices. Such a strategy also reduces the potential overhead cause by implementing these countermeasures directly on controllers or forwarding devices. However, middleboxes can add extra complexity to the network management, i.e., increase the OPEX at the cost of a better performance.

Rate limiting, packet dropping, shorter timeouts and flow aggregations are techniques that can be applied on controlled and forwarding devices to mitigate different types of attacks, such as denial-of-service and information disclosure. For instance, reduced timeouts can be used to mitigate the effect of an attack exploring the reactive operation mode of the network to make the controller install rules that divert traffic to a malicious machine. With reduced timeouts, the attacker would be forced to constantly generate a number of forged packets to avoid timeout expiration, making the attack more likely to be detected. Rate limiting and packet dropping can be applied to avoid DoS attacks on the control plane or stop ongoing attacks directly on the data plane by installing specific rules on the devices where the attacks is being originated.

TABLE XIII
COUNTERMEASURES FOR SECURITY THREATS IN OPENFLOW NETWORKS.

Measure	Short description
Access control	Provide strong authentication and authorization mechanisms on devices.
Attack detection	Implement techniques for detecting different types of attacks.
Event filtering	Allow (or block) certain types of events to be handled by special devices.
Firewall and IPS	Tools for filtering traffic, which can help to prevent different types of attacks.
Flow aggregation	Coarse-grained rules to match multiple flows to prevent information disclosure and DoS attacks.
Forensics support	Allow reliable storage of traces of network activities to find the root causes of different problems.
Intrusion tolerance	Enable control platforms to maintain correct operation despite intrusions.
Packet dropping	Allow devices to drop packets based on security policy rules or current system load.
Rate limiting	Support rate limit control to avoid DoS attacks on the control plane.
Shorter timeouts	Useful to reduce the impact of an attack that diverts traffic.

Forensics and remediation encompass mechanisms such as secure logging, event correlation and consistent reporting. If anything wrong happens with the network, operators should be able to safely figure out the root cause of the problem and put the network to work on a secure operation mode as fast as possible. Additionally, techniques to tolerate faults and intrusions, such as state machine replication [364], proactive-reactive recovery [365], and diversity [147], can be added to control platforms for increasing the robustness and security properties by automatically masking and removing faults. Put differently, SDN controllers should be able to resist against different types of events (e.g., power outages, network disruption, communication failures, network partitioning) and

attacks (e.g., DDoS, resource exhaustion) [254], [150]. One of the most traditional ways of achieving high availability is through replication. Yet, proactive-reactive recover and diversity are two examples of crucial techniques that add value to the system for resisting against different kinds of attacks and failures (e.g., those exploring common vulnerabilities or caused by software aging problems).

Other countermeasures to address different threats and issues of SDN include enhancing the security and dependability of controllers, protection and isolation of applications [356], [254], [135], trust management between controllers and forwarding devices [254], integrity checks of controllers and applications [254], forensics and remediation [356], [254], verification frameworks [366], [135], [367], and resilient control planes [368], [367], [254], [356]. Protection and isolation mechanisms should be part of any controller. Applications should be isolated from each other and from the controller. Different techniques such as security domains (e.g., kernel, security, and user level) and data access protection mechanisms should be put in place in order to avoid security threats from management applications.

Implementing trust between controllers and forwarding is another requirement for insuring that malicious elements cannot harm the network without being detected. An attacker can try to spoof the IP address of the controller and make switches connect to its own controller. This is currently the case since most controllers and switches only establish insecure TCP connections. Complementarly, integrity checks on controller and application software can help to ensure that safe code is being bootstrapped, which eliminates harmful software from being started once the system restarts. Besides integrity checks, other things such as highly specialized malware detection systems should be developed for SDN. Third-party management applications should always be scanned for bad code and vulnerabilities because a malicious application represents a significant security threat to the network.

It is worth mentioning that there are also other approaches for mitigating security threats in SDN, such as declarative languages to eliminate network protocol vulnerabilities [192]. This kind of descriptive languages can specify semantic constraints, structural constraints and safe access properties of OpenFlow messages. Then, a compiler can use these inputs to find programmers' implementation mistakes on message operations. In other words, such languages can help find and eliminate implementation vulnerabilities of southbound specifications.

G. Migration to SDN

A prime SDN adoption challenge relates to organizational barriers that may arise due to the first (and second) order effects of SDN automation capabilities and "layer/domain blurring". Some level of human resistance is to be expected and may affect the decision and deployment processes of SDN, especially by those that may regard the control refactorization of SDN as a risk to the current chain of control and command, or even to their job security. This complex social challenge is similar (and potentially larger) to known issues between the transport and IP network divisions of service providers, or the system administrator, storage, networking, and security teams of enterprise organizations. Such a challenge is observable on today's virtualized data centers, through the shift in role and decision power between the networking and server people. Similarly, the development and operations (DevOps) movement has caused a shift in the locus of influence, not only on the network architecture but also on purchasing, and this is an effect that SDN may exacerbate. These changes in role and power causes a second order effect on the sales division of vendors that are required to adapt accordingly.

Pioneering SDN operational deployments have been mainly greenfield scenarios and/or tightly controlled single administrative domains. Initial roll-out strategies are mainly based on virtual switch overlay models or OpenFlow-only network-wide controls. However, a broader adoption of SDN beyond data center silos – and between themselves – requires considering the interaction and integration with legacy control planes providing traditional switching; routing; and operation, administration, and management (OAM) functions. Certainly, rip-and-replace is not a viable strategy for the broad adoption of new networking technologies.

Hybrid networking in SDN should allow deploying OpenFlow for a subset of all flows only, enable OpenFlow on a subset of devices and/or ports only, and provide options to interact with existing OAM protocols, legacy devices, and neighboring domains. As in any technology transition period where fork-lift upgrades may not be a choice for many, migration paths are critical for adoption.

Hybrid networking in SDN spans several levels. The Migration Working Group of the ONF is tackling the scenario where hybrid switch architectures and hybrid (OpenFlow and non-OpenFlow) devices co-exist. Hybrid switches can be configured to behave as a legacy switch or as an OpenFlow switch and, in some cases, as both simultaneously. This can be achieved, for example, by partitioning the set of ports of a switch, where one subset is devoted to OpenFlow-controlled networks, and the other subset to legacy networks. For these subsets to be active at the same time, each one having its own data plane, multi-table support at the forwarding engine (e.g., via TCAM partitioning) is required. Besides port-based partitioning, it is also possible to rely on VLAN-based (prior to entering the OpenFlow pipeline) or flow-based partitioning using OpenFlow matching and the `LOCAL` and/or `NORMAL` actions to redirect packets to the legacy pipeline or the switch's local networking stack and its management stack. Flow-based partitioning is the most flexible option, as it allows each packet entering a switch to be classified by an OpenFlow flow description and treated by the appropriate data plane (OpenFlow or legacy).

The promises by SDN to deliver easier design, operation and management of computer networks are endangered by challenges regarding incremental deployability, robustness, and scalability. Full SDN deployments are difficult and straightforward only in some green field deployments such as data center networks or by means of an overlay model approach. Hybrid SDN approaches represent however a very likely deployment model that can be pursued by different means, including [369]:

- Topology-based hybrid SDN: Based on a topological separation of the nodes controlled by traditional and SDN paradigms. The network is partitioned in different zones and each node belongs to only one zone.
- Service-based hybrid SDN: Conventional networks and SDN provide different services, where overlapping nodes, controlling a different portion of the FIB (or generalized flow table) of each node. Examples include network-wide services like forwarding that can be based on legacy distributed control, while SDN provides edge-to-edge services such as enforcement of traffic engineering and access policies, or services requiring full traffic visibility (e.g., monitoring).
- Class-based hybrid SDN: Based on the partition of traffic in classes, some controlled by SDN and the remaining by legacy protocols. While each paradigm controls a disjoint set of node forwarding entries, each paradigm is responsible for all network services for the assigned traffic classes.
- Integrated hybrid SDN: A model where SDN is responsible for all the network services, and uses traditional protocols (e.g., BGP) as an interface to node FIBs. For example, it can control forwarding paths by injecting carefully selected routes into a routing system or adjusting protocol settings (e.g., IGP weights). Past efforts on RCPs [37] and the ongoing efforts within ODL [13] can be considered examples of this hybrid model.

In general, benefits of hybrid approaches include enabling flexibility (e.g., easy match on packet fields for middleboxing) and SDN-specific features (e.g., declarative management interface) while partially keeping the inherited characteristics of conventional networking such as robustness, scalability, technology maturity, and low deployment costs. On the negative side, the drawbacks of hybridization include the need for ensuring profitable interactions between the networking paradigms (SDN and traditional) while dealing with the heterogeneity that largely depends on the model.

Initial trade-off analyses suggest that the combination of centralized and distributed paradigms may provide mutual benefits. However, future work is required to devise techniques and interaction mechanisms that maximize such benefits while limiting the added complexity of the paradigm coexistence.

Some efforts have been already devoted to the challenges of migration and hybrid SDNs. RouteFlow [370] implements an IP level control plane on top of an OpenFlow network, allowing the underlying devices to act as IP routers under different possible arrangements. LegacyFlow [371] extends the OpenFlow-based controlled network to embrace non-OpenFlow nodes. The common grounds of these pieces of work are (1) considering hybrid as the coexistence of traditional environments of closed vendor's routers and switches with new OpenFlow-enabled devices; (2) targeting the interconnection of both control and data planes of legacy and new network elements; and (3) taking a controller-centric approach, drawing the hybrid line outside of any device itself, but into the controller application space.

Panopticon [372] defines an architecture and methodology to consistently implement SDN inside enterprise legacy networks through network orchestration under strict budget constraints. The proposed architecture includes policy configurations, troubleshooting and maintenance tasks establishing transitional networks (SDN and legacy) in structures called Solitary Confinement Trees (SCTs), where VLAN IDs are efficiently used by orchestration algorithms to build paths in order to steer traffic through SDN switches. Defying the partial SDN implementation concept, they confirm that this could be a long-term operational strategy solution for enterprise networks.

HybNET [373] presents a network management framework for hybrid OpenFlow-legacy networks. It provides a common centralized configuration interface to build virtual networks using VLANs. An abstraction of the physical network topology is taken into account by a centralized controller that applies a path finder mechanism, in order to calculate network paths and program the OpenFlow switches via REST interfaces [136] and legacy devices using NETCONF [143].

H. SDN for telecom and cloud providers

A number of carrier-grade infrastructure providers (e.g., NTT, AT&T, Verizon, Deutsch Telekom) have already joined the SDN community and its activities with the ultimate goal of solving their long standing networking problems. One of the forefront runners (and early SDN adopter) was NTT, already taking advantage o this new paradigm to provide new on-demand network provisioning models. In 2013, NTT launched an SDN-based, on-demand elastic provisioning platform of network resources (e.g., bandwidth) for HD video broadcasters [374]. Similarly, as a global cloud provider with data centers spread across the globe [375], the same company launched a similar service for its cloud customers, who are now capable of taking advantage of dynamic networking provisioning intra- and inter-data centers [376]. AT&T is another telecom company that is investing heavily in new services, such as user-defined network clouds, that take advantage of recent developments in NFV and SDN [377]. These are some of the early examples of the opportunities SDNs seem to bring to telecom and cloud providers.

Carrier networks are using the SDN paradigm as the technology means for solving a number of long standing problems. Some of these efforts include new architectures for a smooth migration from the current mobile core infrastructure to SDN [154], and techno-economic models for virtualization of these networks [378], [379]; carrier-grade OpenFlow virtualization schemes [380], [64], including virtualized broadband access infrastructures [381], techniques that are allowing the offer of network-as-a-service [382]; flexible control of network resources [383], including offering MPLS services using an SDN approach [384]; and the investigation of novel network architectures, from proposals to separate the network edge from the core [385], [386], with the latter forming the fabric that transports packets as defined by an intelligent edge, to software-defined Internet exchange points [387], [388].

SDN technology also brings new possibilities for cloud providers. By taking advantage of the logically centralized control of network resources [389], [8] it is possible to simplify and optimize network management of data centers and

achieve: (i) efficient intra-datacenter networking, including fast recovery mechanisms for the data and control planes [331], [390], [391], simplified fault-tolerant routing [392], performance isolation [393], and easy and efficient resource migration (e.g., of VMs and virtual networks) [331]; (ii) improved inter-datacenter communication, including the ability to fully utilize the expensive high-bandwidth links without impairing quality of service [8], [394]; (iii) higher levels of reliability (with novel fault management mechanisms, etc.) [392], [331], [390]; and (iv) cost reduction by replacing complex, expensive hardware by simple and cheaper forwarding devices [395], [8].

Table XIV summarizes some of the carrier-grade network and cloud infrastructure providers' requirements. In this table we show the current challenges and what is to be expected with SDN. As we saw before, some of the expectations are already becoming a reality, but many are still open issues. What seems to be clear is that SDN represents an opportunity for telecom and cloud providers, in providing flexibility, cost-effectiveness, and easier management of their networks.

I. SDN: the missing piece towards Software-Defined Environments

The convergence of different technologies is enabling the emergence of fully programmable IT infrastructures. It is already possible to dynamically and automatically configure or reconfigure the entire IT stack, from the network infrastructure up to the applications, to better respond to workload changes. Recent advances makes on-demand provisioning of resources possible, at nearly all infrastructural layers. The fully automated provisioning and orchestration of IT infrastructures as been recently named Software-Defined Environments (SDEs) [117], [118], by IBM. This is a novel approach that is expected to have significant potential in simplifying IT management, optimizing the use of the infrastructure, reduce costs, and reduce the time to market of new ideas and products. In an SDE, workloads can be easily and automatically assigned to the appropriate IT resources based on application characteristics, security and service level policies, and the best-available resources to deliver continuous, dynamic optimization and reconfiguration to address infrastructure issues in a rapid and responsive manner. Table XV summarizes the traditional approaches and some of the key features being enabled by SDEs [400], [401].

In an SDE the workloads are managed independently of the systems and underlying infrastructure, i.e., are not tied to a specific technology or vendor [118], [117]. Another characteristic of this new approach is to offer a programmatic access to the environment as a whole, selecting the best available resources based on the current status of the infrastructure, and enforcing the policies defined. In this sense, it shares much of the philosophy of SDN. Interestingly, one of the missing key pieces of an SDE was, until now, Software-Defined Networking.

The four essential building blocks of an SDE [118], [117], [401] are:

- Software-Defined Networks (SDN) [402], [403],
- Software-Defined Storage (SDS) [400],
- Software-Defined Compute (SDC) [117], and
- Software-Defined Management (SDM) [404].

In the last decade the advances in virtualization of compute and storage, together with the availability of sophisticated cloud orchestration tools have enabled SDS, SDC and SDM. These architectural components have been widely used by cloud providers and for building IT infrastructures in different enterprise environments. However, the lack of programmable network control has so far hindered the realization of a complete Software-Defined Environment. SDN is seen as the technology that may fill this gap, as attested by the emergence of cloud-scale network virtualization platforms based on this new paradigm [64].

