

Survey on Network Virtualization Hypervisors for Software Defined Networking

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Abstract—Software defined networking (SDN) has emerged as a promising paradigm for making the control of communication networks flexible. SDN separates the data packet forwarding plane, i.e., the data plane, from the control plane and employs a central controller. Network virtualization allows the flexible sharing of physical networking resources by multiple users (tenants). Each tenant runs its own applications over its virtual network, i.e., its slice of the actual physical network. The virtualization of SDN networks promises to allow networks to leverage the combined benefits of SDN networking and network virtualization and has therefore attracted significant research attention in recent years. A critical component for virtualizing SDN networks is an SDN hypervisor that abstracts the underlying physical SDN network into multiple logically isolated virtual SDN networks (vSDNs), each with its own controller. We comprehensively survey hypervisors for SDN networks in this paper. We categorize the SDN hypervisors according to their architecture into centralized and distributed hypervisors. We furthermore sub-classify the hypervisors according to their execution platform into hypervisors running exclusively on general-purpose compute platforms, or on a combination of general-purpose compute platforms with general- or special-purpose network elements. We exhaustively compare the network attribute abstraction and isolation features of the existing SDN hypervisors. As part of the future research agenda, we outline the development of a performance evaluation framework for SDN hypervisors.

Index Terms—Centralized hypervisor, distributed hypervisor, multi-tenancy, network attribute abstraction, network attribute isolation, network virtualization, software defined networking.

I. INTRODUCTION

A. Hypervisors: From Virtual Machines to Virtual Networks

HYPERVISORS (also known as virtual machine monitors) have initially been developed in the area of virtual computing to monitor virtual machines [1]–[3]. Multiple virtual machines can operate on a given computing platform. For instance, with full virtualization, multiple virtual machines, each with its own guest operating system, are running on a given (hardware, physical) computing platform [4]–[6]. Aside from monitoring the virtual machines, the hypervisor allocates resources on the physical computing platform, e.g., compute

cycles on central processing units (CPUs), to the individual virtual machines. The hypervisor typically relies on an abstraction of the physical computing platform, e.g., a standard instruction set, for interfacing with the physical computing platform [7]. Virtual machines have become very important in computing as they allow applications to flexibly run their operating systems and programs without worrying about the specific details and characteristics of the underlying computing platform, e.g., processor hardware properties.

Analogously, virtual networks have recently emerged to flexibly allow for new network services without worrying about the specific details of the underlying (physical) network, e.g., the specific underlying networking hardware [8]. Also, through virtualization, multiple virtual networks can flexibly operate over the same physical network infrastructure. In the context of virtual networking, a hypervisor monitors the virtual networks and allocates networking resources, e.g., link capacity and buffer capacity in switching nodes, to the individual virtual networks (slices of the overall network) [9]–[11].

Software defined networking (SDN) is a networking paradigm that separates the control plane from the data (forwarding) plane, centralizes the network control, and defines open, programmable interfaces [12]. The open, programmable interfaces allow for flexible interactions between the networking applications and the underlying physical network (i.e., the data plane) that is employed to provide networking services to the applications. In particular, the OpenFlow (OF) protocol [13] provides a standardized interface between the control plane and the underlying physical network (data plane). The OF protocol thus abstracts the underlying network, i.e., the physical network that forwards the payload data. The standardized data-to-control plane interface provided by the OF protocol has made SDN a popular paradigm for network virtualization.

B. Combining Network Virtualization and Software Defined Networking

Using the OF protocol, a hypervisor can establish multiple *virtual SDN networks (vSDNs)* based on a given physical network. Each vSDN corresponds to a “slice” of the overall network. The virtualization of a given physical SDN network infrastructure through a hypervisor allows multiple tenants (such as service providers and other organizations) to share the SDN network infrastructure. Each tenant can operate its own virtual SDN network, i.e., its own network operating system, independent of the other tenants.

Virtual SDN networks are foreseen as enablers for future networking technologies in fifth generation (5G) wireless

Manuscript received May 28, 2015; revised September 2, 2015; accepted October 3, 2015. Date of publication October 9, 2015; date of current version January 27, 2016.

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Digital Object Identifier 10.1109/COMST.2015.2489183

TABLE I
SUMMARY OF MAIN ACRONYMS

A-CPI	Application-Controller Plane Interface [31], [32]
API	Application Programmers Interface
D-CPI	Data-Controller Plane Interface [31], [32]
IETF	Internet Engineering Task Force
MPLS	Multiple Protocol Label Switching [33]
NE	Network Element
OF	OpenFlow [34]–[36]
SDN	Software Defined Networking, or Software Defined Network, depending on context
TCAM	Ternary Content Addressable Memory [37]
VLAN	Virtual Local Area Network
vSDN	virtual Software Defined Network
WDM	Wavelength Division Multiplexing

networks [14], [15]. Different services, e.g., voice and video, can run on isolated virtual slices to improve the service quality and overall network performance [16]. Furthermore, virtual slices can accelerate the development of new networking concepts by creating virtual testbed environments. For academic research, virtual SDN testbeds, e.g., GENI [17] and OFNLR [18], offer the opportunity to easily create network slices on a short-term basis. These network slices can be used to test new networking concepts. In industry, new concepts can be rolled out and tested in an isolated virtual SDN slice that can operate in parallel with the operational (production) network. This parallel operation can facilitate the roll out and at the same time prevent interruptions of current network operations.

C. Scope of This Survey

This survey considers the topic area at the intersection of virtual networking and SDN networking. More specifically, we focus on hypervisors for virtual SDN networks, i.e., hypervisors for the creation and monitoring of and resource allocation to virtual SDN networks. The surveyed hypervisors slice a given physical SDN network into multiple vSDNs. Thus, a hypervisor enables multiple tenants (organizational entities) to independently operate over a given physical SDN network infrastructure, i.e., to run different network operating systems in parallel.

D. Contributions and Structure of This Article

This article provides a comprehensive survey of hypervisors for virtual SDN networks. We first provide brief tutorial background and review existing surveys on the related topic areas of network virtualization and software defined networking (SDN) in Section II. The main acronyms used in this article are summarized in Table I. In Section III, we introduce the virtualization of SDN networks through hypervisors and describe the two main hypervisor functions, namely the virtualization (abstraction) of network attributes and the isolation of network attributes. In Section IV, we introduce a classification of hypervisors for SDN networks according to their architecture as centralized or distributed hypervisors. We further sub-classify the hypervisors according to their execute platform into hypervisors implemented through software programs executing on general-purpose compute platforms or a combination of

general-purpose compute platforms with general- or special-purpose network elements (NEs). We then survey the existing hypervisors following the introduced classification: centralized hypervisors are surveyed in Section V, while distributed hypervisors are surveyed in Section VI. We compare the surveyed hypervisors in Section VII, whereby we contrast in particular the abstraction (virtualization) of network attributes and the isolation of vSDNs. In Section VIII, we survey the existing performance evaluation tools, benchmarks, and evaluation scenarios for SDN networks and introduce a framework for the comprehensive performance evaluation of SDN hypervisors. Specifically, we initiate the establishment of a sub-area of SDN hypervisor research by defining SDN hypervisor performance metrics and specifying performance evaluation guidelines for SDN hypervisors. In Section IX, we outline an agenda for future research on SDN hypervisors. We conclude this survey article in Section X.

II. BACKGROUND AND RELATED SURVEYS

In this section, we give tutorial background on the topic areas of network virtualization and software defined networking (SDN). We also give an overview of existing survey articles in these topic areas.

A. Network Virtualization

Inspired by the success of virtualization in the area of computing [1], [7], [19]–[22], virtualization has become an important research topic in communication networks. Initially, network virtualization was conceived to “slice” a given physical network infrastructure into multiple virtual networks, also referred to as “slices” [17], [23]–[26]. Network virtualization first abstracts the underlying physical network and then creates separate virtual networks (slices) through specific abstraction and isolation functional blocks that are reviewed in detail in Section III (in the context of SDN). Cloud computing platforms and their virtual service functions have been surveyed in [27]–[29], while related security issues have been surveyed in [30].

In the networking domain, there are several related techniques that can create network “slices.” For instance, wavelength division multiplexing (WDM) [38] creates slices at the physical (photonic) layer, while virtual local area networks (VLANs) [39] create slices at the link layer. Multiple protocol label switching (MPLS) [33] creates slices of forwarding tables in switches. In contrast, network virtualization seeks to create slices of the entire network, i.e., to form virtual networks (slices) across all network protocol layers. A given virtual network (slice) should have its own resources, including its own slice-specific view of the network topology, its own slices of link bandwidths, and its own slices of switch CPU resources and switch forwarding tables.

A given virtual network (slice) provides a setting for examining novel networking paradigms, independent of the constraints imposed by the presently dominant Internet structures and protocols [16]. Operating multiple virtual networks over a given network infrastructure with judicious resource allocation may

improve the utilization of the networking hardware [40], [41]. Also, network virtualization allows multiple network service providers to flexibly offer new and innovative services over an existing underlying physical network infrastructure [8], [42]–[44].

The efficient and reliable operation of virtual networks typically demands specific amounts of physical networking resources. In order to efficiently utilize the resources of the virtualized networking infrastructure, sophisticated resource allocation algorithms are needed to assign the physical resources to the virtual networks. Specifically, the virtual nodes and the virtual paths that interconnect the virtual nodes have to be placed on the physical infrastructure. This assignment problem of virtual resources to physical resources is known as the Virtual Network Embedding (VNE) problem [45]–[47]. The VNE problem is NP-hard and is still intensively studied. Metrics to quantify and compare embedding algorithms include acceptance rate, the revenue per virtual network, and the cost per virtual network. The acceptance rate is defined as the ratio of the number of accepted virtual networks to the total number of virtual network requests. If the resources are insufficient for hosting a virtual network, then the virtual network request has to be rejected. Accepting and rejecting virtual network requests has to be implemented by admission control mechanisms. The revenue defines the gain per virtual network, while the cost defines the physical resources that are expended to accept a virtual network. The revenue-to-cost ratio provides a metric relating both revenue and cost; a high revenue-to-cost ratio indicates an efficient embedding. Operators may select for which metrics the embedding of virtual networks should be optimized. The existing VNE algorithms, which range from exact formulations, such as mixed integer linear programs, to heuristic approaches based, for instance, on stochastic sampling, have been surveyed in [47]. Further, [47] outlines metrics and use cases for VNE algorithms. In Section VIII, we briefly relate the assignment (embedding) of vSDNs to the generic VNE problem and outline the use of the general VNE performance metrics in the SDN context.

Several overview articles and surveys have addressed the general principles, benefits, and mechanisms of network virtualization [48]–[56]. An instrumentation and analytics framework for virtualized networks has been outlined in [57] while convergence mechanisms for networking and cloud computing have been surveyed in [29], [58]. Virtualization in the context of wireless and mobile networks is an emerging area that has been considered in [59]–[68].