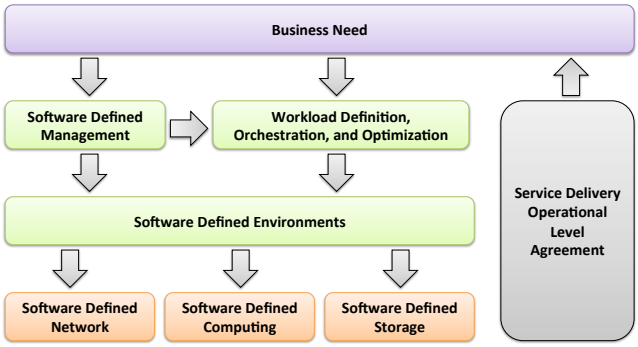

Fig. 11. Overview of an IT infrastructure based on a SDE.

The IBM SmartCloud Orchestrator is one of the first examples of an SDE [118], [117]. It integrates compute, storage, management and networking in a structured way Figure 11 gives a simplified overview of an SDE, by taking the approach developed by IBM as its basis. The main idea of an SDE-based infrastructure is that the business needs that define the workloads trigger the reconfiguration of the global IT infrastructure (compute, storage, network). This is an important step towards a more customizable IT infrastructure that focuses on the business requirements rather than on the limitations of the infrastructure itself.

VI. Conclusion

Traditional networks have always been complex and hard to manage. One of the reasons is that the control and data planes are vertically integrated and vendor specific. Another, concurring reason, is that typical networking devices are also tightly tied to line products and versions. In other words, each line of product may have its own particular configuration and management interfaces, implying long cycles for producing product updates (e.g., new firmware) or upgrades (e.g., new versions of the devices). All this has given rise to vendor lock-in problems for network infrastructure owners, as well as posing severe restrictions to change and innovation.

Software-Defined Networking (SDN) created an opportunity for solving these long-standing problems. Some of the key ideas of SDN are the introduction of dynamic programmability in forwarding devices through open southbound interfaces, the decoupling of the control and data plane, and the global view of the network by logical centralization of the "network

TABLE XIV
CARRIER-GRADE AND CLOUD PROVIDER EXPECTATIONS & CHALLENGES

What	Currently	Expected with SDN
Resource Provisioning	Complex load balancing configuration.	Automatic load balancing reconfiguration. [396], [8]
	Low virtualization capabilities across hardware platforms	NFV for virtualizing network functionality across hardware appliances. [395], [377]
	Hard and costly to provide new services.	Create and deploy new network service quickly. [395], [377]
	No bandwidth on demand.	Automatic bandwidth on demand. [379]
	Per network element scaling.	Better incremental scaling. [396], [390]
	Resources statically pre-provisioned.	Dynamic resource provisioning in response to load. [396], [8], [395], [378], [389]
Traffic Steering	All traffic is filtered.	Only targeted traffic is filtered. [396]
	Fixed only.	Fixed and mobile. [396]
	Per network element scaling.	Better incremental scaling. [378], [390]
	Statically configured on a per-device basis.	Dynamically configurable. [8], [379], [397]
Ad Hoc Topologies	All traffic from all probes collected.	Only targeted traffic from targeted probes is collected.
	Massive bandwidth required.	Efficient use of bandwidth. [8], [379]
	Per network element scaling.	Better incremental scaling. [396], [379]
	Statically configured.	Dynamically configured. [396], [398], [374]
Managed Router Services	Complex configuration, management and upgrade.	Simplified management and upgrade. [8], [396], [395], [379], [390]
	Different kinds of routers, such as CO.	No need for CO routers, reducing aggregation costs. [396], [395], [378]
	Manual provisioning.	Automated provisioning. [396], [379], [397]
	On-premises router deployment.	Virtual routers (either on-site or not). [379], [396], [378]
	Operational burden to support different equipments.	Reduced technology obsolescence. [378]
	Router change-out as technology or needs change.	Pay-as-you grow CAPEX model. [378]
	Systems complex and hard to integrate.	Facilitates simplified system integrations. [396], [395], [398]
Revenue Models	Fixed long term contracts.	More flexible and on-demand contracts. [379], [383]
	Traffic consumption.	QoS metrics per-application. [379], [390], [390], [399]
Middleboxes Deployment & Management	Composition of services is hard to implement.	Easily expand functionality to meet the infrastructure needs. [395]
	Determine where to place middleboxes a priori (e.g., large path inflation problems).	Dynamic placement using shortest or least congested path. [206], [399], [398]
	Excessive over-provisioning to anticipate demands.	Scale up to meet demands, and scale down to conserve resources (elastic middleboxes). [396], [378]
Other Issues	Energy saving strategies are hard to implement.	Flexible and easy to deploy energy saving strategies. [390]
	Complex and static control and data plane restoration techniques.	Automated and flexible restoration techniques for both control and data plane. [390]

TABLE XV
SDE PUSHING IT TO THE NEXT FRONTIER

Traditionally	Expected with SDEs
IT operations manually map the resources for apps for software deployment.	Software maps resources to the workload and deploys the workload.
Networks are mostly statically configured and hard to change.	Networks are virtualized and dynamically configured on-demand.
Optimization and reconfiguration to reactively address issues are manual.	Analytics-based optimization and reconfiguration of infrastructure issues.
Workloads are typically manually assigned to resources.	Workloads are dynamically assigned.

brain". While data plane elements became dumb, but highly efficient and programmable packet forwarding devices, the control plane elements are now represented by a single entity, the controller or network operating system. Applications implementing the network logic run on top of the controller and are much easier to develop and deploy when compared to traditional networks. Given the global view, consistency of policies is straightforward to enforce. SDN represented a major paradigm shift in the development and evolution of networks, introducing a whole new world of possibilities and a new pace of innovation in networking infrastructures.

In spite of recent and interesting attempts to survey this new chapter in the history of networks [405], [406], [407], the literature was still lacking, to the best of our knowledge, a single extensive and comprehensive overview of the building blocks, concepts and challenges of SDNs. Trying to address

this gap, the present paper used a layered approach to methodically dissect the state of the art in terms of concepts, ideas and components of software-defined networking, covering a broad range of existing solutions, as well as future directions.

We started by comparing this new paradigm with traditional networks and discussing how academy and industry helped shape software-defined networking. Following a bottom-up approach, we provided an in-depth overview of what we consider the eight fundamental facets of the SDN problem: 1) hardware infrastructure, 2) southbound interfaces, 3) network virtualization (hypervisor layer between the forwarding devices and the network operating systems), 4) network operating systems (SDN controllers and control platforms), 5) northbound interfaces (common programming abstractions offered to network applications), 6) virtualization using slicing techniques provided by special purpose libraries and/or programming languages and compilers, 7) network programming languages, and finally, 8) management applications.

SDN has successfully managed to pave the way towards next generation networking, spawning an innovative research and development environment, promoting advances in several areas: switch and controller platform design, evolution of scalability and performance of devices and architectures, promotion of security and dependability.

We will continue to witness extensive activity around SDN in the near future. Emerging topics requiring further research are, for example: the migration path to SDN, extending SDN towards carrier transport networks, realization of the network-as-a-service cloud computing paradigm, or software-defined environments (SDE).

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REFERENCES

[1] T. Benson, A. Akella, and D. Maltz, "Unraveling the complexity of network management," in *Proceedings of the 6th USENIX Symposium on Networked Systems Design and Implementation*, ser. NSDI'09, Berkeley, CA, USA, 2009, pp. 335–348.

[2] B. Raghavan, M. Casado, T. Koponen, S. Ratnasamy, A. Ghodsi, and S. Shenker, "Software-defined internet architecture: Decoupling architecture from infrastructure," in *Proceedings of the 11th ACM Workshop on Hot Topics in Networks*, ser. HotNets-XI. New York, NY, USA: ACM, 2012, pp. 43–48.

[3] A. Ghodsi, S. Shenker, T. Koponen, A. Singla, B. Raghavan, and J. Wilcox, "Intelligent design enables architectural evolution," in *Proceedings of the 10th ACM Workshop on Hot Topics in Networks*, ser. HotNets-X. New York, NY, USA: ACM, 2011, pp. 3:1–3:6.

[4] N. Mckeown, "How SDN will Shape Networking," October 2011. [Online]. Available: http://www.youtube.com/watch?v=c9-K5O_qYgA

[5] S. Schenker, "The Future of Networking, and the Past of Protocols," October 2011. [Online]. Available: http://www.youtube.com/watch?v=YHeyuD89n1Y

[6] H. Kim and N. Feamster, "Improving network management with software defined networking," *Communications Magazine, IEEE*, vol. 51, no. 2, pp. 114–119, 2013.

[7] T. Koponen, M. Casado, N. Gude, J. Stribling, L. Poutievski, M. Zhu, R. Ramanathan, Y. Iwata, H. Inoue, T. Hama, and S. Shenker, "Onix: a distributed control platform for large-scale production networks," in *Proceedings of the 9th USENIX conference on Operating systems design and implementation*, ser. OSDI'10. Berkeley, CA, USA: USENIX Association, 2010, pp. 1–6.

[8] S. Jain, A. Kumar, S. Mandal, J. Ong, L. Poutievski, A. Singh, S. Venkata, J. Wanderer, J. Zhou, M. Zhu, J. Zolla, U. Hölzle, S. Stuart, and A. Vahdat, "B4: experience with a globally-deployed software defined wan," in *Proceedings of the ACM SIGCOMM 2013 conference on SIGCOMM*, ser. SIGCOMM '13. New York, NY, USA: ACM, 2013, pp. 3–14.

[9] N. McKeown, T. Anderson, H. Balakrishnan, G. Parulkar, L. Peterson, J. Rexford, S. Shenker, and J. Turner, "Openflow: enabling innovation in campus networks," *SIGCOMM Comput. Commun. Rev.*, vol. 38, no. 2, pp. 69–74, Mar. 2008.

[10] ONF, "Open networking foundation," 2014. [Online]. Available: https://www.opennetworking.org/

[11] S. Yeganeh, A. Tootoonchian, and Y. Ganjali, "On scalability of software-defined networking," *Communications Magazine, IEEE*, vol. 51, no. 2, pp. 136–141, 2013.

[12] VMware, Inc., "VMware NSX Virtualization Platform," 2013. [Online]. Available: https://www.vmware.com/products/nsx/

[13] OpenDaylight, "OpenDaylight: A Linux Foundation Collaborative Project," 2013. [Online]. Available: http://www.opendaylight.org

[14] N. Feamster, J. Rexford, and E. Zegura, "The road to SDN," *Queue*, vol. 11, no. 12, pp. 20:20–20:40, Dec. 2013.

[15] R. Presuhn, "Version 2 of the Protocol Operations for the Simple Network Management Protocol (SNMP)," RFC 3416 (INTERNET STANDARD), Internet Engineering Task Force, Dec. 2002. [Online]. Available: http://www.ietf.org/rfc/rfc3416.txt

[16] N. Feamster and H. Balakrishnan, "Detecting BGP configuration faults with static analysis," in *Proceedings of the 2nd conference on Symposium on Networked Systems Design & Implementation - Volume 2*, ser. NSDI'05. Berkeley, CA, USA: USENIX Association, 2005, pp. 43–56.

[17] R. Barrett, S. Haar, and R. Whitestone, "Routing snafu causes internet outage," *Interactive Week*, 1997.

[18] K. Butler, T. Farley, P. McDaniel, and J. Rexford, "A survey of bgp security issues and solutions," *Proceedings of the IEEE*, vol. 98, no. 1, pp. 100–122, Jan 2010.

[19] J. Sherry and S. Ratnasamy, "A survey of enterprise middlebox deployments," EECS Department, University of California, Berkeley, Tech. Rep. UCB/EECS-2012-24, Feb 2012.

[20] K. Greene, "MIT Tech Review 10 Breakthrough Technologies: Software-defined Networking," http://www2.technologyreview.com/article/412194/tr10-software-defined-networking/, 2009.

[21] H. Alkhatib, P. Faraboschi, E. Frachtenberg, H. Kasahara, D. Lange, P. Laplante, A. Merchant, D. Milojicic, and K. Schwan, "IEEE CS 2022 report (draft)," IEEE Computer Society, Tech. Rep., February 2014.

[22] A. Doria, J. H. Salim, R. Haas, H. Khosravi, W. Wang, L. Dong, R. Gopal, and J. Halpern, "Forwarding and Control Element Separation (ForCES) Protocol Specification," Internet Engineering Task Force, Mar. 2010. [Online]. Available: http://www.ietf.org/rfc/rfc5810.txt

[23] H. Song, "Protocol-oblivious Forwarding: Unleash the power of SDN through a future-proof forwarding plane," in *Proceedings of the Second ACM SIGCOMM Workshop on Hot Topics in Software Defined Networking*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 127–132.

[24] T. D. Nadeau and K. Gray, *SDN : software defined networks*. Sebastopol: O'Reilly, 2013. [Online]. Available: http://opac.inria.fr/record=b1135288

[25] R. Alimi, R. Penno, and Y. Yang, "ALTO Protocol," Internet Draft, Internet Engineering Task Force, March 2014. [Online]. Available: https://datatracker.ietf.org/doc/draft-ietf-alto-protocol/

[26] IETF I2RS Working Group, "Interface to the routing system (I2RS)," Internet Engineering Task Force, 2014. [Online]. Available: http://datatracker.ietf.org/wg/i2rs/charter/

[27] D. King and A. Farrel, "A PCE-based architecture for application-based network operations," Internet Engineering Task Force, Feb 2014. [Online]. Available: http://datatracker.ietf.org/doc/draft-farrkingel-pce-abno-architecture/

[28] N. M. K. Chowdhury and R. Boutaba, "A survey of network virtualization," *Computer Networks*, vol. 54, no. 5, pp. 862 – 876, 2010.

[29] R. Jain and S. Paul, "Network virtualization and software defined networking for cloud computing: a survey," *Communications Magazine, IEEE*, vol. 51, no. 11, pp. 24–31, 2013.

[30] A. Corradi, M. Fanelli, and L. Foschini, "VM consolidation: A real case based on openstack cloud," *Future Generation Computer Systems*, vol. 32, no. 0, pp. 118 – 127, 2014.

[31] A. Shang, J. Liao, and L. Du, "Pica8 Xorplus," 2014. [Online]. Available: http://sourceforge.net/projects/xorplus/

[32] P. Jakma and D. Lamparter, "Introduction to the quagga routing suite," *Network, IEEE*, vol. 28, no. 2, pp. 42–48, March 2014.

[33] "NetFPGA," 2014. [Online]. Available: http://netfpga.org/

[34] J. Martins, M. Ahmed, C. Raiciu, V. Olteanu, M. Honda, R. Bifulco, and F. Huici, "Clickos and the art of network function virtualization," in *11th USENIX Symposium on Networked Systems Design and Implementation (NSDI 14)*. Seattle, WA: USENIX Association, Apr. 2014, pp. 459–473.

[35] D. Tennenhouse, J. Smith, W. Sincoskie, D. Wetherall, and G. Minden, "A survey of active network research," *Communications Magazine, IEEE*, vol. 35, no. 1, pp. 80–86, 1997.

[36] D. Sheinbein and R. P. Weber, "800 service using SPC network capability," *The Bell System Technical Journal*, vol. 61, no. 7, Sep. 1982.

[37] M. Caesar, D. Caldwell, N. Feamster, J. Rexford, A. Shaikh, and J. van der Merwe, "Design and implementation of a routing control platform," in *Proceedings of the 2nd conference on Symposium on Networked Systems Design & Implementation - Volume 2*, ser. NSDI'05. Berkeley, CA, USA: USENIX Association, 2005, pp. 15–28.