B. Software Defined Networking

Software Defined Networking (SDN) decouples the control plane, which controls the operation of the network switches, e.g., by setting the routing tables, from the data (forwarding) plane, which carries out the actual forwarding of the payload data through the physical network of switches and links.

SDN breaks with the traditionally distributed control of the Internet by centralizing the control of an entire physical SDN network in a single logical SDN controller [12], as illustrated in Fig. 1(a). The first SDN controller based on the OpenFlow protocol was NOX [69], [70] and has been followed by a

myriad of controller designs, e.g., [71]–[78], which are written in a variety of programming languages. Efforts to distribute the SDN control plane decision making to local controllers that are “passively” synchronized to maintain central logical control are reported in [79]. Similar efforts to control large-scale SDN network have been examined in [80]–[83], while hybrid SDN networks combining centralized SDN with traditional distributed protocols are outlined in [84].

SDN defines a so-called data-controller plane interface (D-CPI) between the physical data (forwarding) plane and the SDN control plane [31], [32]. This interface has also been referred to as the south-bound application programmers interface (API) or the OF control channel or the control plane channel in some SDN literature, e.g., [85]. The D-CPI relies on a standardized instruction set that abstracts the physical data forwarding hardware. The OF protocol [13] (which employs some aspects from Orphal [86]) is a widely employed SDN instruction set, an alternative developed by the IETF is the forwarding and control element separation (ForCES) protocol [87], [88].

The SDN controller interfaces through the application-controller plane interface (A-CPI) [31], [32], which has also been referred to as north-bound API [85], with the network applications. The network applications, illustrated by App₁ and App₂ in Fig. 1(a), are sometimes combined in a so-called application control plane. Network applications can be developed upon functions that are implemented through SDN controllers. Network application can implement network decisions or traffic steering. Example network applications are firewall, router, network monitor, and load balancer. The data plane of the SDN that is controlled through an SDN controller can then support the classical end-user network applications, such as the web (HTTP) and e-mail (SMTP) [89], [90].

The SDN controller interfaces through the intermediate-controller plane interface (I-CPI) with the controllers in other network domains. The I-CPI includes the formerly defined east-bound API, that interfaces with the control planes of network domains that are not running SDN, e.g., with the MPLS control plane in a non-SDN network domain [85]. The I-CPI also includes the formerly defined west-bound API, that interfaces with the SDN controllers in different network domains [91]–[94].

SDN follows a match and action paradigm. The instruction set pushed by the controller to the SDN data plane includes a match specification that defines a packet flow. This match can be specified based on values in the packet, e.g., values of packet header fields. The OF protocol specification defines a set of fields that an OF controller can use and an OF network element (NE) can match on. This set is generally referred to as the “flowspace.” The OF match set, i.e., flowspace, is updated and extended with newer versions of the OF protocol specification. For example, OF version 1.1 extended OF version 1.0 with a match capability on MPLS labels. The controller instruction set also includes the action to be taken by the data plane once a packet has been matched, e.g., forward to a certain port or queue, drop, or modify the packet. The action set is also continuously updated and extended with newer OF specifications.

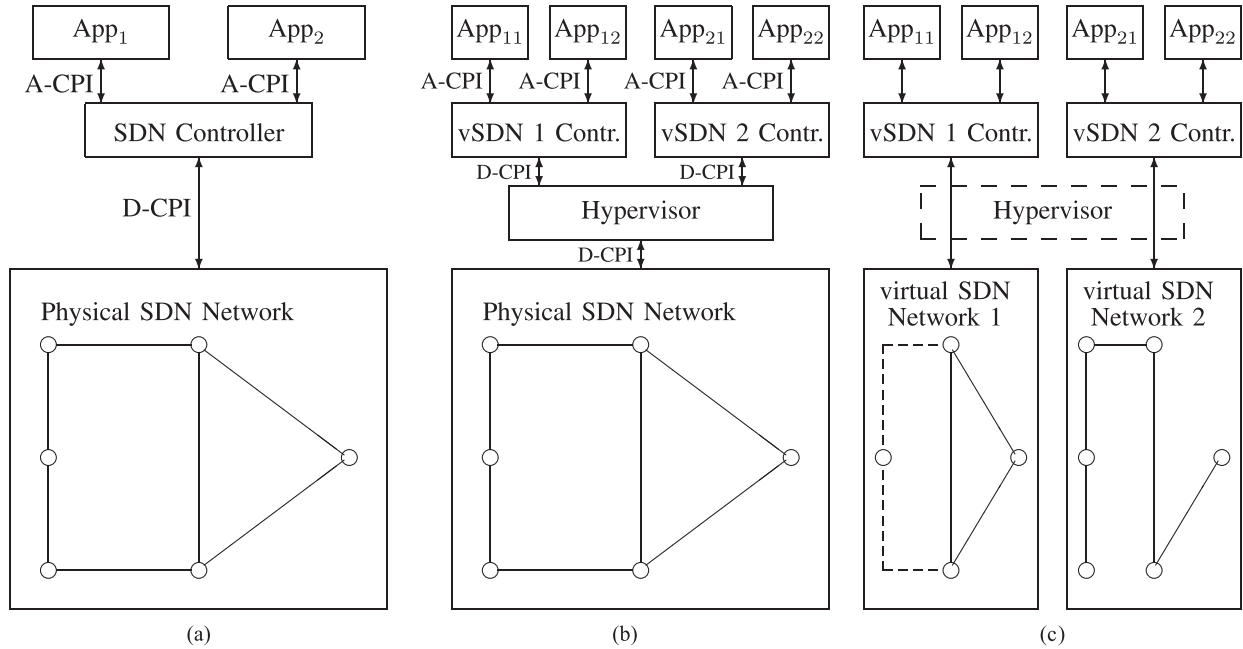


Fig. 1. Conceptual illustration of a conventional physical SDN network and its virtualization: In the conventional (non-virtualized) SDN network illustrated in part (a), network applications (App_1 and App_2) interact through the application-controller plane interface (A-CPI) with the SDN controller, which in turn interacts through the data-controller plane interface (D-CPI) with the physical SDN network. The virtualization of the SDN network, so that the network can be shared by two tenants, is conceptually illustrated in parts (b) and (c). A hypervisor is inserted between the physical SDN network and the SDN controller (control plane). The hypervisor directly interacts with the physical SDN network, as illustrated in part (b). The hypervisor gives each virtual SDN (vSDN) controller the perception that the vSDN controller directly (transparently) interacts with the corresponding virtual SDN network, as illustrated in part (c). The virtual SDN networks are isolated from each other and may have different levels of abstraction and different topology, as illustrated in part (c), although they are both based on the one physical SDN network illustrated in part (b). (a) Conventional SDN network: an SDN controller directly interacts with the physical SDN network to provide services to the applications. (b) Virtualizing the SDN network (perspective of the hypervisor): the inserted hypervisor directly interacts with the physical SDN networks as well as two virtual SDN controllers. (c) Virtual SDN networks (perspective of the virtual SDN controllers): each virtual SDN controller has the perception of transparently interacting with its virtual SDN network.

Several survey articles have covered the general principles of SDN [12], [34], [35], [95]–[103]. The implementation of software components for SDN has been surveyed in [13], [104], [105], while SDN network management has been surveyed in [106]–[108]. SDN issues specific to cloud computing, optical, as well as mobile and satellite networks have been covered in [109]–[126]. SDN security has been surveyed in [127]–[131] while SDN scalability and resilience has been surveyed in [132]–[134].

III. VIRTUALIZING SDN NETWORKS

In this section, we explain how to virtualize SDN networks through a hypervisor. We highlight the main functions that are implemented by a hypervisor to create virtual SDN networks.

A. Managing a Physical SDN Network With a Hypervisor

The centralized SDN controller in conjunction with the outlined interfaces (APIs) result in a “programmable” network. That is, with SDN, a network is no longer a conglomerate of individual devices that require individualized configuration. Instead, the SDN network can be viewed and operated as a single programmable entity. This programmability feature of SDN can be employed for implementing virtual SDN networks (vSDNs) [135].

More specifically, an SDN network can be virtualized by inserting a hypervisor between the physical SDN network and

the SDN control plane, as illustrated in Fig. 1(b) [9]–[11]. The hypervisor views and interacts with the entire physical SDN network through the D-CPI interface. The hypervisor also interacts through multiple D-CPI interfaces with multiple virtual SDN controllers. We consider this interaction of a hypervisor via multiple D-CPIs with multiple vSDN controllers, which can be conventional legacy SDN controllers, as the defining feature of a hypervisor. We briefly note that some controllers for non-virtualized SDN networks, such as OpenDaylight [78], could also provide network virtualization. However, these controllers would allow the control of virtual network slices only via the A-CPI. Thus, legacy SDN controllers could not communicate transparently with their virtual network slices. We do therefore not consider OpenDaylight or similar controllers as hypervisors.

The hypervisor abstracts (virtualizes) the physical SDN network and creates isolated virtual SDN networks that are controlled by the respective virtual SDN controllers. In the example illustrated in Fig. 1, the hypervisor slices (virtualizes) the physical SDN network in Fig. 1(b) to create the two vSDNs illustrated in Fig. 1(c). Effectively, the hypervisor abstracts its view of the underlying physical SDN network in Fig. 1(b), into the two distinct views of the two vSDN controllers in Fig. 1(c). This abstraction is sometimes referred to as an n -to-1 mapping or a many-to-one mapping in that the abstraction involves mappings from multiple vSDN switches to one physical SDN switch [51], [136]. Before we go on to give general background

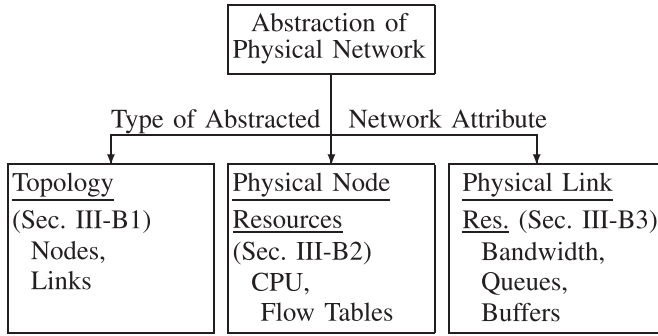


Fig. 2. The hypervisor abstracts three types of physical SDN network attributes, namely topology, node resources, and link resources, with different levels of virtualization, e.g., a given physical network topology is abstracted to more or less virtual nodes or links.

on the two main hypervisor functions, namely the abstraction (virtualization) of network attributes in Section III-B and the isolation of the vSDNs in Section III-C, we briefly review the literature on hypervisors. Hypervisors for virtual computing systems have been surveyed in [2]–[4], [137], while hypervisor vulnerabilities in cloud computing have been surveyed in [138]. However, to the best of our knowledge there has been no prior detailed survey of hypervisors for virtualizing SDN networks into vSDNs. We comprehensively survey SDN hypervisors in this article.