[38] D. L. Tennenhouse and D. J. Wetherall, "Towards an active network architecture," *SIGCOMM Comput. Commun. Rev.*, vol. 37, no. 5, pp. 81–94, Oct. 2007.

[39] B. Schwartz, A. Jackson, W. Strayer, W. Zhou, R. Rockwell, and C. Partridge, "Smart packets for active networks," in *Open Architectures and Network Programming Proceedings, 1999. OPENARCH'99. 1999 IEEE Second Conference on*, Mar 1999, pp. 90–97.

[40] D. Wetherall, J. V. Guttag, and D. Tennenhouse, "Ants: a toolkit for building and dynamically deploying network protocols," in *Open Architectures and Network Programming, 1998 IEEE*, Apr 1998, pp. 117–129.

[41] D. Alexander, W. Arbaugh, M. Hicks, P. Kakkar, A. Keromytis, J. Moore, C. Gunter, S. Nettles, and J. Smith, "The switchware active network architecture," *Network, IEEE*, vol. 12, no. 3, pp. 29–36, May 1998.

[42] K. Calvert, S. Bhattacharjee, E. Zegura, and J. Sterbenz, "Directions in active networks," *Communications Magazine, IEEE*, vol. 36, no. 10, pp. 72–78, Oct 1998.

[43] T. Wolf and J. Turner, "Design issues for high performance active routers," in *Broadband Communications, 2000. Proceedings. 2000 International Zurich Seminar on*, 2000, pp. 199–205.

[44] S. da Silva, Y. Yemini, and D. Florissi, "The NetScript active network system," *IEEE J.Sel. A. Commun.*, vol. 19, no. 3, pp. 538–551, Mar. 2001.

[45] J. Biswas, A. A. Lazar, J. F. Huard, K. Lim, S. Mahjoub, L. F. Pau, M. Suzuki, S. Torstensson, W. Wang, and S. Weinstein, "The IEEE P1520 standards initiative for programmable network interfaces," *Comm. Mag.*, vol. 36, no. 10, pp. 64–70, Oct. 1998.

[46] J. Van der Merwe, S. Rooney, I. Leslie, and S. Crosby, "The tempest-a practical framework for network programmability," *Network, IEEE*, vol. 12, no. 3, pp. 20–28, May 1998.

[47] T. Lakshman, T. Nandagopal, R. Ramjee, K. Sabnani, and T. Woo, "The SoftRouter Architecture," in *Third ACM Workshop on Hot Topics in Networks (HotNets-III)*, San Diego, CA, November 2004.

[48] J. Vasseur and J. L. Roux, "Path Computation Element (PCE) Communication Protocol (PCEP)," RFC 5440 (Proposed Standard), Internet Engineering Task Force, Mar. 2009. [Online]. Available: http://www.ietf.org/rfc/rfc5440.txt

[49] A. Greenberg, G. Hjalmtysson, D. A. Maltz, A. Myers, J. Rexford, G. Xie, H. Yan, J. Zhan, and H. Zhang, "A clean slate 4D approach to network control and management," *SIGCOMM Comput. Commun. Rev.*, vol. 35, no. 5, pp. 41–54, Oct. 2005.

[50] J. Van der Merwe, A. Cepleanu, K. D'Souza, B. Freeman, A. Greenberg, D. Knight, R. McMillan, D. Moloney, J. Mulligan, H. Nguyen, M. Nguyen, A. Ramarajan, S. Saad, M. Satterlee, T. Spencer, D. Toll, and S. Zelingher, "Dynamic connectivity management with an intelligent route service control point," in *Proceedings of the SIGCOMM workshop on Internet network management*, ser. INM '06. New York, NY, USA: ACM, 2006, pp. 29–34.

[51] M. Casado, T. Garfinkel, A. Akella, M. J. Freedman, D. Boneh, N. McKeown, and S. Shenker, "SANE: a protection architecture for enterprise networks," in *Proceedings of the 15th conference on USENIX Security Symposium - Volume 15*, ser. USENIX-SS'06, Berkeley, CA, USA, 2006.

[52] M. Casado, M. J. Freedman, J. Pettit, J. Luo, N. McKeown, and S. Shenker, "Ethane: taking control of the enterprise," in *Proceedings of the 2007 conference on Applications, technologies, architectures, and protocols for computer communications*, ser. SIGCOMM '07. New York, NY, USA: ACM, 2007, pp. 1–12.

[53] N. Gude, T. Koponen, J. Pettit, B. Pfaff, M. Casado, N. McKeown, and S. Shenker, "NOX: towards an operating system for networks," *Comp. Comm. Rev.*, 2008.

[54] M. Macedonia and D. Brutzman, "Mbone provides audio and video across the internet," *Computer*, vol. 27, no. 4, pp. 30–36, 1994.

[55] R. Fink and R. Hinden, "6bone (IPv6 Testing Address Allocation) Phaseout," RFC 3701 (Informational), Internet Engineering Task Force, Mar. 2004. [Online]. Available: http://www.ietf.org/rfc/rfc3701.txt

[56] D. Andersen, H. Balakrishnan, F. Kaashoek, and R. Morris, "Resilient overlay networks," *SIGOPS Oper. Syst. Rev.*, vol. 35, no. 5, pp. 131–145, Oct. 2001.

[57] B. Chun, D. Culler, T. Roscoe, A. Bavier, L. Peterson, M. Wawrzoniak, and M. Bowman, "Planetlab: An overlay testbed for broad-coverage services," *SIGCOMM Comput. Commun. Rev.*, vol. 33, no. 3, pp. 3–12, Jul. 2003.

[58] T. Anderson, L. Peterson, S. Shenker, and J. Turner, "Overcoming the internet impasse through virtualization," *Computer*, vol. 38, no. 4, pp. 34–41, April 2005.

[59] L. Peterson, T. Anderson, D. Blumenthal, D. Casey, D. Clark, D. Estrin, J. Evans, D. Raychaudhuri, M. Reiter, J. Rexford, S. Shenker, and J. Wroclawski, "Geni design principles," *Computer*, vol. 39, no. 9, pp. 102–105, Sept 2006.

[60] A. Bavier, N. Feamster, M. Huang, L. Peterson, and J. Rexford, "In VINI veritas: realistic and controlled network experimentation," *SIGCOMM Comput. Commun. Rev.*, vol. 36, no. 4, pp. 3–14, Aug. 2006.

[61] B. Pfaff, J. Pettit, T. Koponen, K. Amidon, M. Casado, and S. Shenker, "Extending networking into the virtualization layer," in *Proc. of workshop on Hot Topics in Networks (HotNets-VIII)*, 2009.

[62] B. Lantz, B. Heller, and N. McKeown, "A network in a laptop: rapid prototyping for software-defined networks," in *Proceedings of the 9th ACM SIGCOMM Workshop on Hot Topics in Networks*, ser. Hotnets-IX. New York, NY, USA: ACM, 2010, pp. 19:1–19:6.

[63] R. Sherwood, G. Gibb, K.-K. Yap, G. Appenzeller, M. Casado, N. McKeown, and G. Parulkar, "Can the production network be the testbed?" in *Proceedings of the 9th USENIX conference on Operating systems design and implementation*, ser. OSDI'10, Berkeley, CA, USA, 2010, pp. 1–6.

[64] T. Koponen, K. Amidon, P. Balland, M. Casado, A. Chanda, B. Fulton, I. Ganichev, J. Gross, P. Ingram, E. Jackson, A. Lambeth, R. Lenglet, S.-H. Li, A. Padmanabhan, J. Pettit, B. Pfaff, R. Ramanathan, S. Shenker, A. Shieh, J. Stribling, P. Thakkar, D. Wendlandt, A. Yip, and R. Zhang, "Network virtualization in multi-tenant datacenters," in *11th USENIX Symposium on Networked Systems Design and Implementation (NSDI 14)*, Seattle, WA, Apr. 2014, pp. 203–216.

[65] V. Bollapragada, C. Murphy, and R. White, *Inside Cisco IOS software architecture*, 1st ed. Cisco Press, Jul 2000.

[66] Juniper Networks, "Junos OS Architecture Overview," 2012. [Online]. Available: http://www.juniper.net/techpubs/en_US/junos12.1/topics/concept/junos-software-architecture.html

[67] Extreme Networks, "ExtremeXOS Operating System, Version 15.4," 2014. [Online]. Available: http://learn.extremenetworks.com/rs/extreme/images/EXOS-DS.pdf

[68] Alcatel-Lucent, "SR OS," 2014. [Online]. Available: http://www3.alcatel-lucent.com/products/sros/

[69] U. Krishnaswamy, P. Berde, J. Hart, M. Kobayashi, P. Radoslavov, T. Lindberg, R. Sverdlov, S. Zhang, W. Snow, and G. Parulkar, "ONOS: An Open Source Distributed SDN OS," 2013. [Online]. Available: http://www.slideshare.net/umeshkrishnaswamy/open-network-operating-system

[70] A. T. Campbell, I. Katzela, K. Miki, and J. Vicente, "Open signaling for atm, internet and mobile networks (opensig'98)," *SIGCOMM Comput. Commun. Rev.*, vol. 29, no. 1, pp. 97–108, Jan. 1999.

[71] R. Sherwood, M. Chan, A. Covington, G. Gibb, M. Flajslik, N. Handigol, T.-Y. Huang, P. Kazemian, M. Kobayashi, J. Naous, S. Seetharaman, D. Underhill, T. Yabe, K.-K. Yap, Y. Yiakoumis, H. Zeng, G. Appenzeller, R. Johari, N. McKeown, and G. Parulkar, "Carving

research slices out of your production networks with OpenFlow," *SIGCOMM Comput. Commun. Rev.*, vol. 40, no. 1, pp. 129–130, Jan. 2010.

[72] H. Song, J. Gong, J. Song, and J. Yu, "Protocol Oblivious Forwarding (POF)," 2013. [Online]. Available: http://www.poforwarding.org/

[73] ONF, "Charter: Forwarding Abstractions Working Group," April 2014. [Online]. Available: https://www.opennetworking.org/images/stories/downloads/working-groups/charter-forwarding-abstractions.pdf

[74] Centec Networks, "V350 - centec open SDN platform," 2013. [Online]. Available: http://www.valleytalk.org/wp-content/uploads/2013/04/Centec-Open-SDN-Platform.pdf

[75] NEC, "Nec ProgrammableFlow UNIVERGE PF5820," 2013. [Online]. Available: http://www.nec.com/en/global/prod/pflow/images_documents/ProgrammableFlow_Switch_PF5820.pdf

[76] NoviFlow, "NoviSwitch 1248 High Performance OpenFlow Switch," 2013. [Online]. Available: http://205.236.122.20/gestion/NoviSwitch1248Datasheet.pdf

[77] HP, "HP 8200 ZL switch series," 2013. [Online]. Available: http://h17007.www1.hp.com/us/en/networking/products/switches/HP_8200_zl_Switch_Series/

[78] Arista Networks, "7150 series," 2013. [Online]. Available: http://www.aristanetworks.com/media/system/pdf/Datasheets/7150S_Datasheet.pdf

[79] Extreme Networks, "Blackdiamond x8," 2013. [Online]. Available: http://www.extremenetworks.com/libraries/products/DSBDX_1832.pdf

[80] Huawei Technologies Co., Ltd., "Cx600 metro services platform," 2013. [Online]. Available: http://www.huawei.com/ucmf/groups/public/documents/attachments/hw_132369.pdf

[81] Juniper Networks, "Ex9200 ethernet switch," 2013. [Online]. Available: http://www.juniper.net/us/en/local/pdf/datasheets/1000432-en.pdf

[82] I. Yokneam, "EZchip Announces OpenFlow 1.1 Implementations on its NP-4 100-Gigabit Network Processor," 2011. [Online]. Available: http://www.ezchip.com/pr_110713.htm

[83] BROCADE, "Brocade MLX series," 2013. [Online]. Available: http://www.brocade.com/products/all/routers/product-details/netiron-mlx-series/system-options.page

[84] IBM, "IBM System Networking RackSwitch G8264," 2013. [Online]. Available: http://www-03.ibm.com/systems/networking/switches/rack/g8264/

[85] NEC, "Nec ProgrammableFlow family of products," 2013. [Online]. Available: http://www.necam.com/SDN/

[86] Pica8, "Pica8 3920," 2013. [Online]. Available: http://www.pica8.org/documents/pica8-datasheet-64x10gbe-p3780-p3920.pdf

[87] Plexxi, "Plexxi Switch 1," 2013. [Online]. Available: http://www.plexxi.com/wp-content/themes/plexxi/assets/pdf/Plexxi_Switch_1_Datasheet_Dec_2012.pdf

[88] Centec Networks, "Centec v330 OpenFlow switch reference design," 2013. [Online]. Available: http://www.centecnetworks.com/en/SolutionList.asp?ID=42

[89] Cyan, Inc., "Z-series," 2013. [Online]. Available: http://www.cyaninc.com/en/our-solutions/z-series/

[90] Juniper Networks, Inc., "Contrail virtual router," 2013. [Online]. Available: https://github.com/Juniper/contrail-vrouter

[91] FlowForwarding, "LINC-Switch," 2013. [Online]. Available: http://www.flowforwarding.org/

[92] K. Rutka, K. Kaplita, S. Narayan, and S. Bailey, "LINC Switch," 2013. [Online]. Available: http://www.opennetsummit.org/pdf/2013/research_track/poster_papers/ons2013-final36.pdf

[93] CPqD, "ofsoftswitch13," 2013. [Online]. Available: https://github.com/CPqD/ofsoftswitch13

[94] "Open vSwitch," 2013. [Online]. Available: http://vswitch.org/

[95] OpenFlow Community, "OpenFlow switching reference system," 2009. [Online]. Available: http://www.openflow.org/wp/downloads/

[96] Y. Mundada, R. Sherwood, and N. Feamster, "An OpenFlow switch element for click," in *in Symposium on Click Modular Router*, 2009. [Online]. Available: http://www.cc.gatech.edu/~yogeshm3/click_symposium2009.pdf

[97] Big Switch Networks, "Project Floodlight," 2013. [Online]. Available: http://www.projectfloodlight.org/

[98] Y. Yiakoumis, J. Schulz-Zander, and J. Zhu, "Pantou : OpenFlow 1.0 for OpenWRT," 2011. [Online]. Available: http://www.openflow.org/wk/index.php/OpenFlow_1.0_for_OpenWRT

[99] A. Weissberger, "VMware's Network Virtualization Poses Huge Threat to Data Center Switch Fabric Vendors," 2013. [Online]. Available: http://viodi.com/2013/05/06/vmwares-network-virtualization-poses-huge-threat-to-data-center-switch-fabric-vendors/

[100] S. Shenker, "Stanford Seminar - Software-Defined Networking at the Crossroads," June 2013. [Online]. Available: http://www.youtube.com/watch?v=WabdXYzCAOU

[101] M. Casado, "OpenStack and Network Virtualization," April 2013. [Online]. Available: http://blogs.vmware.com/vmware/2013/04/openstack-and-network-virtualization.html

[102] Pica8 Open Networking, "Pica8's os for open switches," 2013. [Online]. Available: http://www.pica8.org/open-switching/open-switching-overview.php

[103] ONIE, "Open Network Install Environment," 2013. [Online]. Available: http://onie.org/

[104] T. Kato, M. Kawakami, T. Myojin, H. Ogawa, K. Hirono, and T. Hasegawa, "Case study of applying SPLE to development of network switch products," in *Proceedings of the 17th International Software Product Line Conference*, ser. SPLC '13. New York, NY, USA: ACM, 2013, pp. 198–207.

[105] B. Pfaff and B. Davie, "The Open vSwitch Database Management Protocol," Internet Draft, Internet Engineering Task Force, September 2013. [Online]. Available: http://tools.ietf.org/id/draft-pfaff-ovsdb-proto-03.txt

[106] M. Smith, M. Dvorkin, Y. Laribi, V. Pandey, P. Garg, and N. Weidenbacher, "OpFlex Control Protocol," Internet Draft, Internet Engineering Task Force, April 2014. [Online]. Available: http://tools.ietf.org/html/draft-smith-opflex-00

[107] T. J. Bittman, G. J. Weiss, M. A. Margevicius, and P. Dawson, "Magic Quadrant for x86 Server Virtualization Infrastructure," Gartner, Tech. Rep., June 2013.

[108] D. W. Cearley, D. Scott, J. Skorupa, and T. J. Bittman, "Top 10 Technology Trends, 2013: Cloud Computing and Hybrid IT Drive Future IT Models," February 2013. [Online]. Available: http://www.gartnersummit.com/Gartnertop_10_technology_trends_201_237716.pdf

[109] C. Peng, M. Kim, Z. Zhang, and H. Lei, "VDN: virtual machine image distribution network for cloud data centers," in *INFOCOM, 2012 Proceedings IEEE*, March 2012, pp. 181–189.

[110] Z. Zhang, Z. Li, K. Wu, D. Li, H. Li, Y. Peng, and X. Lu, "VMThunder: fast provisioning of large-scale virtual machine clusters," *Parallel and Distributed Systems, IEEE Transactions on*, vol. PP, no. 99, pp. 1–1, 2014.

[111] M. Mahalingam, D. Dutt, K. Duda, P. Agarwal, L. Kreeger, T. Sridhar, M. Bursell, and C. Wright, "VXLAN: A Framework for Overlaying Virtualized Layer 2 Networks over Layer 3 Networks," Internet Draft, Internet Engineering Task Force, November 2013. [Online]. Available: http://www.ietf.org/id/draft-mahalingam-dutt-dcops-vxlan-06.txt

[112] M. Sridharan, A. Greenberg, Y. Wang, P. Garg, N. Venkataramiah, K. Duda, I. Ganga, G. Lin, M. Pearson, P. Thaler, and C. Tumuluri, "NVGRE: Network Virtualization using Generic Routing Encapsulation," Internet Draft, Internet Engineering Task Force, August 2013. [Online]. Available: http://tools.ietf.org/id/draft-sridharan-virtualization-nvgre-03.txt

[113] R. Sherwood, G. Gibb, K.-K. Yap, G. Appenzeller, M. Casado, N. McKeown, and G. Parulkar, "FlowVisor: A Network Virtualization Layer," Deutsche Telekom Inc. R&D Lab, Stanford, Nicira Networks, Tech. Rep., 2009.

[114] S. Azodolmolky, R. Nejabati, S. Peng, A. Hammad, M. P. Channegowda, N. Efstathiou, A. Autenrieth, P. Kaczmarek, and D. Simeonidou, "Optical FlowVisor: An OpenFlow-based Optical Network Virtualization Approach," in *National Fiber Optic Engineers Conference*, ser. OSA Technical Digest. Optical Society of America, Mar. 2012.

[115] D. A. Drutskoy, "Software-Defined Network Virtualization with FlowN," Ph.D. dissertation, Department of Computer Science of Princeton University, Jun 2012.

[116] A. Al-Shabibi, M. D. Leenheer, M. Gerolay, A. Koshibe, W. Snow, and G. Parulkar, "OpenVirteX: A Network Hypervisor," 2014. [Online]. Available: http://ovx.onlab.us/wp-content/uploads/2014/04/ovx-ons14.pdf

[117] S. Racherla, D. Cain, S. Irwin, P. Ljungstrom, P. Patil, and A. M. Tarenzio, *Implementing IBM Software Defined Network for Virtual Environments*. IBM RedBooks, May 2014.

[118] C. Li, B. Brech, S. Crowder, D. Dias, H. Franke, M. Hogstrom, D. Lindquist, G. Pacifici, S. Pappe, B. Rajaraman, J. Rao, R. Ratnaparkhi, R. Smith, and M. Williams, "Software defined environments: An introduction," *IBM Journal of Research and Development*, vol. 58, no. 2, pp. 1–11, March 2014.

[119] Z. Bozakov and P. Papadimitriou, "Autoslice: automated and scalable slicing for software-defined networks," in *Proceedings of the 2012 ACM*

conference on CoNEXT student workshop, ser. CoNEXT Student '12. New York, NY, USA: ACM, 2012, pp. 3–4.

[120] D. Drutskoy, E. Keller, and J. Rexford, "Scalable network virtualization in software-defined networks," *Internet Computing, IEEE*, vol. 17, no. 2, pp. 20–27, 2013.

[121] Juniper Networks, "Opencontrail," 2013. [Online]. Available: http://opencontrail.org/

[122] HP, "Hp SDN controller architecture," Hewlett-Packard Development Company, L.P., Tech. Rep., September 2013.

[123] K. Phemius, M. Bouet, and J. Leguay, "DISCO: Distributed Multi-domain SDN Controllers," *ArXiv e-prints*, Aug. 2013.

[124] D. Erickson, "The beacon OpenFlow controller," in *Proceedings of the second ACM SIGCOMM workshop on Hot topics in software defined networking*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 13–18.

[125] A. Tootoonchian, S. Gorbunov, Y. Ganjali, M. Casado, and R. Sherwood, "On controller performance in software-defined networks," in *Proceedings of the 2nd USENIX conference on Hot Topics in Management of Internet, Cloud, and Enterprise Networks and Services*, ser. Hot-ICE'12. Berkeley, CA, USA: USENIX Association, 2012, pp. 10–10.

[126] Z. Cai, A. L. Cox, and T. S. E. Ng, "Maestro: A System for Scalable OpenFlow Control," Rice University, Tech. Rep., 2011.

[127] D. Erickson, "The beacon OpenFlow controller," in *Proceedings of the second workshop on Hot topics in software defined networks*, ser. HotSDN '13. New York, NY, USA: ACM, 2013.

[128] "Floodlight Is A Java-Based OpenFlow Controller," 2012. [Online]. Available: http://floodlight.openflowhub.org/

[129] Y. Takamiya and N. Karanatsios, "Trema OpenFlow controller framework," 2012. [Online]. Available: https://github.com/trema/trema

[130] Nippon Telegraph and Telephone Corporation, "Ryu Network Operating System," 2012. [Online]. Available: http://osrg.github.com/ryu/

[131] M. Banikazemi, D. Olshefski, A. Shaikh, J. Tracey, and G. Wang, "Meridian: an SDN platform for cloud network services," *Communications Magazine, IEEE*, vol. 51, no. 2, pp. 120–127, 2013.

[132] NEC, "Award-winning Software-defined Networking NEC ProgrammableFlow Networking Suite," September 2013. [Online]. Available: http://www.necam.com/docs/?id=67c33426-0a2b-4b87-9a7a-d3cecc14d26a

[133] A. Tootoonchian and Y. Ganjali, "HyperFlow: a distributed control plane for OpenFlow," in *Proceedings of the 2010 internet network management conference on Research on enterprise networking*, ser. INM/WREN'10. Berkeley, CA, USA: USENIX Association, 2010, pp. 3–3.

[134] M. Monaco, O. Michel, and E. Keller, "Applying Operating System Principles to SDN Controller Design," in *Twelfth ACM Workshop on Hot Topics in Networks (HotNets-XII)*, College Park, MD, November 2013.

[135] P. Porras, S. Shin, V. Yegneswaran, M. Fong, M. Tyson, and G. Gu, "A security enforcement kernel for OpenFlow networks," in *Proceedings of the First Workshop on Hot Topics in Software Defined Networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 121–126. [Online]. Available: http://doi.acm.org/10.1145/2342441.2342466

[136] L. Richardson and S. Ruby, *RESTful web services*. O'Reilly Media, Inc., 2008.

[137] T. L. Hinrichs, N. S. Gude, M. Casado, J. C. Mitchell, and S. Shenker, "Practical declarative network management," in *Proceedings of the 1st ACM workshop on Research on enterprise networking*, ser. WREN '09. New York, NY, USA: ACM, 2009, pp. 1–10.

[138] N. Foster, R. Harrison, M. J. Freedman, C. Monsanto, J. Rexford, A. Story, and D. Walker, "Frenetic: a network programming language," *SIGPLAN Not.*, 2011.

[139] C. Monsanto, N. Foster, R. Harrison, and D. Walker, "A compiler and run-time system for network programming languages," *SIGPLAN Not.*, vol. 47, no. 1, pp. 217–230, Jan. 2012.

[140] ONF, "OpenFlow Notifications Framework OpenFlow Management," October 2014. [Online]. Available: https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow-config/of-notifications-framework-1.0.pdf

[141] A. Singla and B. Rijsman, "Contrail Architecture," Juniper Networks, Tech. Rep., 2013.

[142] ONF, "OpenFlow Management and Configuration Protocol (OF-Config 1.1.1)," March 2014. [Online]. Available: https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow-config/of-config-1-1-1.pdf

[143] R. Enns, M. Bjorklund, J. Schoenwaelder, and A. Bierman, "Network Configuration Protocol (NETCONF)," RFC 6241 (Proposed Standard), Internet Engineering Task Force, Jun. 2011. [Online]. Available: http://www.ietf.org/rfc/rfc6241.txt

[144] D. Harrington, R. Presuhn, and B. Wijnen, "An Architecture for Describing Simple Network Management Protocol (SNMP) Management Frameworks," Internet Engineering Task Force, dec 2002. [Online]. Available: http://www.ietf.org/rfc/rfc3411.txt

[145] Y. Rekhter, T. Li, and S. Hares, "A Border Gateway Protocol 4 (BGP-4)," RFC 4271 (Draft Standard), Internet Engineering Task Force, Jan. 2006. [Online]. Available: http://www.ietf.org/rfc/rfc4271.txt

[146] H. Yin, H. Xie, T. Tsou, D. Lopez, P. Aranda, and R. Sidi, "SDNi: A Message Exchange Protocol for Software Defined Networks (SDNS) across Multiple Domains," Internet Draft, Internet Engineering Task Force, June 2012. [Online]. Available: http://tools.ietf.org/id/draft-yin-sdn-sdni-00.txt

[147] M. Garcia, A. Bessani, I. Gashi, N. Neves, and R. Obelheiro, "Analysis of operating system diversity for intrusion tolerance," *Software: Practice and Experience*, vol. 44, no. 6, pp. 735–770, 2014.

[148] Z. Wang, T. Tsou, J. Huang, X. Shi, and X. Yin, "Analysis of Comparisons between OpenFlow and ForCES," Internet Draft, Internet Engineering Task Force, December 2011. [Online]. Available: http://tools.ietf.org/id/draft-wang-forces-compare-openflow-forces-00.txt

[149] K. Ogawa, W. M. Wang, E. Haleplidis, and J. H. Salim, "ForCES Intra-NE High Availability," Internet Draft, Internet Engineering Task Force, October 2013. [Online]. Available: http://tools.ietf.org/id/draft-ietf-forces-ceha-08.txt

[150] F. A. Botelho, F. M. V. Ramos, D. Kreutz, and A. N. Bessani, "On the feasibility of a consistent and fault-tolerant data store for SDNs," in *Proceedings of the 2013 Second European Workshop on Software Defined Networks*, ser. EWSDN '13. Washington, DC, USA: IEEE Computer Society, 2013, pp. 38–43.

[151] S. Vinoski, "Advanced message queuing protocol," *IEEE Internet Computing*, vol. 10, no. 6, pp. 87–89, Nov. 2006.

[152] A. Ghodsi, "Distributed k-ary system: Algorithms for distributed hash tables," Ph.D. dissertation, KTH-Royal Institute of Technology, 2006.

[153] W. Stallings, "Software-Defined Networks and OpenFlow," *The Internet Protocol Journal*, vol. 16, no. 1, 2013.

[154] K. Pentikousis, Y. Wang, and W. Hu, "MobileFlow: Toward software-defined mobile networks," *Communications Magazine, IEEE*, vol. 51, no. 7, pp. 44–53, 2013.

[155] A. Voellmy and P. Hudak, "Nettle: taking the sting out of programming network routers," in *Proceedings of the 13th international conference on Practical aspects of declarative languages*, ser. PADL'11. Berlin, Heidelberg: Springer-Verlag, 2011, pp. 235–249.

[156] A. Voellmy, H. Kim, and N. Feamster, "Procera: a language for high-level reactive network control," in *Proceedings of the first workshop on Hot topics in software defined networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 43–48.

[157] C. Monsanto, J. Reich, N. Foster, J. Rexford, and D. Walker, "Composing software-defined networks," in *Proceedings of the 10th USENIX conference on Networked Systems Design and Implementation*, ser. nsdi'13. Berkeley, CA, USA: USENIX Association, 2013, pp. 1–14.

[158] S. Hassas Yeganeh and Y. Ganjali, "Kandoo: A framework for efficient and scalable offloading of control applications," in *Proceedings of the First Workshop on Hot Topics in Software Defined Networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 19–24.

[159] D. Saikia, "MuL OpenFlow controller," 2013. [Online]. Available: http://sourceforge.net/projects/mul/

[160] M. McCauley, "POX," 2012. [Online]. Available: http://www.noxrepo.org/

[161] H. Shimonishi and S. Ishii, "Virtualized network infrastructure using OpenFlow," in *Network Operations and Management Symposium Workshops (NOMS Wksps), 2010 IEEE/IFIP*, 2010, pp. 74–79.

[162] G. Appenzeller, "SNAC," 2011. [Online]. Available: http://www.openflowhub.org/display/Snac

[163] B. Casemore, "SDN controller ecosystems critical to market success," 2012. [Online]. Available: http://nerdtwilight.wordpress.com/2012/06/05/sdn-controller-ecosystems-critical-to-market-success/

[164] R. Kwan and C. Leung, "A survey of scheduling and interference mitigation in lte," *JECE*, vol. 2010, pp. 1:1–1:10, Jan. 2010. [Online]. Available: http://dx.doi.org/10.1155/2010/273486

[165] A. Gudipati, D. Perry, L. E. Li, and S. Katti, "SoftRAN: Software defined radio access network," in *Proceedings of the second workshop on Hot topics in software defined networks*, ser. HotSDN '13. New York, NY, USA: ACM, 2013.

[166] J. Dix, "Clarifying the role of software-defined networking northbound APIs," May 2013. [Online]. Available: http://www.networkworld.com/news/2013/050213-sherwood-269366.html

[167] I. GUIS, "The SDN Gold Rush To The Northbound API," November 2012. [Online]. Available: http://www.sdncentral.com/technology/the-sdn-gold-rush-to-the-northbound-api/2012/11/

[168] B. Salisbury, "The northbound API- a big little problem," 2012.