B. Network Attribute Virtualization

The term “abstraction” can generally be defined as [139]: the act of considering something as a general quality or characteristic, apart from concrete realities, specific objects, or actual instances. In the context of an SDN network, a hypervisor abstracts the specific characteristic details (attributes) of the underlying physical SDN network. The abstraction (simplified representation) of the SDN network is communicated by the hypervisor to the controllers of the virtual tenants, i.e., the virtual SDN controllers. We refer to the degree of simplification (abstraction) of the network representation as the *level of virtualization*.

Three types of attributes of the physical SDN network, namely topology, physical node resources, and physical link resources, are commonly considered in SDN network abstraction. For each type of network attribute, we consider different levels (degrees, granularities) of virtualization, as summarized in Fig. 2.

1) *Topology Abstraction*: For the network attribute topology, virtual nodes and virtual links define the level of virtualization. The hypervisor can abstract an end-to-end network path traversing multiple physical links as one end-to-end virtual link [42], [140]. A simple example of link virtualization where two physical links (and an intermediate node) are virtualized to a single virtual link is illustrated in the left part of Fig. 3. For another example of link virtualization consider the left middle node in Fig. 1(b), which is connected via two links and the upper left node with the node in the top middle. These two links and the intermediate (upper left corner) node are abstracted to a single virtual link (drawn as a dashed line) in vSDN 1 in the left part of Fig. 1(c). Similarly, the physical link from the left

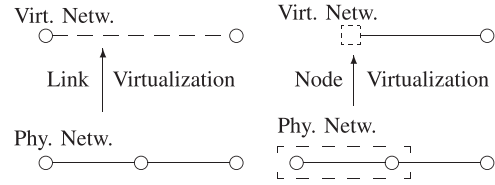


Fig. 3. Illustration of link and node virtualization: for link virtualization, the two physical network links and intermediate network node are virtualized to a single virtual link (drawn as a dashed line). For node virtualization, the left two nodes and the physical link connecting the two nodes are virtualized to a single virtual node (drawn as a dashed box).

middle node in Fig. 1(b) via the bottom right corner node to the node in the bottom middle is abstracted to a single virtual link (dashed line) in the left part of Fig. 1(c).

Alternatively, the hypervisor can abstract multiple physical nodes to a single virtual node [51]. In the example illustrated in the right part of Fig. 3, two physical nodes and their connecting physical link are virtualized to a single virtualized node (drawn as a dashed box).

The least (lowest) level of virtualization of the topology represents the physical nodes and physical links in an identical virtual topology, i.e., the abstraction is a transparent 1-to-1 mapping in that the physical topology is *not* modified to obtain the virtual topology. The highest level of virtualization abstracts the entire physical network topology as a single virtual link or node. Generally, there is a range of levels of virtualization between the outlined lowest and highest levels of virtualization link [42]. For instance, a complex physical network can be abstracted to a simpler virtual topology with fewer virtual nodes and links, as illustrated in the view of vSDN 1 controller in Fig. 1(c) of the actual physical network in Fig. 1(b). Specifically, the vSDN 1 controller in Fig. 1(c) “sees” only a vSDN 1 consisting of four nodes interconnected by five links, whereas the underlying physical network illustrated in Fig. 1(b) has six nodes interconnected by seven links. This abstraction is sometimes referred to as 1-to- N mapping or as one-to-many mapping as a single virtual node or link is mapped to several physical nodes or links [51]. In particular, the mapping of one virtual switch to multiple physical switches is also sometimes referred to as the “big switch” abstraction [141].

2) *Abstraction of Physical Node Resources*: For the network attribute physical node resources, mainly the CPU resources and the flow table resources of an SDN switch node define the level of virtualization [42]. Depending on the available level of CPU hardware information, the CPU resources may be represented by a wide range of CPU characterizations, e.g., number of assigned CPU cores or percentage of CPU capacity in terms of the capacity of a single core, e.g., for a CPU with two physical cores, 150% of the capacity corresponds to one and a half cores. The flow table abstraction may similarly involve a wide range of resources related to flow table processing, e.g., the number of flow tables or the number of ternary content-addressable memories (TCAMs) [37], [142] for flow table processing. The abstraction of the SDN switch physical resources can be beneficial for the tenants’ vSDN controllers.

3) *Abstraction of Physical Link Resources*: For the network attribute physical link resources, the bandwidth (transmission

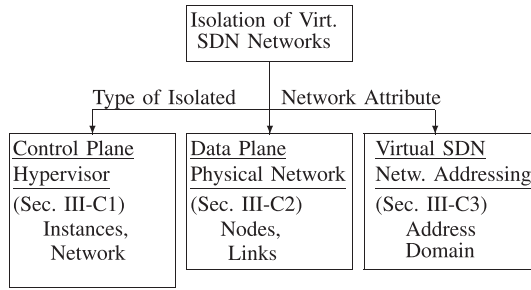


Fig. 4. The hypervisor isolates three main attributes of virtual SDN networks, namely control plane, data plane, and vSDN addressing.

bit rate, link capacity) as well as the available link queues and link buffers define the level of virtualization [42].

C. Isolation Attributes

The hypervisor should provide isolated slices for the vSDNs sharing a physical SDN network. As summarized in Fig. 4, the isolation should cover the SDN control plane and the SDN data plane. In addition, the vSDN addressing needs to be isolated, i.e., each vSDN should have unique flow identifiers.

1) *Control Plane Isolation*: SDN decouples the data plane from the control plane. However, the performance of the control plane impacts the data plane performance [70], [79]. Thus, isolation of the tenants' control planes is needed. Each vSDN controller should have the impression of controlling its own vSDN without interference from other vSDNs (or their controllers).

The control plane performance is influenced by the resources available for the hypervisor instances on the hosting platforms, e.g., commodity servers or NEs [143], [144]. Computational resources, e.g., CPU resources, can affect the performance of the hypervisor packet processing and translation, while storage resources limit control plane buffering. Further, the network resources of the links/paths forming the hypervisor layer, e.g., link/path data rates and the buffering capacities need to be isolated to provide control plane isolation.

2) *Data Plane Isolation*: Regarding the data plane, physical node resources mainly relate to network element CPU and flow tables. Isolation of the physical link resources relates to the link transmission bit rate. More specifically, the performance of the data plane physical nodes (switches) depends on their processing capabilities, e.g., their CPU capacity and their hardware accelerators. Under different work loads, the utilization of these resources may vary, leading to varying performance, i.e., changing delay characteristics for packet processing actions. Switch resources should be assigned (reserved) for a given vSDN to avoid performance degradation. Isolation mechanisms should prevent cross-effects between vSDNs, e.g., that one vSDN over-utilizes its assigned switch element resources and starves another vSDN of its resources.

Besides packet processing capabilities, an intrinsic characteristic of an SDN switch is the capacity for storing and matching flow rules. The OF protocol stores rules in flow tables. Current OF-enabled switches often use fast TCAMs for storing and matching rules. For proper isolation, specific amounts of TCAM capacity should be assigned to the vSDNs.

Hypervisors should provide physical link transmission bit rate isolation as a prerequisite towards providing Quality-of-Service (QoS). For instance, the transmission rate may need to be isolated to achieve low latency. Thus, the hypervisor should be able to assign a specific amount of transmission rate to each tenant. Resource allocation and packet scheduling mechanisms, such as Weighted Fair Queuing (WFQ) [145]–[147], may allow assigning prescribed amounts of resources. In order to impact the end-to-end latency, mechanisms that assign the available buffer space on a per-link or per-queue basis are needed as well. Furthermore, the properties of the queue operation, such as First-In-First-Out (FIFO) queueing, may impact specific isolation properties.

3) *vSDN Addressing Isolation*: As SDN follows a match and action paradigm (see Section II-B), flows from different vSDNs must be uniquely addressed (identified). An addressing solution must guarantee that forwarding decisions of tenants do not conflict with each other. The addressing should also maximize the flowspace, i.e., the match set, that the vSDN controllers can use. One approach is to split the flowspace, i.e., the match set, and provide the tenants with non-overlapping flowspaces. If a vSDN controller uses an OF version, e.g., OF v1.0, lower than the hypervisor, e.g., OF v1.3, then the hypervisor could use the extra fields in the newer OF version for tenant identification. This way such a controller can use the full flowspace of its earlier OF version for the operation of its slice. However, if the vSDN controller implements the same or a newer OF version than the hypervisor, then the vSDN controller cannot use the full flowspace.

Another addressing approach is to use fields outside of the OF matching flowspace, i.e., fields not defined in the OF specifications, for the unique addressing of vSDNs. In this case, independent of the implemented OF version of the vSDN controllers, the full flowspace can be offered to the tenants.

IV. CLASSIFICATION STRUCTURE OF HYPERVISOR SURVEY

In this section, we introduce our hypervisor classification, which is mainly based on the architecture and the execution platform, as illustrated in Fig. 5. We first classify SDN hypervisors according to their architecture into centralized and distributed hypervisors. We then sub-classify the hypervisors according to their execution platform into hypervisors running exclusively on general-purpose compute platforms as well as hypervisors running on general-purpose computing platforms in combination with general- or/and special-purpose NEs. We proceed to explain these classification categories in detail.

A. Type of Architecture

A hypervisor has a centralized architecture if it consists of a single central entity. This single central entity controls multiple network elements (NEs), i.e., OF switches, in the physical network infrastructure. Also, the single central entity serves potentially multiple tenant controllers. Throughout our classification, we classify hypervisors that do not require the distribution of their hypervisor functions as centralized. We

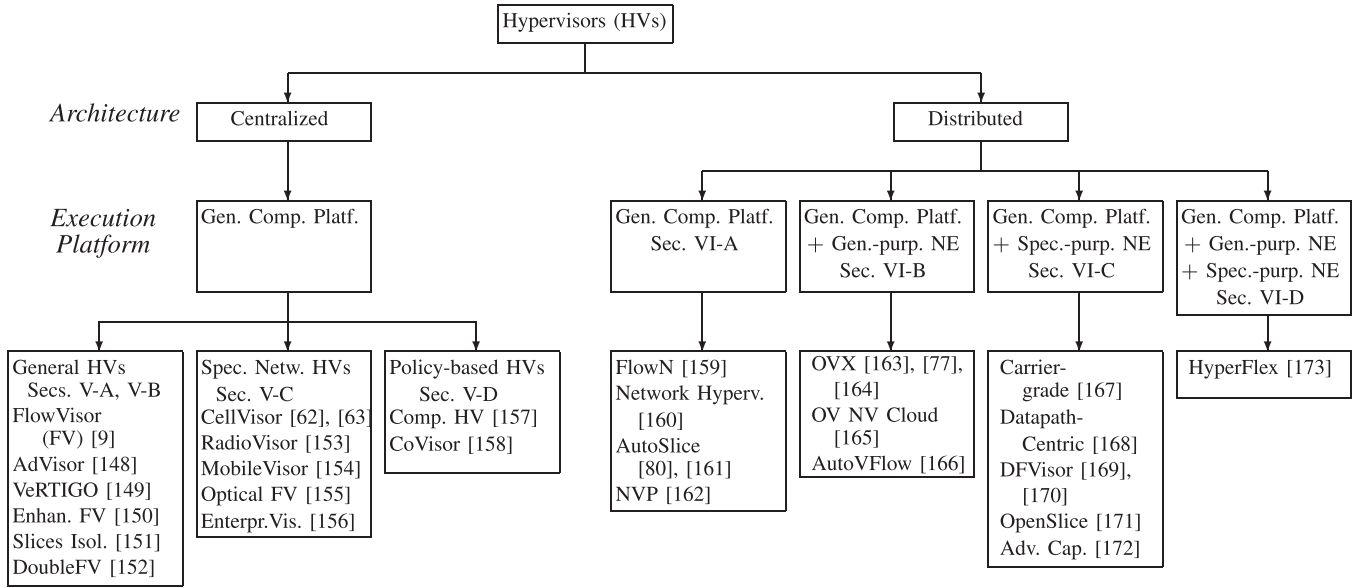


Fig. 5. Hypervisor classification: Our top-level classification criterion is the hypervisor architecture (centralized or distributed). Our second-level classification is according to the hypervisor execution platform (general-purpose compute platform only or combination of general-purpose compute platform and general- or special-purpose network elements). For the large set of centralized compute-platform hypervisors, we further distinguish hypervisors for special network types (wireless, optical, or enterprise network) and policy-based hypervisors.

also classify hypervisors as centralized, when no detailed distribution mechanisms for the hypervisor functions have been provided. We sub-classify the centralized hypervisors into hypervisors for general networks, hypervisors for special network types (e.g., optical or wireless networks), and policy-based hypervisors. Policy-based hypervisors allow multiple network applications through different vSDN controllers, e.g., App₁₁ through vSDN 1 Controller and App₂₁ through vSDN 2 Controller in Fig. 1(b), to “logically” operate on the same traffic flow in the underlying physical SDN network. The policy-based hypervisors compose the OF rules of the two controllers to achieve this joint operation on the same traffic flow, as detailed in Section V-D.

We classify an SDN hypervisor as a distributed hypervisor if the virtualization functions can run logically separated from each other. A distributed hypervisor appears logically as consisting of a single entity (similar to a centralized hypervisor); however, a distributed hypervisor consists of several distributed functions. A distributed hypervisor may decouple management functions from translation functions or isolation functions. However, the hypervisor functions may depend on each other. For instance, in order to protect the translation functions from over-utilization, the isolation functions should first process the control traffic. Accordingly, the hypervisor needs to provide mechanisms for orchestrating and managing the functions, so as to guarantee the valid operation of dependent functions. These orchestration and management mechanisms could be implemented and run in a centralized or in a distributed manner.

B. Hypervisor Execution Platform

We define the hypervisor execution platform to characterize the (hardware) infrastructure (components) employed for implementing (executing) a hypervisor. Hypervisors are commonly

implemented through software programs (and sometimes employ specialized NEs). The existing centralized hypervisors are implemented through software programs that run on general-purpose compute platforms, e.g., commodity compute servers and personal computers (PCs), henceforth referred to as “compute platforms” for brevity.

Distributed hypervisors may employ compute platforms in conjunction with general-purpose NEs or/and special-purpose NEs, as illustrated in Fig. 5. We define a general-purpose NE to be a commodity off-the-shelf switch without any specialized hypervisor extensions. We define a special-purpose NE to be a customized switch that has been augmented with specialized hypervisor functionalities or extensions to the OF specification, such as the capability to match on labels outside the OF specification.

We briefly summarize the pros and cons of the different execution platforms as follows. Software implementations offer “portability” and ease of operation on a wide variety of general-purpose (commodity) compute platforms. A hypervisor implementation on a general-purpose (commodity) NE can utilize the existing hardware-integrated NE processing capabilities, which can offer higher performance compared to general-purpose compute platforms. However, general-purpose NEs may lack some of the hypervisor functions required for creating vSDNs. Hence commodity NEs can impose limitations. A special-purpose NE offers high hardware performance and covers the set of hypervisor functions. However replacing commodity NEs in a network with special-purpose NEs can be prohibitive due to the additional cost and equipment migration effort.

As illustrated in Fig. 5, we sub-classify the distributed hypervisors into hypervisors designed to execute on compute platforms, hypervisors executing on compute platforms in conjunction with *general-purpose* NEs, hypervisors executing on compute platforms in conjunction with *special-purpose* NEs,

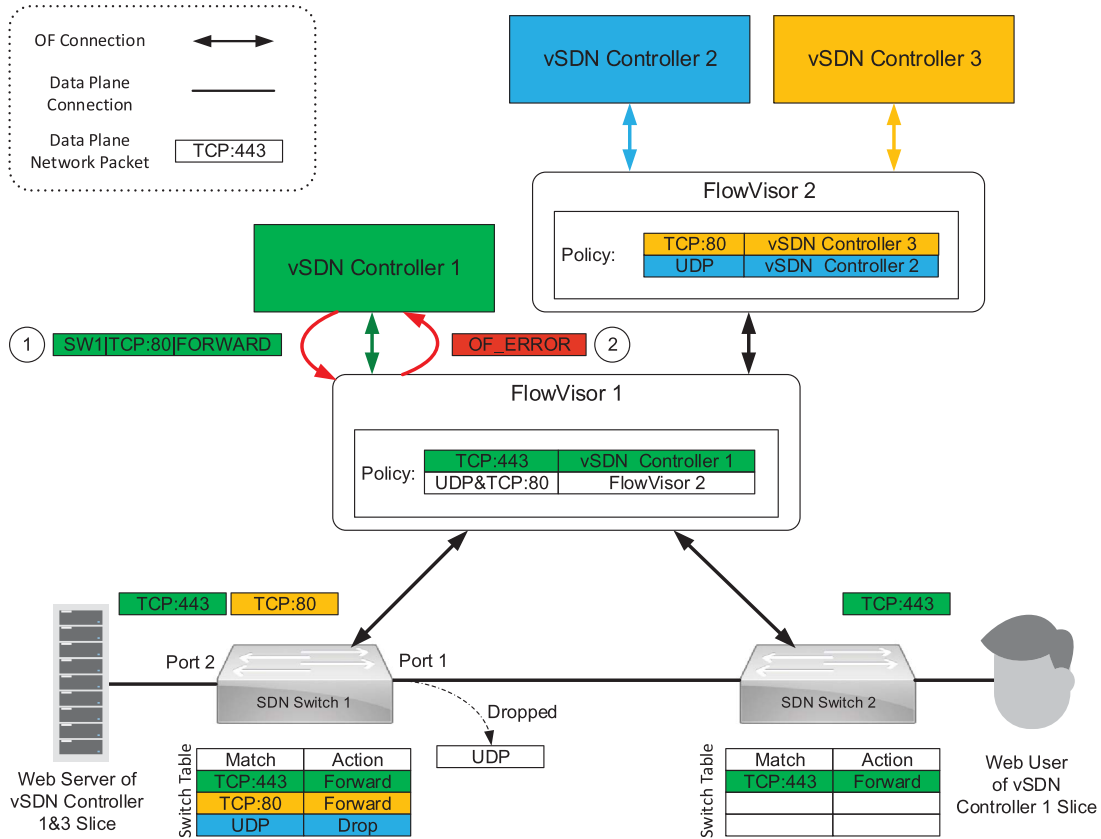


Fig. 6. Illustrative example of SDN network virtualization with FlowVisor: FlowVisor 1 creates a vSDN that vSDN Controller 1 uses to control HTTPS traffic with TCP port number 443 on SDN switches 1 and 2. FlowVisor 2 is nested on top of FlowVisor 1 and controls only SDN Switch 1. FlowVisor 2 lets vSDN Controller 3 control the HTTP traffic with TCP port number 80 on SDN Switch 1 (top-priority rule in FlowVisor 2, second-highest priority rule in SDN Switch 1) and lets vSDN Controller 2 drop all UDP traffic.

as well as hypervisors executing on compute platforms in conjunction with a mix of general- and special-purpose NEs.

V. CENTRALIZED HYPERVISORS

In this section, we comprehensively survey the existing hypervisors (HVs) with a centralized architecture. All existing centralized hypervisors are executed on a central general-purpose computing platform. FlowVisor [9] was a seminal hypervisor for virtualizing SDN networks. We therefore dedicate a separate subsection, namely Section V-A, to a detailed overview of FlowVisor. We survey the other hypervisors for general networks in Section V-B. We cover hypervisors for special network types in Section V-C, while policy-based hypervisors are covered in Section V-D.

A. FlowVisor

1) *General Overview*: FlowVisor [9] was the first hypervisor for virtualizing and sharing software defined networks based on the OF protocol. The main motivation for the development of FlowVisor was to provide a hardware abstraction layer that facilitates innovation above and below the virtualization layer. In general, a main FlowVisor goal is to run production and experimental networks on the same physical SDN networking hardware. Thus, FlowVisor particularly focuses on mechanisms

to isolate experimental network traffic from production network traffic. Additionally, general design goals of FlowVisor are to work in a transparent manner, i.e., without affecting the hosted virtual networks, as well as to provide extensible, modular, and flexible definitions of network slices.

2) *Architecture*: FlowVisor is a pure software implementation. It can be deployed on general-purpose (commodity) computing servers running commodity operating systems. In order to control and manage access to the slices, i.e., physical hardware, FlowVisor sits between the tenant's controllers and the physical (hardware) SDN network switches, i.e., at the position of the box marked "Hypervisor" in Fig. 1. Thus, FlowVisor controls the views that the tenants' controllers have of the SDN switches. FlowVisor also controls the access of the tenants' controllers to the switches.

FlowVisor introduces the term *flowspace* for a sub-space of the header fields space [36] of an OF-based network. FlowVisor allocates each vSDN (tenant) its own flowspace, i.e., its own sub-space of the OF header fields space and ensures that the flowspaces of distinct vSDNs do not overlap. The vSDN controller of a given tenant operates on its flowspace, i.e., its sub-space of the OF header fields space. The flowspace concept is illustrated for an OF-based example network shared by three tenants in Fig. 6. The policy (prioritized list of forwarding rules) of vSDN Controller 1 specifies the control of all HTTPS traffic (with highest priority); thus, vSDN Controller 1 controls all

packets whose TCP port header field matches the value 443. The policy of a second vSDN tenant of FlowVisor 1, which is a nested instance of a hypervisor, namely FlowVisor 2, specifies to control all HTTP (TCP port value 80) and UDP traffic. FlowVisor 1 defines policies through the matching of OF header fields to guarantee that the virtual slices do not interfere with each other, i.e., the virtual slices are isolated from each other.