[169] G. Ferro, "Northbound API, southbound api, east/north lan navigation in an OpenFlow world and an SDN compass," Aug. 2012.

[170] B. Casemore, "Northbound API: The standardization debate," Sept. 2012. [Online]. Available: http://nerdtwilight.wordpress.com/2012/09/18/northbound-api-the-standardization-debate/

[171] I. Pepelnjak, "SDN controller northbound API is the crucial missing piece," Sept. 2012. [Online]. Available: http://blog.ioshints.info/2012/09/sdn-controller-northbound-api-is.html

[172] S. Johnson, "A primer on northbound APIs: Their role in a software-defined network," December 2012. [Online]. Available: http://searchsdn.techtarget.com/feature/A-primer-on-northbound-APIs-Their-role-in-a-software-defined-network

[173] R. G. Little, "ONF to standardize northbound API for SDN applications?" October 2013. [Online]. Available: http://searchsdn.techtarget.com/news/2240206604/ONF-to-standardize-northbound-API-for-SDN-applications

[174] M. Yu, A. Wundsam, and M. Raju, "NOSIX: A lightweight portability layer for the sdn os," *SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 2, pp. 28–35, Apr. 2014.

[175] R. Chua, "OpenFlow northbound API: A new olympic sport," 2012. [Online]. Available: http://www.sdncentral.com/sdn-blog/openflow-northbound-api-olympics/2012/07/

[176] J. Reich, C. Monsanto, N. Foster, J. Rexford, and D. Walker, "Modular SDN Programming with Pyretic," *USENIX ;login*, vol. 38, no. 5, October 2013.

[177] K.-K. Yap, T.-Y. Huang, B. Dodson, M. S. Lam, and N. McKeown, "Towards software-friendly networks," in *Proceedings of the first ACM asia-pacific workshop on Workshop on systems*, ser. APSys '10. New York, NY, USA: ACM, 2010, pp. 49–54.

[178] S. Gutz, A. Story, C. Schlesinger, and N. Foster, "Splendid isolation: A slice abstraction for software-defined networks," in *Proceedings of the First Workshop on Hot Topics in Software Defined Networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 79–84.

[179] D. Turull, M. Hidell, and P. Sjödin, "Evaluating OpenFlow in libnetvirt," in *The 8th Swedish National Computer Networking Workshop 2012 (SNCNW 2012)*, Oct 2012.

[180] Quantum Communicty, "OpenStack Networking ("Quantum")," 2012.

[181] M. Guzdial, "Education: Paving the way for computational thinking," *Commun. ACM*, vol. 51, no. 8, pp. 25–27, Aug. 2008.

[182] M. S. Farooq, S. A. Khan, F. Ahmad, S. Islam, and A. Abid, "An evaluation framework and comparative analysis of the widely used first programming languages," *PLoS ONE*, vol. 9, no. 2, 02 2014.

[183] A. D. Ferguson, A. Guha, C. Liang, R. Fonseca, and S. Krishnamurthi, "Hierarchical policies for software defined networks," in *Proceedings of the first workshop on Hot topics in software defined networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 37–42.

[184] T. Nelson, A. Guha, D. J. Dougherty, K. Fisler, and S. Krishnamurthi, "A balance of power: expressive, analyzable controller programming," in *Proceedings of the second ACM SIGCOMM workshop on Hot topics in software defined networking*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 79–84.

[185] N. P. Katta, J. Rexford, and D. Walker, "Logic programming for software-dedefine networks," in *ACM SIGPLAN Workshop on Cross-Model Language Design and Implementation*, ser. XLDI, 2012.

[186] S. Shin, P. Porras, V. Yegneswaran, M. Fong, G. Gu, and M. Tyson, "FRESCO: Modular composable security services for software-defined networks," in *Internet Society NDSS.*, Feb. 2013.

[187] S. Son, S. Shin, V. Yegneswaran, P. Porras, and G. Gu, "Model checking invariant security properties in OpenFlow," in *Communications (ICC), 2013 IEEE International Conference on*, June 2013, pp. 1974–1979.

[188] A. Tootoonchian, M. Ghobadi, and Y. Ganjali, "OpenTM: traffic matrix estimator for OpenFlow networks," in *Proceedings of the 11th international conference on Passive and active measurement*, ser. PAM'10. Berlin, Heidelberg: Springer-Verlag, 2010, pp. 201–210.

[189] M. Reitblatt, M. Canini, A. Guha, and N. Foster, "Fattire: Declarative fault tolerance for software defined networks," in *Proceedings of the second workshop on Hot topics in software defined networks*, ser. HotSDN '13. New York, NY, USA: ACM, 2013.

[190] A. Voellmy, J. Wang, Y. R. Yang, B. Ford, and P. Hudak, "Maple: simplifying SDN programming using algorithmic policies," in *Proceedings of the ACM SIGCOMM 2013 conference on SIGCOMM*, ser. SIGCOMM '13. New York, NY, USA: ACM, 2013, pp. 87–98.

[191] R. Soule, S. Basu, R. Kleinberg, E. G. Sirer, and N. Foster, "Managing the Network with Merlin," in *Twelfth ACM Workshop on Hot Topics in Networks (HotNets-XII)*, College Park, MD, November 2013.

[192] C. Jasson Casey, A. Sutton, G. Dos Reis, and A. Sprintson, "Eliminating Network Protocol Vulnerabilities Through Abstraction and Systems Language Design," *ArXiv e-prints*, Nov. 2013.

[193] P. Pereini, M. Kuzniar, and D. Kostic, "OpenFlow needs you! a call for a discussion about a cleaner OpenFlow API," in *Software Defined Networks (EWSDN), 2013 Second European Workshop on*, Oct 2013, pp. 44–49.

[194] F. Facca, E. Salvadori, H. Karl, D. Lopez, P. Aranda Gutierrez, D. Kostic, and R. Riggio, "NetIDE: First steps towards an integrated development environment for portable network apps," in *Software Defined Networks (EWSDN), 2013 Second European Workshop on*, Oct 2013, pp. 105–110.

[195] M. Scharf, V. Gurbani, T. Voith, M. Stein, W. Roome, G. Soprovich, and V. Hilt, "Dynamic VPN optimization by ALTO guidance," in *Software Defined Networks (EWSDN), 2013 Second European Workshop on*, Oct 2013, pp. 13–18.

[196] M. Stiemerling, S. Kiesel, S. Previdi, and M. Scharf, "ALTO Deployment Considerations," Internet Draft, Internet Engineering Task Force, February 2014. [Online]. Available: http://tools.ietf.org/html/draft-ietf-alto-deployments-09

[197] N. Handigol, S. Seetharaman, M. Flajslik, A. Gember, N. McKeown, G. Parulkar, A. Akella, N. Feamster, R. Clark, A. Krishnamurthy, V. Brajkovic, and T. A. and, "Aster*x: Load-Balancing Web Traffic over Wide-Area Networks," 2009.

[198] B. Heller, S. Seetharaman, P. Mahadevan, Y. Yiakoumis, P. Sharma, S. Banerjee, and N. McKeown, "ElasticTree: saving energy in data center networks," in *Proceedings of the 7th USENIX conference on Networked systems design and implementation*, ser. NSDI'10. Berkeley, CA, USA: USENIX Association, 2010, pp. 17–17.

[199] M. Al-Fares, S. Radhakrishnan, B. Raghavan, N. Huang, and A. Vahdat, "Hedera: dynamic flow scheduling for data center networks," in *Proceedings of the 7th USENIX conference on Networked systems design and implementation*, ser. NSDI'10. Berkeley, CA, USA: USENIX Association, 2010, pp. 19–19.

[200] C. Macapuna, C. Rothenberg, and M. Magalhaes, "In-packet bloom filter based data center networking with distributed OpenFlow controllers," in *GLOBECOM Workshops (GC Wkshps), 2010 IEEE*, 2010, pp. 584–588.

[201] H. Egilmez, S. Dane, K. Bagci, and A. Tekalp, "Openqos: An OpenFlow controller design for multimedia delivery with end-to-end quality of service over software-defined networks," in *Signal Information Processing Association Annual Summit and Conference (APSIPA ASC), 2012 Asia-Pacific*, 2012, pp. 1–8.

[202] N. Handigol, S. Seetharaman, M. Flajslik, N. McKeown, and R. Johari, "Plug-n-serve: Load-balancing web traffic using OpenFlow," 2009.

[203] K. Jeong, J. Kim, and Y.-T. Kim, "QoS-aware Network Operating System for software defined networking with Generalized OpenFlows," in *Network Operations and Management Symposium (NOMS), 2012 IEEE*, april 2012, pp. 1167 –1174.

[204] W. Kim, P. Sharma, J. Lee, S. Banerjee, J. Tourrilhes, S.-J. Lee, and P. Yalagandula, "Automated and scalable QoS control for network convergence," in *Proceedings of the 2010 internet network management conference on Research on enterprise networking*, ser. INM/WREN'10. Berkeley, CA, USA: USENIX Association, 2010, pp. 1–1.

[205] A. Ishimori, F. Farias, E. Cerqueira, and A. Abelem, "Control of multiple packet schedulers for improving qos on OpenFlow/SDN networking," in *Software Defined Networks (EWSDN), 2013 Second European Workshop on*, Oct 2013, pp. 81–86.

[206] Z. A. Qazi, C.-C. Tu, L. Chiang, R. Miao, V. Sekar, and M. Yu, "SIMPLE-fying middlebox policy enforcement using SDN," in *Proceedings of the Conference on Applications, technologies, architectures, and protocols for computer communications*, ser. SIGCOMM '13. New York, NY, USA: ACM, 2013.

[207] P. Skoldstrom and B. C. Sanchez, "Virtual Aggregation using SDN," in *2013 Second European Workshop on Software Defined Networks*, 2013, pp. –.

[208] H. Ali-Ahmad, C. Cicconetti, A. de la Oliva, M. Draxler, R. Gupta, V. Mancuso, L. Roullet, and V. Sciancalepore, "CROWD: An SDN approach for densenets," in *Software Defined Networks (EWSDN), 2013 Second European Workshop on*, Oct 2013, pp. 25–31.

[209] J. Vestin, P. Dely, A. Kassler, N. Bayer, H. Einsiedler, and C. Peylo, "CloudMAC: towards software defined WLANs," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 16, no. 4, pp. 42–45, Feb. 2013.

[210] Y. Yamasaki, Y. Miyamoto, J. Yamato, H. Goto, and H. Sone, "Flexible access management system for campus VLAN based on OpenFlow," in *Applications and the Internet (SAINT), 2011 IEEE/IPSJ 11th International Symposium on*, 2011, pp. 347–351.

[211] L. Suresh, J. Schulz-Zander, R. Merz, A. Feldmann, and T. Vazao, "Towards programmable enterprise WLANS with Odin," in *Proceedings of the first workshop on Hot topics in software defined networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 115–120.

[212] M. Yang, Y. Li, D. Jin, L. Su, S. Ma, and L. Zeng, "OpenRAN: a software-defined ran architecture via virtualization," in *Proceedings of the ACM SIGCOMM 2013 conference on SIGCOMM*, ser. SIGCOMM '13. New York, NY, USA: ACM, 2013, pp. 549–550.

[213] K.-K. Yap, M. Kobayashi, R. Sherwood, T.-Y. Huang, M. Chan, N. Handigol, and N. McKeown, "OpenRoads: empowering research in mobile networks," *SIGCOMM Comput. Commun. Rev.*, vol. 40, no. 1, pp. 125–126, Jan. 2010.

[214] Small Cell Forum, "Femto APIs," 2013. [Online]. Available: http://www.smallcellforum.org/developers/

[215] V. Chandrasekhar, J. Andrews, and A. Gatherer, "Femtocell networks: a survey," *Communications Magazine, IEEE*, vol. 46, no. 9, pp. 59–67, September 2008.

[216] S. Shirali-Shahreza and Y. Ganjali, "FleXam: flexible sampling extension for monitoring and security applications in OpenFlow," in *Proceedings of the second ACM SIGCOMM workshop on Hot topics in software defined networking*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 167–168.

[217] C. Yu, C. Lumezanu, Y. Zhang, V. Singh, G. Jiang, and H. V. Madhyastha, "Flowsense: monitoring network utilization with zero measurement cost," in *Proceedings of the 14th international conference on Passive and Active Measurement*, ser. PAM'13. Berlin, Heidelberg: Springer-Verlag, 2013, pp. 31–41.

[218] L. Jose, M. Yu, and J. Rexford, "Online measurement of large traffic aggregates on commodity switches," in *Proceedings of the 11th USENIX conference on Hot topics in management of internet, cloud, and enterprise networks and services*, ser. Hot-ICE'11. Berkeley, CA, USA: USENIX Association, 2011, pp. 13–13.

[219] M. Yu, L. Jose, and R. Miao, "Software defined traffic measurement with OpenSketch," in *Proceedings of the 10th USENIX conference on Networked Systems Design and Implementation*, ser. nsdi'13. Berkeley, CA, USA: USENIX Association, 2013, pp. 29–42.

[220] C. Argyropoulos, D. Kalogeras, G. Androulidakis, and V. Maglaris, "PaFloMon – a slice aware passive flow monitoring framework for OpenFlow enabled experimental facilities," in *Software Defined Networking (EWSDN), 2012 European Workshop on*, 2012, pp. 97–102.

[221] R. Hand, M. Ton, and E. Keller, "Active Security," in *Twelfth ACM Workshop on Hot Topics in Networks (HotNets-XII)*, College Park, MD, November 2013.

[222] S. Shin, V. Yegneswaran, P. Porras, and G. Gu, "AVANT-GUARD: Scalable and Vigilant Switch Flow Management in Software-De?ned Networks," in *Proceedings of the 2013 ACM conference on Computer and communications security*, ser. CCS '13. New York, NY, USA: ACM, 2013.

[223] S. Shin and G. Gu, "Cloudwatcher: Network security monitoring using OpenFlow in dynamic cloud networks (or: How to provide security monitoring as a service in clouds?)," in *Proceedings of the 2012 20th IEEE International Conference on Network Protocols (ICNP)*, ser. ICNP '12. Washington, DC, USA: IEEE Computer Society, 2012, pp. 1–6.

[224] R. Braga, E. Mota, and A. Passito, "Lightweight DDoS flooding attack detection using NOX/OpenFlow," in *Local Computer Networks (LCN), 2010 IEEE 35th Conference on*, oct. 2010, pp. 408 –415.

[225] G. Stabler, A. Rosen, S. Goasguen, and K.-C. Wang, "Elastic ip and security groups implementation using OpenFlow," in *Proceedings of the 6th international workshop on Virtualization Technologies in Distributed Computing Date*, ser. VTDC '12. New York, NY, USA: ACM, 2012, pp. 53–60.

[226] K. Wang, Y. Qi, B. Yang, Y. Xue, and J. Li, "LiveSec: Towards Effective Security Management in Large-Scale Production Networks," in *Distributed Computing Systems Workshops (ICDCSW), 2012 32nd International Conference on*, june 2012, pp. 451 –460.

[227] Y. Wang, Y. Zhang, V. Singh, C. Lumezanu, and G. Jiang, "NetFuse: Short-Circuiting Traffic Surges in the Cloud," in *IEEE International Conference on Communications*, 2013.