3) *Abstraction and Isolation Features*: FlowVisor provides the vSDNs with bandwidth isolation, topology isolation, switch CPU isolation, flow-space isolation, isolation of the flow entries, and isolation of the OF control channel (on the D-CPI). The FlowVisor version examined in [9] maps the packets of a given slice to a prescribed Virtual Local Area Network (VLAN) Priority Code Point (PCP). The 3-bit VLAN PCP allows for the mapping to eight distinct priority queues [174]. More advanced bandwidth isolation (allocation) and scheduling mechanisms are evaluated in research that extends FlowVisor, such as Enhanced FlowVisor [150], see Section V-B3.

For topology isolation, only the physical resources, i.e., the ports and switches, that are part of a slice are shown to the respective tenant controller. FlowVisor achieves the topology isolation by acting as a proxy between the physical resources and the tenants' controllers. Specifically, FlowVisor edits OF messages to only report the physical resources of a given slice to the corresponding tenant controller. Fig. 6 illustrates the topology abstraction. In order to provide secure HTTPS connections to its applications, vSDN Controller 1 controls a slice spanning SDN Switches 1 and 2. In contrast, since the tenants of FlowVisor 2 have only traffic traversing SDN Switch 1, FlowVisor 2 sees only SDN Switch 1. As illustrated in Fig. 6, vSDN Controller 1 has installed flow rules on both switches, whereas vSDN Controllers 2 and 3 have only rules installed on SDN Switch 1.

The processing of OF messages can overload the central processing unit (CPU) in a physical SDN switch, rendering the switch unusable for effective networking. In order to ensure that each slice is effectively supported by the switch CPU, FlowVisor limits the rates of the different types of OF messages exchanged between physical switches and the corresponding tenant controllers.

The flow-spaces of distinct vSDNs are not allowed to overlap. If one tenant controller tries to set a rule that affects traffic outside its slice, FlowVisor rewrites such a rule to the tenant's slice. If a rule cannot be rewritten, then FlowVisor sends an OF error message. Fig. 6 illustrates the flow-space isolation. When vSDN Controller 1 sends an OF message to control HTTP traffic with TCP port field value 80, i.e., traffic that does not match TCP port 443, then FlowVisor 1 responds with an OF error message.

Furthermore, in order to provide a simple means for defining varying policies, FlowVisor instances can run on top of each other. This means that they can be nested in order to provide different levels of abstraction and policies. As illustrated in Fig. 6, FlowVisor 2 runs on top of FlowVisor 1. FlowVisor 1 splits the OF header fields space between vSDN Controller 1 and FlowVisor 2. In the illustrated example, vSDN Controller 1 controls HTTPS traffic. FlowVisor 2, in turn serves vSDN Controller 2, which implements a simple firewall that drops all

UDP packets, and vSDN Controller 3, which implements an HTTP traffic controller. The forwarding rules for HTTPS (TCP port 443) packet traffic and HTTP (TCP port 80) packet traffic are listed higher, i.e., have higher priority, than the drop rule of vSDN Controller 2. Thus, SDN Switch 1 forwards HTTPS and HTTP traffic, but drops other traffic, e.g., UDP datagrams.

SDN switches typically store OF flow entries (also sometimes referred to as OF rules), in a limited amount of TCAM memory, the so-called flow table memory. FlowVisor assigns each tenant a part of the flow table memory in each SDN switch. In order to provide isolation of flow entries, each switch keeps track of the number of flow entries inserted by a tenant controller. If a tenant exceeds a prescribed limit of flow entries, then FlowVisor replies with a message indicating that the flow table of the switch is full.

The abstraction and isolation features reviewed so far relate to the physical resources of the SDN network. However, for effective virtual SDN networking, the data-controller plane interface (D-CPI) (see Section II-B) should also be isolated. FlowVisor rewrites the OF transaction identifier to ensure that the different vSDNs utilize distinct transaction identifiers. Similarly, controller buffer accesses and status messages are modified by FlowVisor to create isolated OF control slices.

FlowVisor has been extended with an intermediate control plane slicing layer that contains a Flow-space Slicing Policy (FSP) engine [175]. The FSP engine adds three control plane slicing methods: domain-wide slicing, switch-wide slicing, and port-wide slicing. The three slicing methods differ in their proposed granularity of flow-space slicing. With the FSP engine, tenants can request abstracted virtual networks, e.g., end-to-end paths only. According to the demanded slicing policy, FSP translates the requests into multiple isolated flow-spaces. The concrete flow-spaces are realized via an additional proxy, e.g., FlowVisor. The three slicing methods are evaluated and compared in terms of acceptance ratio, required hypervisor memory, required switch flow table size, and additional control plane latency added by the hypervisor. Specifying virtual networks more explicitly (with finer granularity), i.e., matching on longer header information, the port-wide slicing can accept the most virtual network demands while requiring the most resources.

4) *Evaluation Results*: The FlowVisor evaluations in [9] cover the overhead as well as isolation of transmission (bit rate) rate, flow-space, and switch CPUs through measurements in a testbed. FlowVisor sits as an additional component between SDN controllers and SDN switches adding latency overhead to the tenant control operations. The measurements reported in [9] indicate that FlowVisor adds an average latency overhead of 16 ms for adding new flows and 0.48 ms for requesting port status. These latency overheads can be reduced through optimized request handling.

The bandwidth isolation experiments in [9] let a vSDN (slice) sending a TCP flow compete with a vSDN sending constant-bit-rate (CBR) traffic at the full transmission bit rate of the shared physical SDN network. The measurements indicate that without bandwidth isolation, the TCP flow receives only about one percent of the link bit rate. With bandwidth isolation that maps the TCP slice to a specific class, the reported measurements indicate that the TCP slice received close to the prescribed

bit rate, while the CBR slice uses up the rest of the bit rate. FlowSpace isolation is evaluated with a test suite that verifies the correct isolation for 21 test cases, e.g., verifying that a vSDN (slice) cannot manipulate traffic of another slice. The reported measurements for the OF message throttling mechanism indicate that a malicious slice can fully saturate the experimental switch CPU with about 256 port status requests per second. The FlowVisor switch CPU isolation, however, limits the switch CPU utilization to less than 20%.

B. General Hypervisors Building on FlowVisor

We proceed to survey the centralized hypervisors for general networks. These general hypervisors build on the concepts introduced by FlowVisor. Thus, we focus on the extensions that each hypervisor provides compared to FlowVisor.

1) *AdVisor*: AdVisor [148] extends FlowVisor in three directions. First, it introduces an improved abstraction mechanism that hides physical switches in virtual topologies. In order to achieve a more flexible topology abstraction, AdVisor does not act as a transparent proxy between tenant (vSDN) controllers and SDN switches. Instead, AdVisor directly replies to the SDN switches. More specifically, FlowVisor provides a transparent 1-to-1 mapping with a detailed view of intermediate physical links and nodes. That is, FlowVisor can present 1-to-1 mapped subsets of the underlying topology to the vSDN controllers, e.g., the subset of the topology illustrated in vSDN network 2 in the right part of Fig. 1(c). However, FlowVisor cannot “abstract away” intermediate physical nodes and links, i.e., FlowVisor cannot create vSDN network 1 in the left part of Fig. 1(c). In contrast, AdVisor extends the topology abstraction mechanisms by hiding intermediate physical nodes of a virtual path. That is, AdVisor can show only the endpoints of a virtual path to the tenants’ controllers, and thus create vSDN network 1 in the left part of Fig. 1(c). When a physical SDN switch sends an OF message, AdVisor checks whether this message is from an endpoint of a virtual path. If the switch is an endpoint, then the message is forwarded to the tenant controller. Otherwise, i.e., if the switch has been “abstracted away,” then AdVisor processes the OF message and controls the forwarding of the traffic independently from the tenant controller.

The second extension provided by AdVisor is the sharing of the flowSpace (sub-space of the OF header fields space) by multiple (vSDNs) slices. In order to support this sharing of the OF header fields space, AdVisor defines the flowSpace for the purpose of distinguishing vSDNs (slices) to consist only of the bits of the OSI-layer 2. Specifically, the AdVisor flowSpace definition introduced so called *slice_tags*, which encompass *VLAN id*, *MPLS labels*, or *IEEE802.1ad-based multiple VLAN tagging* [33], [174], [176]. This restricted definition of the AdVisor flowSpace enables the sharing of the remaining OF header fields among the slices. However, labeling adds processing overhead to the NEs. Furthermore, AdVisor is limited to NEs that provide labeling capabilities. Restricting to VLAN ids limits the available number of slices. When only using the VLAN id, the 4096 possible distinct VLAN ids may not be enough for networks requiring many slices. Large cloud providers have already on the order of 1 Million customers

today. If a large fraction of these customers were to request their own virtual networks, then the virtual networks could not be distinguished.

2) *VerTIGO*: VerTIGO [149] takes the virtual network abstraction of AdVisor [148] yet a step further. VerTIGO allows the vSDN controllers to select the desired level of virtual network abstraction. At the “most detailed” end of the abstraction spectrum, VerTIGO can provide the entire set of assigned virtual resources, with full virtual network control. At the other, “least detailed” end of the abstraction spectrum, VerTIGO abstracts the entire vSDN to a single abstract resource; whereby the network operation is carried out by the hypervisor, while the tenant focuses on services deployment on top. While VerTIGO gives high flexibility in provisioning vSDNs, VerTIGO has increased complexity. In the evaluations reported in [149], the average latencies for new flow requests are increased roughly by 35% compared to FlowVisor.

3) *Enhanced FlowVisor*: Enhanced FlowVisor [150] extends FlowVisor addressing and tackles FlowVisor’s simple bandwidth allocation and lack of admission control. Enhanced FlowVisor is implemented as an extension to the NOX SDN controller [69]. Enhanced FlowVisor uses VLAN PCP [174] to achieve flow-based bandwidth guarantees. Before a virtual network request is accepted, the admission control module checks whether enough link capacity is available. In case the residual link bandwidth is not sufficient, a virtual network request is rejected.

4) *Slices Isolator*: Slices Isolator [151] mainly focuses on concepts providing isolation between virtual slices sharing an SDN switch. Slice Isolator is implemented as a software extension of the hypervisor layer, which is positioned between the physical SDN network and the virtual SDN controllers, as illustrated in Fig. 1(b). The main goal of Slices Isolator is to adapt to the isolation demands of the virtual network users. Slices Isolator introduces an isolation model for NE resources with eight isolation levels. Each isolation level is a combination of activated or deactivated isolation of the main NE resources, namely interfaces, packet processing, and buffer memory. The lowest isolation level does not isolate any of these resources, i.e., there is no interface isolation, no packet processing isolation, and no buffer memory isolation. The highest level isolates interfaces, packet processing, and buffer memory.

If multiple slices (vSDNs) share a physical interface (port), Slices Isolator provides interface isolation by mapping incoming packets to the corresponding slice processing pipeline. Packet processing isolation is implemented via allocating flow tables to vSDNs. In order to improve processing, Slices Isolator introduces the idea of sharing flow tables for common operations. For example, two vSDNs operating only on Layer 3 can share a flow table that provides ARP table information. Memory isolation targets the isolation of shared buffer for network packets. If memory isolation is required, a so-called traffic manager sets up separated queues, which guarantee memory isolation.

5) *Double-FlowVisors*: The Double-FlowVisors approach [152] employs two instances of FlowVisor. The first FlowVisor sits between the vSDN controllers and the physical SDN network (i.e., in the position of the Hypervisor in Fig. 1(b)). The

second FlowVisor is positioned between the vSDN controllers and the applications. This second FlowVisor gives applications a unified view of the vSDN controller layer, i.e., the second FlowVisor virtualizes (abstracts) the vSDN control.

C. Hypervisors for Special Network Types

In this section, we survey the hypervisors that have to date been investigated for special network types. We first cover wireless and mobile networks, followed by optical networks, and then enterprise networks.

1) *CellVisor*: CellSDN targets an architecture for cellular core networks that builds on SDN in order to simplify network control and management [62], [63]. Network virtualization is an important aspect of the CellSDN architecture and is achieved through an integrated CellVisor hypervisor that is an extension of FlowVisor. In order to manage and control the network resources according to subscriber demands, CellVisor flexibly slices the wireless network resources, i.e., CellVisor slices the base stations and radio resources. Individual controllers manage and control the radio resources for the various slices according to subscriber demands. The controllers conduct admission control for the sliced resources and provide mobility. CellVisor extends FlowVisor through the new feature of slicing the base station resources. Moreover, CellVisor adds a so called “slicing of the semantic space.” The semantic space encompasses all subscribers whose packets belong to the same classification. An example classification could be traffic of all roaming subscribers or all subscribers from a specific mobile Internet provider. For differentiation, CellVisor uses MPLS tags or VLAN tags.

2) *RadioVisor*: The conceptual structure and operating principles of a RadioVisor for sharing radio access networks are presented in [153], [177]. RadioVisor considers a three dimensional (3D) resource grid consisting of space (represented through spatially distributed radio elements), time slots, and frequency slots. The radio resources in the 3D resource grid are sliced by RadioVisor to enable sharing by different controllers. The controllers in turn provide wireless services to applications. RadioVisor periodically (for each time window with a prescribed duration) slices the 3D resource grid to assign radio resources to the controllers. The resource allocation is based on the current (or predicted) traffic load of the controllers and their service level agreement with RadioVisor. Each controller is then allowed to control its allocated radio resources from the 3D resource grid for the duration of the current time window. A key consideration for RadioVisor is that the radio resources allocated to distinct controllers should have isolated wireless communication properties. Each controller should be able to independently utilize its allocated radio resources without coordinating with other controllers. Therefore, RadioVisor can allocate the same time and frequency slot to multiple spatially distributed radio elements only if the radio elements are so far apart that they do not interfere with each other when simultaneously transmitting on the same frequency.

3) *MobileVisor*: The application of the FlowVisor approach for mobile networks is outlined through the overview of a MobileVisor architecture in [154]. MobileVisor integrates the

FlowVisor functionality into the architectural structure of a virtual mobile packet (core) network that can potentially consist of multiple underlying physical mobile networks, e.g., a 3G and a 4G network.

4) *Optical FlowVisor*: For the context of an SDN-based optical network [178], the architecture and initial experimental results for an Optical FlowVisor have been presented in [155]. Optical FlowVisor employs the FlowVisor principles to create virtual optical networks (VONs) from an underlying optical circuit-switched network. Analogous to the consideration of the wireless communication properties in RadioVisor (see Section V-C2), Optical FlowVisor needs to consider the physical layer impairments of the optical communication channels (e.g., wavelength channels in a WDM network [38]). The VONs should be constructed such that each controller can utilize its VON without experiencing significant physical layer impairments due to the transmissions on other VONs.

5) *EnterpriseVisor*: For an enterprise network with a specific configuration, an EnterpriseVisor is proposed in [156] to complement the operation of the conventional FlowVisor. The EnterpriseVisor operates software modules in the hypervisor layer to monitor and analyze the network deployment. Based on the network configuration stored in a database in the EnterpriseVisor, the goal is to monitor the FlowVisor operation and to assist FlowVisor with resource allocation.

D. Policy-Based Hypervisors

In this section, we survey hypervisors that focus on supporting heterogeneous SDN controllers (and their corresponding network applications) while providing the advantages of virtualization, e.g., abstraction and simplicity of management. The policy-based hypervisors compose OF rules for operating SDN switches from the inputs of multiple distinct network applications (e.g., a firewall application and a load balancing application) and corresponding distinct SDN controllers.

1) *Compositional Hypervisor*: The main goal of the Compositional Hypervisor [157] is to provide a platform that allows SDN network operators to choose network applications developed for different SDN controllers. Thereby, the Compositional Hypervisors gives network operators the flexibility to choose from a wide range of SDN applications, i.e., operators are not limited to the specifics of only one particular SDN controller (and the network applications supported by the controller). The Compositional Hypervisor enables SDN controllers to “logically” cooperate on the same traffic. For conceptual illustration, consider Fig. 1(b) and suppose that App₁₁ is a firewall application written for the vSDN 1 Controller, which is the Python controller Ryu [75]. Further suppose that App₂₁ is a load-balancing application written for the vSDN 2 Controller, which is the C++ controller NOX [69]. The Compositional Hypervisor allows these two distinct network applications through their respective vSDN controllers to logically operate on the same traffic.

Instead of strictly isolating the traffic, the Compositional Hypervisor forms a “composed policy” from the individual policies of the multiple vSDN controllers. More specifically, a policy represents a prioritized list of OF rules for operating each

SDN switch. According to the network applications, the vSDN controllers give their individual policies to the Compositional Hypervisor. The Compositional Hypervisor, in turn, prepares a composed policy, i.e., a composed prioritized list of OF rules for the SDN switches. The individual policies are composed according to a composition configuration. For instance, in our firewall and load balancing example, a reasonable composition configuration may specify that the firewall rules have to be processed first and that the load-balancing rules are not allowed to overwrite the firewall rules.

The Compositional Hypervisor evaluation in [157] focuses on the overhead for the policy composition. The Compositional Hypervisor needs to update the composed policy when a vSDN controller wants to add, update, or delete an OF rule. The overhead is measured in terms of the computation overhead and the rule-update overhead. The computation overhead is the time for calculating the new flow table, which has to be installed on the switch. The rule-update overhead is the amount of messages that have to be sent to convert the old flow table state of a switch to the newly calculated flow table.

2) *CoVisor*: CoVisor [158] builds on the concept of the Compositional Hypervisor. Similar to the Compositional Hypervisor, CoVisor focuses on the cooperation of heterogeneous SDN controllers, i.e., SDN controllers written in different programming languages, on the same network traffic. While the Compositional Hypervisor study [157] focused on algorithms for improving the policy composition process, the CoVisor study [158] focuses on improving the performance of the physical SDN network, e.g., how to compose OF rules to save flow table space or how to abstract the physical SDN topology to improve the performance of the vSDN controllers. Again, the policies (prioritized OF rules) from multiple network applications running on different vSDN controllers are composed to a single composed policy, which corresponds to a flow table setting. The single flow table still has to be correct, i.e., to work as if no policy composition had occurred. Abstraction mechanisms are developed in order to provide a vSDN controller with only the “necessary” topology information. For instance, a firewall application may not need a detailed view of the underlying topology in order to decide whether packets should be dropped or forwarded. Furthermore, CoVisor provides mechanisms to protect the physical SDN network against malicious or buggy vSDN controllers.

The CoVisor performance evaluation in [158] compares the CoVisor policy update algorithm with the Compositional Hypervisor algorithm. The results show improvements on the order of two to three orders of magnitude due to the more sophisticated flow table updates and the additional virtualization capabilities (topology abstraction).

VI. DISTRIBUTED HYPERVERISORS

A. Execution on General Computing Platform

1) *FlowN*: FlowN [159] is a distributed hypervisor for virtualizing SDN networks. However, tenants cannot employ their own vSDN controller. Instead, FlowN provides a container-based application virtualization. The containers host the tenant

controllers, which are an extension of the NOX controller. Thus, FlowN users are limited to the capabilities of the NOX controller.

Instead of only slicing the physical network, FlowN completely abstracts the physical network and provides virtual network topologies to the tenants. An advantage of this abstraction is, for example, that virtual nodes can be transparently migrated on the physical network. Tenants are not aware of these resource management actions as they see only their virtual topologies. Furthermore, FlowN presents only virtual address spaces to the tenants. Thus, FlowN always has to map between virtual and physical address spaces. For this purpose, FlowN uses an additional data base component for providing a consistent mapping. For scalability, FlowN relies on a master-slave database principle. The state of the master database is replicated among multiple slave databases. Using this database concept, FlowN can be distributed among multiple physical servers. Each physical server can be equipped with a database and a controller, which is hosting a particular number of containers, i.e., controllers.

To differentiate between vSDNs, edge switches encapsulate and decapsulate the network packets with VLAN tagging. Furthermore, each tenant gets only a pre-reserved amount of available flowspace on each switch. In order to provide resource isolation between the tenant controllers, FlowN assigns one processing thread per container.

The evaluation in [159] compares the FlowN architecture with two databases with FlowVisor in terms of the hypervisor latency overhead. The number of virtual networks is increased from 0 to 100. While the latency overhead of FlowVisor increases steadily, FlowN always shows a constant latency overhead. However, the latency overhead of FlowVisor is lower for 0 to 80 virtual networks than for FlowN.

2) *Network Hypervisor*: The Network Hypervisor [160] addresses the challenge of “stitching” together a vSDN slice from different underlying physical SDN infrastructures (networks). The motivation for the Network Hypervisor is the complexity of SDN virtualization arising from the current heterogeneity of SDN infrastructures. Current SDN infrastructures provide different levels of abstraction and a variety of SDN APIs. The proposed Network Hypervisor mainly contributes to the abstraction of multiple SDN infrastructures as a virtual slice. Similar to FlowN, the Network Hypervisor acts as a controller to the network applications of the vSDN tenants. Network applications can use a higher-level API to interact with the Network Hypervisor, while the Network Hypervisor interacts with the different SDN infrastructures and complies with their respective API attributes. This Network Hypervisor design provides vSDN network applications with a transparent operation of multi-domain SDN infrastructures.

A prototype Network Hypervisor was implemented on top of GENI testbed and supports the GENI API [17]. The demonstration in [160] mapped a virtual SDN slice across both a Kentucky Aggregate and a Utah Aggregate on the GENI testbed. The Network Hypervisor fetches resource and topology information from both aggregates via the discover API call.

3) *AutoSlice*: AutoSlice [161], [179] strives to improve the scalability of a logically centralized hypervisor by distributing

the hypervisor workload. AutoSlice targets software deployment on general-purpose computing platforms. The AutoSlice concept segments the physical infrastructure into non-overlapping SDN domains. The AutoSlice hypervisor is partitioned into a single management module and multiple controller proxies, one proxy for each SDN physical domain. The management module assigns the virtual resources to the proxies. Each proxy stores the resource assignment and translates the messages exchanged between the vSDN controllers and the physical SDN infrastructure in its domain. Similar to FlowVisor, AutoSlice is positioned between the physical SDN network and the vSDN controllers, see Fig. 1(b). AutoSlice abstracts arbitrary SDN topologies, processes and rewrites control messages, and enables SDN node and link migration. In case of migrations due to substrate link failures or vSDN topology changes, AutoSlice migrates the flow tables and the affected network traffic between SDN switches in the correct update sequence.