[228] J. H. Jafarian, E. Al-Shaer, and Q. Duan, "OpenFlow random host mutation: transparent moving target defense using software defined networking," in *Proceedings of the first workshop on Hot topics in software defined networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 127–132.

[229] J. R. Ballard, I. Rae, and A. Akella, "Extensible and scalable network monitoring using OpenSAFE," in *Proceedings of the 2010 internet network management conference on Research on enterprise networking*, ser. INM/WREN'10. Berkeley, CA, USA: USENIX Association, 2010, pp. 8–8.

[230] D. Kotani, K. Suzuki, and H. Shimonishi, "A design and implementation of OpenFlow controller handling ip multicast with fast tree switching," in *Applications and the Internet (SAINT), 2012 IEEE/IPSJ 12th International Symposium on*, 2012, pp. 60–67.

[231] G. Yao, J. Bi, and P. Xiao, "Source address validation solution with OpenFlow/NOX architecture," in *Network Protocols (ICNP), 2011 19th IEEE International Conference on*, 2011, pp. 7–12.

[232] G. Wang, T. E. Ng, and A. Shaikh, "Programming your network at run-time for big data applications," in *HotSDN*. ACM, 2012.

[233] T. Benson, A. Akella, A. Shaikh, and S. Sahu, "Cloudnaas: a cloud networking platform for enterprise applications," in *Proceedings of the 2nd ACM Symposium on Cloud Computing*, ser. SOCC '11. New York, NY, USA: ACM, 2011, pp. 8:1–8:13.

[234] A. Das, C. Lumezanu, Y. Zhang, V. Singh, G. Jiang, and C. Yu, "Transparent and flexible network management for big data processing in the cloud," in *Proceedings of the 5th USENIX conference on Hot Topics in Cloud Ccomputing*, ser. HotCloud'13. Berkeley, CA, USA: USENIX Association, 2013.

[235] A. Arefin, V. K. Singh, G. Jiang, Y. Zhang, and C. Lumezanu, "Diagnosing data center behavior flow by flow," in *IEEE 33rd International Conference on Distributed Computing Systems*. Philadelphia, USA: IEEE, July 2013.

[236] E. Keller, S. Ghorbani, M. Caesar, and J. Rexford, "Live migration of an entire network (and its hosts)," in *Proceedings of the 11th ACM Workshop on Hot Topics in Networks*, ser. HotNets-XI. New York, NY, USA: ACM, 2012, pp. 109–114.

[237] R. Raghavendra, J. Lobo, and K.-W. Lee, "Dynamic graph query primitives for sdn-based cloudnetwork management," in *Proceedings of the first workshop on Hot topics in software defined networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 97–102.

[238] M. Ghobadi, "TCP Adaptation Framework in Data Centers," Ph.D. dissertation, Graduate Department of Computer Science of University of Toronto, 2013.

[239] R. Wang, D. Butnariu, and J. Rexford, "OpenFlow-based server load balancing gone wild," in *Proceedings of the 11th USENIX conference on Hot topics in management of internet, cloud, and enterprise networks and services*, ser. Hot-ICE'11. Berkeley, CA, USA: USENIX Association, 2011, pp. 12–12.

[240] H. Ballani, P. Francis, T. Cao, and J. Wang, "Making routers last longer with viaggre," in *Proceedings of the 6th USENIX symposium on Networked systems design and implementation*, ser. NSDI'09. Berkeley, CA, USA: USENIX Association, 2009, pp. 453–466.

[241] D. Meyer, L. Zhang, and K. Fall, "Report from the IAB Workshop on Routing and Addressing," RFC 4984 (Informational), Internet Engineering Task Force, Sep. 2007. [Online]. Available: http://www.ietf.org/rfc/rfc4984.txt

[242] M. Jarschel, F. Wamser, T. Hohn, T. Zinner, and P. Tran-Gia, "SDN-based application-aware networking on the example of youtube video streaming," in *Software Defined Networks (EWSDN), 2013 Second European Workshop on*, Oct 2013, pp. 87–92.

[243] H. Kumar, H. H. Gharakheili, and V. Sivaraman, "User control of quality of experience in home networks using SDN," in *Advanced Networks and Telecommuncations Systems (ANTS), 2013 IEEE International Conference on*, 2013.

[244] L. Li, Z. Mao, and J. Rexford, "Toward software-defined cellular networks," in *Software Defined Networking (EWSDN), 2012 European Workshop on*, 2012, pp. 7–12.

[245] X. Jin, L. Erran Li, L. Vanbever, and J. Rexford, "SoftCell: Scalable and Flexible Cellular Core Network Architecture," in *Proceedings of the 9th international conference on Emerging networking experiments and technologies*, ser. CoNEXT '13. New York, NY, USA: ACM, 2013.

[246] P. Dely, A. Kassler, and N. Bayer, "OpenFlow for wireless mesh networks," in *Computer Communications and Networks (ICCCN), 2011 Proceedings of 20th International Conference on*, 31 2011-aug. 4 2011, pp. 1 –6.

[247] M. J. Yang, S. Y. Lim, H. J. Park, and N. H. Park, "Solving the data overload: Device-to-device bearer control architecture for cellular data offloading," *Vehicular Technology Magazine, IEEE*, vol. 8, no. 1, pp. 31–39, March 2013.

[248] K.-K. Yap, R. Sherwood, M. Kobayashi, T.-Y. Huang, M. Chan, N. Handigol, N. McKeown, and G. Parulkar, "Blueprint for introducing innovation into wireless mobile networks," in *Proceedings of the second ACM SIGCOMM workshop on Virtualized infrastructure systems and architectures*, ser. VISA '10. New York, NY, USA: ACM, 2010, pp. 25–32.

[249] M. Bansal, J. Mehlman, S. Katti, and P. Levis, "Openradio: a programmable wireless dataplane," in *Proceedings of the first workshop on Hot topics in software defined networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 109–114.

[250] S. Sundaresan, W. de Donato, N. Feamster, R. Teixeira, S. Crawford, and A. Pescapè, "Broadband internet performance: a view from the gateway," *SIGCOMM Comput. Commun. Rev.*, vol. 41, no. 4, pp. 134–145, Aug. 2011.

[251] S. A. Mehdi, J. Khalid, and S. A. Khayam, "Revisiting traffic anomaly detection using software defined networking," in *Proceedings of the 14th international conference on Recent Advances in Intrusion Detection*, ser. RAID'11. Berlin, Heidelberg: Springer-Verlag, 2011, pp. 161–180.

[252] P. Wette and H. Karl, "Which flows are hiding behind my wildcard rule?: adding packet sampling to OpenFlow," in *Proceedings of the ACM SIGCOMM 2013 conference on SIGCOMM*, ser. SIGCOMM '13. New York, NY, USA: ACM, 2013, pp. 541–542.

[253] G. Bianchi, M. Bonola, G. Picierro, S. Pontarelli, and M. Monaci, "StreaMon: a data-plane programming abstraction for Software-defined Stream Monitoring," *ArXiv e-prints*, Nov. 2013.

[254] D. Kreutz, F. M. Ramos, and P. Verissimo, "Towards secure and dependable software-defined networks," in *Proceedings of the second ACM SIGCOMM workshop on Hot topics in software defined networking*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 55–60.

[255] K. Kant, "Data center evolution: A tutorial on state of the art, issues, and challenges," *Computer Networks*, vol. 53, no. 17, pp. 2939 – 2965, 2009, virtualized Data Centers.

[256] A. Greenberg, J. Hamilton, D. A. Maltz, and P. Patel, "The cost of a cloud: Research problems in data center networks," *SIGCOMM Comput. Commun. Rev.*, vol. 39, no. 1, pp. 68–73, Dec. 2008. [Online]. Available: http://doi.acm.org/10.1145/1496091.1496103

[257] M. Bari, R. Boutaba, R. Esteves, L. Granville, M. Podlesny, M. Rabbani, Q. Zhang, and M. Zhani, "Data center network virtualization: A survey," *Communications Surveys Tutorials, IEEE*, vol. 15, no. 2, pp. 909–928, 2013.

[258] P. Calyam, S. Rajagopalan, A. Selvadhurai, S. Mohan, A. Venkataraman, A. Berryman, and R. Ramnath, "Leveraging OpenFlow for resource placement of virtual desktop cloud applications," in *Integrated Network Management (IM 2013), 2013 IFIP/IEEE International Symposium on*, 2013, pp. 311–319.

[259] J. Parraga, "Avior," 2013. [Online]. Available: http://openflow.marist.edu/avior

[260] GlobalNOC, "OESS - Open Exchange Software Suite," 2013. [Online]. Available: http://globalnoc.iu.edu/sdn/oess.html

[261] C. Duckett, "Software Defined Networking: HP has an App Store for that," 2013. [Online]. Available: http://www.zdnet.com/software-defined-networking-hp-has-an-app-store-for-that-7000021365/

[262] HP, "SDN App Store," 2013. [Online]. Available: http://h17007.www1.hp.com/us/en/networking/solutions/technology/sdn/devcenter/#sdnAppstore

[263] B. H. Sigelman, L. A. Barroso, M. Burrows, P. Stephenson, M. Plakal, D. Beaver, S. Jaspan, and C. Shanbhag, "Dapper, a large-scale distributed systems tracing infrastructure," Google, Inc., Tech. Rep., 2010.

[264] L. Layman, M. Diep, M. Nagappan, J. Singer, R. Deline, and G. Venolia, "Debugging revisited: Toward understanding the debugging needs of contemporary software developers," in *Empirical Software Engineering and Measurement, 2013 ACM / IEEE International Symposium on*, Oct 2013, pp. 383–392.

[265] U. Erlingsson, M. Peinado, S. Peter, M. Budiu, and G. Mainar-Ruiz, "Fay: Extensible distributed tracing from kernels to clusters," *ACM Trans. Comput. Syst.*, vol. 30, no. 4, pp. 13:1–13:35, Nov. 2012.

[266] S. Tomaselli and O. Landsiedel, "Towards Lightweight Logging and Replay of Embedded, Distributed Systems," in *Proceedings of Workshop ASCoMS (Architecting Safety in Collaborative Mobile Systems) of the 32nd International Conference on Computer Safety, Reliability and Security*, M. ROY, Ed., Toulouse, France, Sep. 2013.

[267] J. Tan, S. Kavulya, R. Gandhi, and P. Narasimhan, "Visual, log-based causal tracing for performance debugging of mapreduce systems," in *Distributed Computing Systems (ICDCS), 2010 IEEE 30th International Conference on*, June 2010, pp. 795–806.

[268] R. Fonseca, G. Porter, R. H. Katz, S. Shenker, and I. Stoica, "X-trace: a pervasive network tracing framework," in *Proceedings of the 4th USENIX conference on Networked systems design & implementation*, ser. NSDI'07. Berkeley, CA, USA: USENIX Association, 2007, pp. 20–20.

[269] V. Trivedi, "Software development: Debugging and testing," in *How to Speak Tech*. Apress, 2014, pp. 89–95.

[270] A. Anand and A. Akella, "Netreplay: a new network primitive," *SIGMETRICS Perform. Eval. Rev.*, vol. 37, no. 3, pp. 14–19, Jan. 2010.

[271] Y. Zhuang, E. Gessiou, S. Portzer, F. Fund, M. Muhammad, I. Beschastnikh, and J. Cappos, "Netcheck: Network diagnoses from blackbox traces," in *11th USENIX Symposium on Networked Systems Design and Implementation (NSDI 14)*. Seattle, WA: USENIX Association, Apr. 2014, pp. 115–128.

[272] N. Handigol, B. Heller, V. Jeyakumar, D. Maziéres, and N. McKeown, "Where is the debugger for my software-defined network?" in *Proceedings of the First Workshop on Hot Topics in Software Defined Networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 55–60.

[273] A. Wundsam, D. Levin, S. Seetharaman, and A. Feldmann, "OFRewind: enabling record and replay troubleshooting for networks," in *Proceedings of the 2011 USENIX conference on USENIX annual technical conference*, ser. USENIXATC'11. Berkeley, CA, USA: USENIX Association, 2011, pp. 29–29.

[274] M. Canini, D. Venzano, P. Perešíni, D. Kostić, and J. Rexford, "A NICE way to test OpenFlow applications," in *Proceedings of the 9th USENIX conference on Networked Systems Design and Implementation*, ser. NSDI'12. Berkeley, CA, USA: USENIX Association, 2012, pp. 10–10.

[275] C. Rotsos, N. Sarrar, S. Uhlig, R. Sherwood, and A. W. Moore, "OFLOPS: an open framework for OpenFlow switch evaluation," in *Proceedings of the 13th international conference on Passive and Active Measurement*, ser. PAM'12. Berlin, Heidelberg: Springer-Verlag, 2012, pp. 85–95.

[276] E. Al-Shaer and S. Al-Haj, "FlowChecker: configuration analysis and verification of federated OpenFlow infrastructures," in *Proceedings of the 3rd ACM workshop on Assurable and usable security configuration*, ser. SafeConfig '10. New York, NY, USA: ACM, 2010, pp. 37–44.

[277] A. Khurshid, W. Zhou, M. Caesar, and P. B. Godfrey, "VeriFlow: verifying network-wide invariants in real time," in *HotSDN*, 2012.

[278] M. Kuzniar, M. Canini, and D. Kostic, "OFTEN Testing OpenFlow Networks," in *Proceedings of the 1st European Workshop on Software Defined Networks (EWSDN)*, 2012.

[279] G. Altekar and I. Stoica, "Focus Replay Debugging Effort On the Control Plane," Electrical Engineering and Computer Sciences University of California at Berkeley, Tech. Rep., May 2010.

[280] N. Handigol, B. Heller, V. Jeyakumar, D. Mazières, and N. McKeown, "I know what your packet did last hop: Using packet histories to troubleshoot networks," in *11th USENIX Symposium on Networked Systems Design and Implementation (NSDI 14)*. Seattle, WA: USENIX Association, Apr. 2014, pp. 71–85.

[281] N. Ruchansky and D. Proserpio, "A (not) nice way to verify the OpenFlow switch specification: formal modelling of the OpenFlow switch using alloy," in *Proceedings of the ACM SIGCOMM 2013 conference on SIGCOMM*, ser. SIGCOMM '13. New York, NY, USA: ACM, 2013, pp. 527–528.

[282] H. Zeng, S. Zhang, F. Ye, V. Jeyakumar, M. Ju, J. Liu, N. McKeown, and A. Vahdat, "Libra: Divide and conquer to verify forwarding tables in huge networks," in *11th USENIX Symposium on Networked Systems Design and Implementation (NSDI 14)*. Seattle, WA: USENIX Association, Apr. 2014, pp. 87–99.

[283] P. Kazemian, G. Varghese, and N. McKeown, "Header space analysis: Static checking for networks," in *Proceedings of the 9th USENIX Conference on Networked Systems Design and Implementation*, ser. NSDI'12. Berkeley, CA, USA: USENIX Association, 2012, pp. 9–9.

[284] H. Mai, A. Khurshid, R. Agarwal, M. Caesar, P. B. Godfrey, and S. T. King, "Debugging the data plane with anteater," *SIGCOMM Comput. Commun. Rev.*, vol. 41, no. 4, pp. 290–301, Aug. 2011.