Regarding isolation, a partial control plane offloading could be offered by distributing the hypervisor over multiple proxies. For scalability, AutoSlice deploys auxiliary software datapaths (ASDs) [180]. Each ASD is equipped with a software switch, e.g., Open vSwitch (OVS) [181], running on a commodity server. Commodity servers have plentiful memory and thus can cache the full copies of the OF rules. Furthermore, to improve scalability on the virtual data plane, AutoSlice differentiates between mice and elephant network flows [182]–[184]. Mice flows are cached in the corresponding ASD switches, while elephant flows are stored in the dedicated switches. AutoSlice uses a so-called virtual flow table identifier (VTID) to differentiate flow table entries of vSDNs on the SDN switches. For realization of the VTIDs, AutoSlice assumes the use of MPLS [33] or VLAN [174] techniques. Using this technique, each vSDN receives the full flowspace. Within each SDN domain, the control plane isolation problem still persists. The AutoSlice studies [161], [179] do not provide any performance evaluation, nor demonstrate a prototype implementation.

4) *NVP*: The Network Virtualization Platform (NVP) [162] targets the abstraction of data center network resources to be managed by cloud tenants. In today's multi-tenant data centers, computation and storage have long been successfully abstracted by computing hypervisors, e.g., VMware [5], [6] or KVM [4]. However, tenants have typically not been given the ability to manage the cloud's networking resources.

Similar to FlowN, NVP does not allow tenants to run their own controllers. NVP acts as a controller that provides the tenants' applications with an API to manage their virtual slice in the data center. NVP wraps the ONIX controller platform [184], and thus inherits the distributed controller architecture of ONIX. NVP can run a distributed controller cluster within a data center to scale to the operational load and requirements of the tenants.

NVP focuses on the virtualization of the SDN software switches, e.g., Open vSwitches (OVSs) [186], that steer the traffic to virtual machines (VMs), i.e., NVP focuses on the software switches residing on the host servers. The network infrastructure in the data center between servers is not controlled by NVP, i.e., not virtualized. The data center physical network

is assumed to provide a uniform balanced capacity, as is common in current data centers. In order to virtualize (abstract) the physical network, NVP creates logical datapaths, i.e., overlay tunnels, between the source and destination OVSs. Any packet entering the host OVS, either from a VM or from the overlay tunnel is sent through a logical pipeline corresponding to the logical datapath to which the packet belongs.

The logical paths and pipelines abstract the data plane for the tenants, whereby a logical path and a logical pipeline are assigned for each virtual slice. NVP abstracts also the control plane, whereby a tenant can set the routing configuration and protocols to be used in its virtual slice. Regarding isolation, NVP assigns flow tables from the OVSs to each logical pipeline with a unique identifier. This enforces isolation from other logical datapaths and places the lookup entry at the proper logical pipeline.

The NVP evaluation in [162] focuses on the concept of logical datapaths, i.e., tunnels for data plane virtualization. The throughput of two encapsulation methods for tunneling, namely Generic Routing Encapsulation (GRE) [187] and Stateless Transport Tunneling (STT) [188], is compared to a non-tunneled (non-encapsulated) benchmark scenario. The results indicate that STT achieves approximately the same throughput as the non-tunneled benchmark, whereas GRE encapsulation reduces the throughput to less than a third (as GRE does not employ hardware offloading).

B. Computing Platform + General-Purpose NE Based

1) *OpenVirteX*: OpenVirteX [77], [163], [164] provides two main contributions: address virtualization and topology virtualization. OpenVirteX builds on the design of FlowVisor, and operates (functions) as an intermediate layer between vSDNs and controllers.

OpenVirteX tackles the so-called flowspace problem: The use of OF header fields to distinguish vSDNs prevents hypervisors from offering the entire OF header fields space to the vSDNs. OpenVirteX provides each tenant with the full header fields space. In order to achieve this, OpenVirteX places edge switches at the borders of the physical SDN network. The edge switches re-write the virtually assigned IP and MAC addresses, which are used by the hosts of each vSDN (tenant), into disjoint addresses to be used within the physical SDN network. The hypervisor ensures that the correct address mapping is stored at the edge switches. With this mapping approach, the entire flowspace can be provided to each vSDN.

To provide topology abstraction, OpenVirteX does not operate completely transparently (compared to the transparent FlowVisor operation). Instead, as OpenVirteX knows the exact mapping of virtual to physical networks, OpenVirteX answers Link Layer Discovery Protocol (LLDP) [189] controller messages (instead of the physical SDN switches). No isolation concepts, neither for the data plane, nor for the control plane, have been presented. In addition to topology customization, OpenVirteX provides an advanced resilience feature based on its topology virtualization mechanisms. A virtual link can be mapped to multiple physical links; vice versa, a virtual SDN switch can be realized by multiple physical SDN counterparts.

The OpenVirteX evaluation in [77], [163], [164] compares the control plane latency overheads of OpenVirteX, FlowVisor, FlowN, and a reference case without virtualization. For benchmarking, Cbench [70] is used and five switch instances are created. Each switch serves a specific number of hosts, serving as one virtual network per switch. Compared to the other hypervisors, OpenVirteX achieves better performance and adds a latency of only 0.2 ms compared to the reference case. Besides the latency, also the instantiation time of virtual networks was benchmarked.

2) *OpenFlow-Based Virtualization Framework for the Cloud (OF NV Cloud)*: OF NV Cloud [165] addresses virtualization of data centers, i.e., virtualization inside a data center and virtualization of the data center interconnections. Furthermore, OF NV Cloud addresses the virtualization of multiple physical infrastructures. OF NV Cloud uses a MAC addressing scheme for address virtualization. In order to have unique addresses in the data centers, the MAC addresses are globally administered and assigned. In particular, the MAC address is divided into a 14 bit *vio_id* (virtual infrastructure operator) field, a 16 bit *vnode_id* field, and a 16 bit *vhost_id* field. In order to interconnect data centers, parts of the *vio_id* field are reserved. The *vio_id* is used to identify vSDNs (tenants). The resource manager, i.e., the entity responsible for assigning and managing the unique MAC addresses as well as for access to the infrastructure, is similarly designed as FlowVisor. However, the OF NV Cloud virtualization cannot be implemented for OF 1.1 as it does not provide rules based on MAC prefixes. In terms of data plane resources, flow tables of switches are split among vSDNs. No evaluation of the OF NV Cloud architecture has been reported.

3) *AutoVFlow*: AutoVFlow [166], [190] is a distributed hypervisor for SDN virtualization. In a wide-area network, the infrastructure is divided into non-overlapping domains. One possible distributed hypervisor deployment concept has a proxy responsible for each domain and a central hypervisor administrator that configures the proxies. The proxies would only act as containers, similar to the containers in FlowN, see Section VI-A-1, to enforce the administrator's configuration, i.e., abstraction and control plane mapping, in their own domain. The motivation for AutoVFlow is that such a distributed structure would highly load the central administrator. Therefore, AutoVFlow removes the central administrator and delegates the configuration role to distributed administrators, one for each domain. From an architectural point-of-view, AutoVFlow adopts a flat distributed hypervisor architecture without hierarchy.

Since a virtual slice can span multiple domains, the distributed hypervisor administrators need to exchange the virtualization configuration and policies among each other in order to maintain the slice state. AutoVFlow uses virtual identifiers, e.g., virtual MAC addresses, to identify data plane packet flows from different slices. These virtual identifiers can be different from one domain to the other. In case a packet flow from one slice is entering another domain, the hypervisor administrator of the new domain identifies the virtual slice based on the identifier of the flow in the previous domain. Next, the administrator of the new domain replaces the identifier from the previous domain by the identifier assigned in the new domain.

The control plane latency overhead induced by adding AutoVFlow, between the tenant controller and the SDN network, has been evaluated in [166], [190]. The evaluation setup included two domains with two AutoVFlow administrators. The latency was measured for OF PCKT_IN, PCKT_OUT, and FLOW_MOD messages. The highest impact was observed for FLOW_MOD messages, which experienced a latency overhead of 5.85 ms due to AutoVFlow.

C. Computing Platform + Special-Purpose NE-Based

1) *Carrier-Grade*: A distributed SDN virtualization architecture referred to as Carrier-grade has been introduced in [167], [191]. Carrier-grade extends the physical SDN hardware in order to realize vSDN networks. On the data plane, vSDNs are created and differentiated via labels, e.g., MPLS labels, and the partitioning of the flow tables. In order to demultiplex encapsulated data plane packets and to determine the corresponding vSDN flow tables, a virtualization controller controls a virtualization table. Each arriving network packet is first matched against rules in the virtualization table. Based on the flow table entries for the labels, packets are forwarded to the corresponding vSDN flow tables. For connecting vSDN switches to vSDN controllers, Carrier-grade places translation units in every physical SDN switch. The virtualization controller provides the set of policies and rules, which include the assigned label, flow table, and port for each vSDN slice, to the translation units. Accordingly, each vSDN controller has only access to its assigned flow tables. Based on the sharing of physical ports, Carrier-grade uses different technologies, e.g., VLAN and per port queuing, to improve data plane performance and service guarantees.

The distributed Carrier-grade architecture aims at minimizing the overhead of a logically centralized hypervisor by providing direct access from the vSDN controllers to the physical infrastructure. However, Carrier-grade adds processing complexity to the physical network infrastructure. Thus, the Carrier-grade evaluation [167], [191] examines the impact of the additional encapsulation in the data plane on the latency and throughput. As a baseline setup with only one virtual network running on the data plane is considered, conclusions about the performance in case of interfering vSDNs and overload scenarios cannot be given. Carrier-grade adds a relative latency of 11%.

The evaluation in [167], [191] notes that the CPU load due to the added translation unit should be negligible. However, a deeper analysis has not been provided. The current Carrier-grade design does not specify how the available switch resources (e.g., CPU and memory) are used by the translation unit and are shared among multiple tenants. Furthermore, the scalability aspects have to be investigated in detail in future research.

2) *Datapath Centric*: Datapath Centric [168] is a hypervisor designed to address the single point of failure in the FlowVisor design [9] and to improve the performance of the virtualization layer by implementing virtualization functions as switch extensions. Datapath Centric is based on the eXtensible Datapath Daemon (xDPd) project, which is an open-source datapath

project [192]. xDPd in its used versions supports OF 1.0 and OF 1.2. Relying on xDPd, Datapath Centric simultaneously supports different OF switch versions, i.e., it can virtualize physical SDN networks that are composed of switches supporting OF versions from 1.0 to 1.2.