[285] P. Kazemian, M. Chang, H. Zeng, G. Varghese, N. McKeown, and S. Whyte, "Real time network policy checking using header space analysis," in *Proceedings of the 10th USENIX conference on Networked Systems Design and Implementation*, ser. NSDI'13. Berkeley, CA, USA: USENIX Association, 2013, pp. 99–112.

[286] N. Handigol, B. Heller, V. Jeyakumar, B. Lantz, and N. McKeown, "Reproducible network experiments using container-based emulation," in *Proceedings of the 8th international conference on Emerging networking experiments and technologies*, ser. CoNEXT '12. New York, NY, USA: ACM, 2012, pp. 253–264.

[287] V. Antonenko and R. Smelyanskiy, "Global network modelling based on Mininet approach." in *Proceedings of the second ACM SIGCOMM workshop on Hot topics in software defined networking*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 145–146.

[288] J. Teixeira, G. Antichi, D. Adami, A. Del Chiaro, S. Giordano, and A. Santos, "Datacenter in a box: Test your sdn cloud-datacenter controller at home," in *Software Defined Networks (EWSDN), 2013 Second European Workshop on*, Oct 2013, pp. 99–104.

[289] ns-3 project, "ns-3: OpenFlow switch support," 2013. [Online]. Available: http://www.nsnam.org/docs/release/3.13/models/html/openflow-switch.html

[290] J. Sommers, R. Bowden, B. Eriksson, P. Barford, M. Roughan, and N. Duffield, "Efficient network-wide flow record generation," in *INFOCOM, 2011 Proceedings IEEE*, 2011, pp. 2363–2371.

[291] ucb-sts, "STS - SDN troubleshooting simulator," 2013. [Online]. Available: http://ucb-sts.github.io/sts/

[292] R. Sherwood and K.-K. Yap, "Cbench controller benchmarker," 2011. [Online]. Available: http://www.openflow.org/wk/index.php/Oflops

[293] M. Jarschel, F. Lehrieder, Z. Magyari, and R. Pries, "A flexible OpenFlow-controller benchmark," in *Proceedings of the 2012 European Workshop on Software Defined Networking*, ser. EWSDN '12. Washington, DC, USA: IEEE Computer Society, 2012, pp. 48–53. [Online]. Available: http://dx.doi.org/10.1109/EWSDN.2012.15

[294] M. Gupta, J. Sommers, and P. Barford, "Fast, accurate simulation for sdn prototyping," in *Proceedings of the Second ACM SIGCOMM Workshop on Hot Topics in Software Defined Networking*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 31–36.

[295] A. R. Curtis, J. C. Mogul, J. Tourrilhes, P. Yalagandula, P. Sharma, and S. Banerjee, "DevoFlow: scaling flow management for high-performance networks," *Comput. Commun. Rev.*, vol. 41, no. 4, pp. 254–265, Aug. 2011.

[296] C. J. Casey, A. Sutton, and A. Sprintson, "tinyNBI: Distilling an API from essential OpenFlow abstractions," *CoRR*, vol. abs/1403.6644, 2014.

[297] L. Ogrodowczyk et al., "Hardware abstraction layer for non-OpenFlow capable devices," in *The 30th Trans European Research and Education Networking Conference (TNC)*. TERENA, 2014.

[298] A. Vidal, C. E. Rothenberg, and F. L. Verdi, "The libfluid OpenFlow driver implementation," in *SBRC*, 2014.

[299] M. APPELMAN and M. D. BOER, "Performance Analysis of OpenFlow Hardware," University of Amsterdam, Tech. Rep., Feb 2012.

[300] K. Kannan and S. Banerjee, "Compact tcam: Flow entry compaction in tcam for power aware sdn," in *Distributed Computing and Networking*, ser. Lecture Notes in Computer Science, D. Frey, M. Raynal, S. Sarkar, R. Shyamasundar, and P. Sinha, Eds. Springer Berlin Heidelberg, 2013, vol. 7730, pp. 439–444.

[301] J. Liao, "SDN System Performance," June 2012. [Online]. Available: http://pica8.org/blogs/?p=201

[302] B. Agrawal and T. Sherwood, "Modeling tcam power for next generation network devices," in *Performance Analysis of Systems and Software, 2006 IEEE International Symposium on*, 2006, pp. 120–129.

[303] B. Owens, "OpenFlow Switching Performance: Not All TCAM Is Created Equal," February 2013. [Online]. Available: http://packetpushers.net/openflow-switching-performance-not-all-tcam-is-created-equal/

[304] B. Salisbury, "TCAMs and OpenFlow - What Every SDN Practitioner Must Know," Jul. 2012. [Online]. Available: http://www.sdncentral.com/technology/sdn-openflow-tcam-need-to-know/2012/07/

[305] B. Stephens, A. Cox, W. Felter, C. Dixon, and J. Carter, "Past: scalable ethernet for data centers," in *Proceedings of the 8th international conference on Emerging networking experiments and technologies*, ser. CoNEXT '12. New York, NY, USA: ACM, 2012, pp. 49–60.

[306] M. Kobayashi, S. Seetharaman, G. Parulkar, G. Appenzeller, J. Little, J. van Reijendam, P. Weissmann, and N. McKeown, "Maturing of OpenFlow and software-defined networking through deployments," *Computer Networks*, vol. 61, no. 0, pp. 151 – 175, 2014, special issue on Future Internet Testbeds Part I. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S138912861300371X

[307] J. C. Mogul and P. Congdon, "Hey, you darned counters!: Get off my asic!" in *Proceedings of the First Workshop on Hot Topics in Software Defined Networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 25–30.

[308] P. Bosshart, G. Gibb, H.-S. Kim, G. Varghese, N. McKeown, M. Izzard, F. Mujica, and M. Horowitz, "Forwarding metamorphosis: fast programmable match-action processing in hardware for SDN," in *Proceedings of the ACM SIGCOMM 2013 conference on SIGCOMM*, ser. SIGCOMM '13. New York, NY, USA: ACM, 2013, pp. 99–110.

[309] O. Ferkouss, I. Snaiki, O. Mounaouar, H. Dahmouni, R. Ben Ali, Y. Lemieux, and C. Omar, "A 100gig network processor platform for openflow," in *Network and Service Management (CNSM), 2011 7th International Conference on*, 2011, pp. 1–4.

[310] J. Naous, D. Erickson, G. A. Covington, G. Appenzeller, and N. McKeown, "Implementing an OpenFlow switch on the netfpga platform," in *Proceedings of the 4th ACM/IEEE Symposium on Architectures for Networking and Communications Systems*, ser. ANCS '08. New York, NY, USA: ACM, 2008, pp. 1–9.

[311] G. Memon, M. Varvello, R. Laufer, T. Lakshman, J. Li, and M. Zhang, "FlashFlow: a GPU-based Fully Programmable OpenFlow Switch," University of Oregon, Tech. Rep., 2013.

[312] Y. Luo, P. Cascon, E. Murray, and J. Ortega, "Accelerating OpenFlow switching with network processors," in *Proceedings of the 5th ACM/IEEE Symposium on Architectures for Networking and Communications Systems*, ser. ANCS '09. New York, NY, USA: ACM, 2009, pp. 70–71.

[313] A. Rostami, T. Jungel, A. Koepsel, H. Woesner, and A. Wolisz, "Oran: OpenFlow routers for academic networks," in *High Performance Switching and Routing (HPSR), 2012 IEEE 13th International Conference on*, 2012, pp. 216–222.

[314] G. Pongracz, L. Molnar, and Z. Kis, "Removing roadblocks from SDN: OpenFlow software switch performance on intel DPDK," in *Software Defined Networks (EWSDN), 2013 Second European Workshop on*, Oct 2013, pp. 62–67.

[315] B. Stephens, "Designing Scalable Networks for Future Large Datacenters," Ph.D. dissertation, Rice University, May 2012.

[316] Y. Li, D. Zhang, K. Huang, D. He, and W. Long, "A memory-efficient parallel routing lookup model with fast updates," *Comput. Commun.*, vol. 38, pp. 60–71, Feb. 2014.

[317] N. Katta, J. Rexford, and D. Walker, "Infinite CacheFlow in Software-Defined Networks," Princeton School of Engineering and Applied Science, Tech. Rep., October 2013.

[318] Intel Processors, "Software Defined Networking and Softwarebased Services with Intel Processors," Intel Corporation, 2012. [Online]. Available: http://www.intel.com/content/dam/doc/white-paper/communications-ia-software-defined-networking-paper.pdf

[319] G. Brebner, "Softly defined networking," in *Proceedings of the eighth ACM/IEEE symposium on Architectures for networking and communications systems*, ser. ANCS '12. New York, NY, USA: ACM, 2012, pp. 1–2.

[320] C. Matsumoto, "Arista's new hardware packs SDN," 2012. [Online]. Available: http://www.lightreading.com/document.asp?doc_id=225028

[321] A. Bianco, R. Birke, L. Giraudo, and M. Palacin, "OpenFlow Switching: Data Plane Performance," in *Communications (ICC), 2010 IEEE International Conference on*, may 2010, pp. 1 –5.

[322] Intel Corporation, "Intel data plane development kit," 2014. [Online]. Available: http://www.intel.com/content/dam/www/public/us/en/documents/guides/intel-dpdk-getting-started-guide.pdf

[323] A. Sivaraman, K. Winstein, S. Subramanian, and H. Balakrishnan, "No Silver Bullet: Extending SDN to the Data Plane," in *Twelfth ACM Workshop on Hot Topics in Networks (HotNets-XII)*, College Park, MD, November 2013.

[324] S. Hauger, T. Wild, A. Mutter, A. Kirstaedter, K. Karras, R. Ohlendorf, F. Feller, and J. Scharf, "Packet processing at 100 gbps and beyond - challenges and perspectives," in *Photonic Networks, 2009 ITG Symposium on*, May 2009, pp. 1–10.

[325] P. Bosshart, D. Daly, M. Izzard, N. McKeown, J. Rexford, D. Talayco, A. Vahdat, G. Varghese, and D. Walker, "Programming protocol-independent packet processors," *CoRR*, vol. abs/1312.1719, 2013.

[326] S. Azodolmolky, P. Wieder, and R. Yahyapour, "Performance evaluation of a scalable software-defined networking deployment," in *Software Defined Networks (EWSDN), 2013 Second European Workshop on*, Oct 2013, pp. 68–74.

[327] A. AuYoung, S. Banerjee, J. Lee, J. C. Mogul, J. Mudigonda, L. Popa, P. Sharma, and Y. Turner, "Corybantic: Towards the Modular Composition of SDN Control Programs," in *Twelfth ACM Workshop on Hot Topics in Networks (HotNets-XII)*, College Park, MD, November 2013.

[328] M. Desai and T. Nandagopal, "Coping with link failures in centralized control plane architectures," in *Communication Systems and Networks (COMSNETS), 2010 Second International Conference on*. IEEE, 2010, pp. 1–10.

[329] H. Kim, J. Santos, Y. Turner, M. Schlansker, J. Tourrilhes, and N. Feamster, "Coronet: Fault tolerance for software defined networks," in *Network Protocols (ICNP), 2012 20th IEEE International Conference on*, Oct 2012, pp. 1–2.

[330] J. Kempf, E. Bellagamba, A. Kern, D. Jocha, A. Takacs, and P. Skoldstrom, "Scalable fault management for OpenFlow," in *Communications (ICC), 2012 IEEE International Conference on*, June 2012, pp. 6606–6610.

[331] S. Sharma, D. Staessens, D. Colle, M. Pickavet, and P. Demeester, "Openflow: Meeting carrier-grade recovery requirements," *Comput. Commun.*, vol. 36, no. 6, pp. 656–665, Mar. 2013.

[332] A. Panda, C. Scott, A. Ghodsi, T. Koponen, and S. Shenker, "Cap for networks," in *Proceedings of the second ACM SIGCOMM workshop on Hot topics in software defined networking*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 91–96.

[333] M. Kuźniar, P. Perešíni, N. Vasić, M. Canini, and D. Kostić, "Automatic failure recovery for software-defined networks," in *Proceedings of the Second ACM SIGCOMM Workshop on Hot Topics in Software Defined Networking*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 159–160.

[334] A. Dixit, F. Hao, S. Mukherjee, T. Lakshman, and R. Kompella, "Towards an elastic distributed SDN controller," in *Proceedings of the second ACM SIGCOMM workshop on Hot topics in software defined networking*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 7–12.

[335] R. Ramos, M. Martinello, and C. Esteve Rothenberg, "SlickFlow: Resilient source routing in data center networks unlocked by OpenFlow," in *Local Computer Networks (LCN), 2013 IEEE 38th Conference on*, Oct 2013, pp. 606–613.

[336] J. T. Araújo, R. Landa, R. G. Clegg, and G. Pavlou, "Software-defined network support for transport resilience," in *IEEE NOMS*, 2014.

[337] E. Brewer, "Pushing the cap: Strategies for consistency and availability," *Computer*, vol. 45, no. 2, pp. 23–29, Feb. 2012.

[338] T. Benson, A. Akella, and D. A. Maltz, "Network traffic characteristics of data centers in the wild," in *Proceedings of the 10th ACM SIGCOMM Conference on Internet Measurement*, ser. IMC '10. New York, NY, USA: ACM, 2010, pp. 267–280.

[339] M. Yu, J. Rexford, M. J. Freedman, and J. Wang, "Scalable flow-based networking with difane," *SIGCOMM Comput. Commun. Rev.*, vol. 41, no. 4, pp. –, Aug. 2010.

[340] M. F. Bari, A. R. Roy, S. R. Chowdhury, Q. Zhang, M. F. Zhani, R. Ahmed, and R. Boutaba, "Dynamic controller provisioning in software defined networks," in *9th International Conference on Network and Service Management*, ser. CNSM'13, 2013.

[341] V. Yazici, M. O. Sunay, and A. O. Ercan, "Controlling a software-defined network via distributed controllers," in *Proceedings of the Conference on Implementing Future Media Internet Towards New Horizons*, ser. 2012 NEM SUMMIT. Heidelberg, Germany: Eurescom GmbH, Oct. 2012, pp. 16–22.

[342] D. Levin, A. Wundsam, B. Heller, N. Handigol, and A. Feldmann, "Logically centralized? state distribution trade-offs in software defined networks," in *Proceedings of the first workshop on Hot topics in software defined networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 1–6.

[343] M. Jarschel, S. Oechsner, D. Schlosser, R. Pries, S. Goll, and P. Tran-Gia, "Modeling and performance evaluation of an OpenFlow architecture," in *Teletraffic Congress (ITC), 2011 23rd International*, Sept 2011, pp. 1–7.

[344] R. Pries, M. Jarschel, and S. Goll, "On the usability of OpenFlow in data center environments," in *Communications (ICC), 2012 IEEE International Conference on*, June 2012, pp. 5533–5537.

[345] J. Hwang, K. K. Ramakrishnan, and T. Wood, "Netvm: High performance and flexible networking using virtualization on commodity platforms," in *11th USENIX Symposium on Networked Systems Design and Implementation (NSDI 14)*. Seattle, WA: USENIX Association, Apr. 2014, pp. 445–458.

[346] Y. Dong, Z. Yu, and G. Rose, "Sr-iov networking in xen: Architecture, design and implementation," in *Proceedings of the First Conference on I/O Virtualization*, ser. WIOV'08. Berkeley, CA, USA: USENIX Association, 2008, pp. 10–10.

[347] B. Heller, R. Sherwood, and N. McKeown, "The controller placement problem," in *Proceedings of the first workshop on Hot topics in software defined networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 7–12.

[348] S. Azodolmolky, R. Nejabati, M. Pazouki, P. Wieder, R. Yahyapour, and D. Simeonidou, "An analytical model for software defined networking: A network calculus-based approach," in *IEEE GlobeCom 2013*, Oct. 2013.

[349] M. Marchetti, M. Colajanni, M. Messori, L. Aniello, and Y. Vigfusson, "Cyber attacks on financial critical infrastructures," in *Collaborative Financial Infrastructure Protection*, R. Baldoni and G. Chockler, Eds. Springer Berlin Heidelberg, 2012, pp. 53–82.

[350] S. Amin and A. Giacomoni, "Smart grid, safe grid," *Power and Energy Magazine, IEEE*, vol. 10, no. 1, pp. 33–40, 2012.

[351] A. Nicholson, S. Webber, S. Dyer, T. Patel, and H. Janicke, "SCADA security in the light of cyber-warfare," *Computers & Security*, vol. 31, no. 4, pp. 418 – 436, 2012.

[352] K.-K. R. Choo, "The cyber threat landscape: Challenges and future research directions," *Computers & Security*, vol. 30, no. 8, pp. 719 – 731, 2011.

[353] D. Kushner, "The Real Story of Stuxnet," *IEEE Spectrum*, Mar 2013. [Online]. Available: http://spectrum.ieee.org/telecom/security/the-real-story-of-stuxnet

[354] R. Perez-Pena, "Universities face a rising barrage of cyberattacks," Jul. 2013. [Online]. Available: http://www.nytimes.com/2013/07/17/education/barrage-of-cyberattacks-challenges-campus-culture.html

[355] C. Tankard, "Advanced persistent threats and how to monitor and deter them," *Network Security*, vol. 2011, no. 8, pp. 16 – 19, 2011.

[356] S. Sorensen, "Security implications of software-defined networks," 2012. [Online]. Available: http://www.fiercetelecom.com/story/security-implications-software-defined-networks/2012-05-14

[357] S. M. Kerner, "Is SDN Secure?" Mar 2013. [Online]. Available: http://www.enterprisenetworkingplanet.com/netsecur/is-sdn-secure.html

[358] A. Agapi, K. Birman, R. Broberg, C. Cotton, T. Kielmann, M. Millnert, R. Payne, R. Surton, and R. van Renesse, "Routers for the cloud: Can the internet achieve 5-nines availability?" *Internet Computing, IEEE*, vol. 15, no. 5, pp. 72–77, 2011.

[359] R. Kloti, "Openflow: A security analysis," Master's thesis, Swiss Federal Institute of Technology Zurich (ETH), Zurich, Swiss, 2013.

[360] M. Wasserman and S. Hartman, "Security analysis of the open networking foundation (onf) OpenFlow switch specification," Internet Engineering Task Force, Apr 2013. [Online]. Available: https://datatracker.ietf.org/doc/draft-mrw-sdnsec-openflow-analysis/

[361] S. Shin and G. Gu, "Attacking software-defined networks: A first feasibility study," in *Proceedings of the second workshop on Hot topics in software defined networks*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 1–2.

[362] K. Benton, L. J. Camp, and C. Small, "OpenFlow vulnerability assessment," in *Proceedings of the second ACM SIGCOMM workshop on Hot topics in software defined networking*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 151–152.

[363] S. Hernan, S. Lambert, T. Ostwald, and A. Shostack, "Uncover security design flaws using the STRIDE approach," *MSDN Magazine*, Nov. 2006.

[364] W. J. Bolosky, D. Bradshaw, R. B. Haagens, N. P. Kusters, and P. Li, "Paxos replicated state machines as the basis of a high-performance data store," in *Symposium on Networked Systems Design and Implementation (NSDI)*, 2011, pp. 141–154.

[365] P. Sousa, A. Bessani, M. Correia, N. Neves, and P. Verissimo, "Highly available intrusion-tolerant services with proactive-reactive recovery," *Parallel and Distributed Systems, IEEE Transactions on*, vol. 21, no. 4, pp. 452–465, April 2010.

[366] R. Chua, "SDN security: Oxymoron? new interview with phil porras of SRI international," 2013. [Online]. Available: http://www.sdncentral.com/technology/sdn-security-oxymoron-phil-porras-sri/2013/02/

[367] J. Korniak, "The GMPLS controlled optical networks as industry communication platform," *Industrial Informatics, IEEE Transactions on*, vol. 7, no. 4, pp. 671–678, Nov 2011.

[368] P. Fonseca, R. Bennesby, E. Mota, and A. Passito, "A replication component for resilient OpenFlow-based networking," in *Network Operations and Management Symposium (NOMS), 2012 IEEE*, april 2012, pp. 933 –939.

[369] S. Vissicchio, L. Vanbever, and O. Bonaventure, "Opportunities and research challenges of hybrid software defined networks," *SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 2, pp. 70–75, Apr. 2014.

[370] C. E. Rothenberg, M. R. Nascimento, M. R. Salvador, C. N. A. Corrêa, S. Cunha de Lucena, and R. Raszuk, "Revisiting routing control platforms with the eyes and muscles of software-defined networking," in *Proceedings of the First Workshop on Hot Topics in Software Defined Networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 13–18.

[371] C. E. Rothenberg, A. Vidal, M. R. Salvador, C. Correa, S. Lucena, F. Farias, E. Cerqueira, and A. Abelem, "Hybrid networking towards a software defined era," in Network Innovation through OpenFlow and SDN: Principles and Design book, Taylor & Francis LLC, CRC Press., 2014.

[372] D. Levin, M. Canini, S. Schmid, and A. Feldmann, "Incremental SDN deployment in enterprise networks," in *Proceedings of the ACM SIGCOMM 2013 conference on SIGCOMM*, ser. SIGCOMM '13. New York, NY, USA: ACM, 2013, pp. 473–474.

[373] H. Lu, N. Arora, H. Zhang, C. Lumezanu, J. Rhee, and G. Jiang, "Hybnet: Network manager for a hybrid network infrastructure," in *Proceedings of the Industrial Track of the 13th ACM/IFIP/USENIX International Middleware Conference*, ser. Middleware Industry '13. New York, NY, USA: ACM, 2013, pp. 6:1–6:6.

[374] P. Bernier, "NTT Recognized with IBC Award for SDN-based HDTV Service," September 2013. [Online]. Available: http://www.sdnzone.com/topics/software-defined-network/articles/353466-ntt-recognized-with-ibc-award-sdn-based-hdtv.htm

[375] NTT DATA, "Infrastructure Services," 2014. [Online]. Available: http://www.nttdata.com/global/en/services/infrastructure/solution.html

[376] M. Wagner, "NTT Taps SDN to Enhance Cloud Flexibility," March 2014. [Online]. Available: http://www.lightreading.com/ntt-taps-sdn-to-enhance-cloud-flexibility/d/d-id/708133

[377] AT&T Inc., "AT&T Introduces the "User-Defined Network Cloud": A Vision for the Network of the Future," February 2014. [Online]. Available: http://www.att.com/gen/press-room?pid=25274&cdvn=news&newsarticleid=37439&mapcode=

[378] B. Naudts, M. Kind, F. Westphal, S. Verbrugge, D. Colle, and M. Pickavet, "Techno-economic analysis of software defined networking as architecture for the virtualization of a mobile network," in *Software Defined Networking (EWSDN), 2012 European Workshop on*, Oct 2012, pp. 67–72.

[379] ONF, "Operator network monetization through OpenFlow-enabled SDN," Apr. 2013. [Online]. Available: https://www.opennetworking.org/images/stories/downloads/sdn-resources/solution-briefs/sb-network-monetization.pdf

[380] P. Skoldstrom and W. John, "Implementation and evaluation of a carrier-grade OpenFlow virtualization scheme," in *Software Defined Networks (EWSDN), 2013 Second European Workshop on*, Oct 2013, pp. 75–80.

[381] H. H. Gharakheili and V. Sivaraman, "Virtualizing National Broadband Access Infrastructure," in *Proceedings of the 9th international conference on Emerging networking experiments and technologies*, ser. CoNEXT '13. New York, NY, USA: ACM, 2013.

[382] Pacnet, "Pacnet Offers First Pan-Asia Network-as-a-Service Architecture," 2013. [Online]. Available: http://www.cmo.com.au/mediareleases/17701/pacnet-offers-first-pan-asia-network-as-a-service/

[383] N. D. Corporation, "NTT DATA Advance in SDN Business Provides Highly-Flexible Control of Network by Software," June 2012. [Online]. Available: http://www.nttdata.com/global/en/news-center/pressrelease/2012/060801.html

[384] S. Das, A. Sharafat, G. Parulkar, and N. McKeown, "MPLS with a simple OPEN control plane," in *Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2011 and the National Fiber Optic Engineers Conference*, 2011, pp. 1–3.

[385] M. Casado, T. Koponen, S. Shenker, and A. Tootoonchian, "Fabric: a retrospective on evolving SDN," in *Proceedings of the first workshop on Hot topics in software defined networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012, pp. 85–90.

[386] M. Martinello, M. Ribeiro, R. de Oliveira, and R. de Angelis Vitoi, "Keyflow: a prototype for evolving SDN toward core network fabrics," *Network, IEEE*, vol. 28, no. 2, pp. 12–19, March 2014.

[387] N. Feamster, J. Rexford, S. Shenker, R. Clark, R. Hutchins, D. Levin, and J. Bailey, "SDX: A software-defined internet exchange," IETF 86 Proceedings, Orlando, US, March 2013. [Online]. Available: http://www.ietf.org/proceedings/86/slides/slides-86-sdnrg-6

[388] J. P. Stringer, Q. Fu, C. Lorier, R. Nelson, and C. E. Rothenberg, "Cardigan: deploying a distributed routing fabric," in *Proceedings of the second ACM SIGCOMM workshop on Hot topics in software defined networking*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 169–170.

[389] C.-Y. Hong, S. Kandula, R. Mahajan, M. Zhang, V. Gill, M. Nanduri, and R. Wattenhofer, "Achieving high utilization with software-driven WAN," in *Proceedings of the ACM SIGCOMM 2013 conference on SIGCOMM*, ser. SIGCOMM '13. New York, NY, USA: ACM, 2013, pp. 15–26.

[390] D. Staessens, S. Sharma, D. Colle, M. Pickavet, and P. Demeester, "Software Defined Networking: Meeting Carrier Grade Requirements," in *Local Metropolitan Area Networks (LANMAN), 2011 18th IEEE Workshop on*, oct. 2011, pp. 1 –6.

[391] S. Sharma, D. Staessens, D. Colle, M. Pickavet, and P. Demeester, "A demonstration of automatic bootstrapping of resilient OpenFlow networks," in *Integrated Network Management (IM 2013), 2013 IFIP/IEEE International Symposium on*, 2013, pp. 1066–1067.

[392] R. Niranjan Mysore, A. Pamboris, N. Farrington, N. Huang, P. Miri, S. Radhakrishnan, V. Subramanya, and A. Vahdat, "PortLand: A scalable fault-tolerant layer 2 data center network fabric," *SIGCOMM Comput. Commun. Rev.*, vol. 39, no. 4, pp. 39–50, Aug. 2009.

[393] A. Greenberg, J. R. Hamilton, N. Jain, S. Kandula, C. Kim, P. Lahiri, D. A. Maltz, P. Patel, and S. Sengupta, "VL2: a scalable and flexible data center network," in *Proceedings of the ACM SIGCOMM 2009 conference on Data communication*, ser. SIGCOMM '09. New York, NY, USA: ACM, 2009, pp. 51–62.

[394] A. Sadasivarao, S. Syed, P. Pan, C. Liou, I. Monga, C. Guok, and A. Lake, "Bursting data between data centers: Case for transport SDN," in *High-Performance Interconnects (HOTI), 2013 IEEE 21st Annual Symposium on*, 2013, pp. 87–90.

[395] J. C. Tanner, "Taking SDN to transport and beyond," 2013. [Online]. Available: http://www.telecomasia.net/content/taking-sdn-transport-and-beyond

[396] S. Elby, "Carrier Vision of SDN," 2012. [Online]. Available: http://www.brighttalk.com/webcast/6985/58527

[397] B. Anwer, T. Benson, N. Feamster, D. Levin, and J. Rexford, "A slick control plane for network middleboxes," in *Proceedings of the second ACM SIGCOMM workshop on Hot topics in software defined networking*, ser. HotSDN '13. New York, NY, USA: ACM, 2013, pp. 147–148.

[398] C. Gerlach and H.-M. Foisel, "OIF carrier WG requirements on transport networks in SDN architectures," Optical Internetworking Forum, The Optical Internetworking Forum, 48377 Fremont Blvd., Suite 117, Fremont, CA 94538, Tech. Rep., September 2013.

[399] L. Velasco, A. Asensio, J. Berral, A. Castro, and V. Lopez, "Towards a carrier SDN: An example for elastic inter-datacenter connectivity," in *Optical Communication (ECOC 2013), 39th European Conference and Exhibition on*, 2013, pp. 1–3.

[400] A. Alba, G. Alatorre, C. Bolik, A. Corrao, T. Clark, S. Gopisetty, R. Haas, R. Kat, B. Langston, N. Mandagere, D. Noll, S. Padbidri, R. Routray, Y. Song, C. Tan, and A. Traeger, "Efficient and agile storage management in software defined environments," *IBM Journal of Research and Development*, vol. 58, no. 2, pp. 1–12, March 2014.

[401] W. Arnold, D. Arroyo, W. Segmuller, M. Spreitzer, M. Steinder, and A. Tantawi, "Workload orchestration and optimization for software defined environments," *IBM Journal of Research and Development*, vol. 58, no. 2, pp. 1–12, March 2014.

[402] C. Dixon, D. Olshefski, V. Jain, C. DeCusatis, W. Felter, J. Carter, M. Banikazemi, V. Mann, J. Tracey, and R. Recio, "Software defined networking to support the software defined environment," *IBM Journal of Research and Development*, vol. 58, no. 2, pp. 1–14, March 2014.

[403] IBM Systems and Technology Group, "IBM software defined network for virtual environments," IBM Corporation, Tech. Rep., January 2014.

[404] IBM Systems, "Manage all workloads with an efficient, scalable software defined environment (SDE)," 2014. [Online]. Available: http://www-03.ibm.com/systems/infrastructure/us/en/software-defined-environment/

[405] A. Lara, A. Kolasani, and B. Ramamurthy, "Network innovation using OpenFlow: A survey," *Communications Surveys Tutorials, IEEE*, vol. 16, no. 1, pp. 493–512, First 2014.

[406] Y. Jarraya, T. Madi, and M. Debbabi, "A survey and a layered taxonomy of software-defined networking," *Communications Surveys Tutorials, IEEE*, vol. PP, no. 99, pp. 1–1, 2014.

[407] B. Nunes, M. Mendonca, X. Nguyen, K. Obraczka, and T. Turletti, "A survey of software-defined networking: Past, present, and future of programmable networks," *Communications Surveys Tutorials, IEEE*, vol. PP, no. 99, pp. 1–18, 2014.

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