The Datapath Centric architecture consists of the Virtualization Agents (VAs, one in each switch) and a single Virtualization Agent Orchestrator (VAO). The VAO is responsible for the slice configuration and monitoring, i.e., adding slices, removing slices, or extending flowspace of existing slices. The VAs implement the distributed slicing functions, e.g., the translation function. They directly communicate with the vSDN controllers. Additionally, the VAs abstract the available switch resources and present them to the VAO. Due to the separation of VAs and VAO, Datapath Centric avoids the single point of failure in the FlowVisor architecture. Even in case the VAO fails, the VAs can continue operation. Datapath Centric relies on the flowspace concept as introduced by FlowVisor. Bandwidth isolation on the data plane is not available but its addition is in the planning based on the QoS capabilities of xDPd.

The latency overhead added by the VA agent has been evaluated for three cases [168]: a case only running xDPd without the VA (reference), a case where the VA component is added, and a final case where FV is used. The VA case adds an additional overhead of 18% compared to the reference case. The gap between the VA and FV is on average 0.429 ms. In a second evaluation, the scalability of Datapath Centric was evaluated for 500 to 10 000 rules. It is reported that the additional latency is constant from 100 to 500 rules, and then scales linearly from 500 to 10 000 rules, with a maximum of 3 ms. A failure scenario was not evaluated. A demonstration of Datapath Centric was shown in [193].

3) *DFVisor*: Distributed FlowVisor (DFVisor) [169], [170] is a hypervisor designed to address the scalability issue of FlowVisor as a centralized SDN virtualization hypervisor. DFVisor realizes the virtualization layer on the SDN physical network itself. This is done by extending the SDN switches with hypervisor capabilities, resulting in so-called “enhanced OpenFlow switches.” The SDN switches are extended by a local vSDN slicer and tunneling module. The slicer module implements the virtual SDN abstraction and maintains the slice configuration on the switch. DFVisor uses GRE tunneling [187] to slice the data plane and encapsulate the data flows of each slice. The adoption of GRE tunneling is motivated by the use of the GRE header stack to provide slice QoS.

DFVisor also includes a distributed synchronized two-level database system that consists of local databases on the switches and a global database. The global database maintains the virtual slices state, e.g., flow statistics, by synchronizing with the local databases residing on the switches. This way the global database can act as an interface to the vSDN controllers. Thereby, vSDN controllers do not need to access individual local databases, which are distributed on the switches. This can facilitate the network operation and improve the virtualization scalability.

4) *OpenSlice*: OpenSlice [171], [194] is a hypervisor design for elastic optical networks (EONs) [195], [196]. EONs adaptively allocate the optical communications spectrum to

end-to-end optical paths so as to achieve different transmission bit rates and to compensate for physical layer optical impairments. The end-to-end optical path are routed through the EON by distributed bandwidth-variable wavelength cross-connects (BV-WXCs) [196]. The OpenSlice architecture interfaces the optical layer (EON) with OpenFlow-enabled IP packet routers through multi-flow optical transponders (MOTPs) [197]. A MOTP identifies packets and maps them to flows.

OpenSlice extends the OpenFlow protocol messages to carry the EON adaption parameters, such as optical central frequency, slot width, and modulation format. OpenSlice extends the conventional MOTPs and BV-WXCs to communicate the EON parameters through the extended OpenFlow protocol. OpenSlice furthermore extends the conventional NOX controller to perform routing and optical spectrum assignment. The extended OpenSlice NOX controller assigns optical frequencies, slots, and modulation formats according to the traffic flow requirements.

The evaluation in [171] compares the path provisioning latency of OpenSlice with Generalized Multiple Protocol Label Switching (GMPLS) [198]. The reported results indicate that the centralized SDN-based control in OpenSlice has nearly constant latency as the number of path hops increases, whereas the hop-by-hop decentralized GMPLS control leads to increasing latencies with increasing hop count. Extensions of the OpenSlice concepts to support a wider range of optical transport technologies and more flexible virtualization have been examined in [178], [199]–[206].

5) *Advanced Capabilities*: The Advanced Capabilities OF virtualization framework [172] is designed to provide SDN virtualization with higher levels of flexibility than FlowVisor [9]. First, FlowVisor requires all SDN switches to operate with the same version of the OF protocol. The Advanced Capabilities framework can manage vSDNs that consist of SDN switches running different OF versions. The introduced framework also accommodates flexible forwarding mechanisms and flow matching in the individual switches. Second, the Advanced Capabilities framework includes a network management framework that can control the different distributed vSDN controllers. The network management framework can centrally monitor and maintain the different vSDN controllers. Third, the Advanced Capabilities framework can configure queues in the SDN switches so as to employ QoS packet scheduling mechanisms. The Advanced Capabilities framework implements the outlined features through special management modules that are inserted in the distributed SDN switches. The specialized management modules are based on the network configuration protocol [207] and use the YANG data modeling language [208]. The study [172] reports on a proof-of-concept prototype of the Advanced Capabilities framework, detailed quantitative performance measurements are not provided.

D. Computing Platform + Special- and General-Purpose NE-Based

1) *HyperFlex*: HyperFlex [173] introduces the idea of realizing the hypervisor layer via multiple different virtualization functions. Furthermore, HyperFlex explicitly addresses the

control plane virtualization of SDN networks. It can operate in a centralized or distributed manner. It can realize the virtualization according to the available capacities of the physical network and the commodity server platforms. Moreover, HyperFlex operates and interconnects the functions needed for virtualization, which as a whole realize the hypervisor layer. In detail, the HyperFlex concept allows to realize functions in software, i.e., they can be placed and run on commodity servers, or in hardware, i.e., they can be realized via the available capabilities of the physical networking (NE) hardware. The HyperFlex design thus increases the flexibility and scalability of existing hypervisors. Based on the current vSDN demands, hypervisor functions can be adaptively scaled. This dynamic adaptation provides a fine resource management granularity.

The HyperFlex concept has initially been realized and demonstrated for virtualizing the control plane of SDN networks. The software isolation function operates on the application layer, dropping OF messages that exceed a prescribed vSDN message rate. The network isolation function operates on layers 2–4, policing (limiting) the vSDN control channel rates on NEs. It was shown that control plane virtualization functions either realized in software or in hardware can isolate vSDNs. In case the hypervisor layer is over-utilized, e.g., its CPU is completely utilized, the performance of several or all vSDN slices can be degraded, even if only one vSDN is responsible for the over-utilization. In order to avoid hypervisor over-utilization due to a tenant, the hypervisor CPU has to be sliced as well. This means that specific amounts of the available CPU resources are assigned to the tenants. In order to quantify the relationship between CPU and control plane traffic per tenant, i.e., the amount of CPU resources needed to process the tenants' control traffic, the hypervisor has to be benchmarked first. The benchmarking measures, for example, the average CPU resource amount needed for the average control plane traffic, i.e., OF control packets. The hypervisor isolation functions are then configured according to the benchmark measurements, i.e., they are set to support a guaranteed OF traffic rate.

In order to achieve control plane isolation, software and hardware isolation solutions exhibit trade-offs, e.g., between OF control message latency and OF control message loss. More specifically, a hardware solution polices (limits) the OF control traffic on the network layer, for instance, through shapers (egress) or policers (ingress) of general-purpose or special-purpose NEs. However, the shapers do not specifically drop OF messages, which are application layer messages. This is because current OF switches cannot match and drop application layer messages (dropping specifically OF messages would require a proxy, as control channels may be encrypted). Thus, hardware solutions simply drop network packets based on matches up to layer 4 (transport layer). In case of using TCP as the control channel transmission protocol, the retransmissions of dropped packets lead to an increasing backlog of buffered packets in the sender and NEs; thus, increasing control message latency. On the other hand, the software solution drops OF messages arriving from the network stack in order to reduce the workload of subsequent hypervisor functions. This, however, means a loss of OF packets, which a tenant controller would have to compensate for. A demonstration of the HyperFlex

architecture with its hardware and software isolation functions was provided in [209].

VII. SUMMARY COMPARISON OF SURVEYED HYPERVISORS

In this section, we present a comparison of the surveyed SDN hypervisors in terms of the network abstraction attributes (see Section III-B) and the isolation attributes (see Section III-C). The comparison gives a summary of the differences between existing SDN hypervisors. The summary comparison helps to place the various hypervisors in context and to observe the focus areas and strengths, but also the limitations of each proposed hypervisor. We note that if an abstraction or isolation attribute is not examined in a given hypervisor study, we consider the attribute as not provided in the comparison.

A. Physical Network Attribute Abstraction

As summarized in Table II, SDN hypervisors can be differentiated according to the physical network attributes that they can abstract and provide to their tenant vSDN controllers in abstracted form.

1) *Topology Abstraction*: In a non-virtualized SDN network, the topology view assists the SDN controller in determining the flow connections and the network configuration. Similarly, a vSDN controller requires a topology view of its vSDN to operate its virtual SDN slice. A requested virtual link in a vSDN slice could be mapped onto several physical links. Also, a requested virtual node could map to a combination of multiple physical nodes. This abstraction of the physical topology for the vSDN controllers, i.e., providing an end-to-end mapping (embedding) of virtual nodes and links without exposing the underlying physical mapping, can bring several advantages. First, the operation of a vSDN slice is simplified, i.e., only end-to-end virtual resources need to be controlled and operated. Second, the actual physical topology is not exposed to the vSDN tenants, which may alleviate security concerns as well as concerns about revealing operational practices. Only two existing centralized hypervisors abstract the underlying physical SDN network topology, namely VerTIGO and CoVisor. Moreover, as indicated in Table II, a handful of decentralized hypervisors, namely FlowN, Network Hypervisor, AutoSlice, and OpenVirteX, can abstract the underlying physical SDN network topology.

We note that different hypervisors abstract the topology for different reasons. VerTIGO, for instance, targets the flexibility of the vSDNs and their topologies. CoVisor intends to hide unnecessary topology information from network applications. FlowN, on the other hand, abstracts the topology in order to facilitate the migration of virtual resources in a transparent manner to the vSDN tenants.

2) *Physical Node and Link Resource Abstraction*: In addition to topology abstraction, attributes of physical nodes and links can be abstracted to be provided within a vSDN slice to the vSDN controllers. As outlined in Section III-B, SDN physical node attributes include the CPU and flow tables, while physical link attributes include bandwidth, queues,

TABLE II
SUMMARY COMPARISON OF ABSTRACTION OF PHYSICAL NETWORK ATTRIBUTES BY EXISTING HYPERVERSORS (THE CHECK MARK INDICATES THAT A NETWORK ATTRIBUTE IS VIRTUALIZED; WHEREAS “-” INDICATES THAT A NETWORK ATTRIBUTE IS NOT VIRTUALIZED)

Classification			Hypervisor	Topology	Physical Node Resources	Physical Link Resources
Centr.	Gen. Comp. Platf.	Gen., Secs. V-A, V-B	FlowVisor [9]	-	-	-
			ADVisor [148]	-	✓	-
			VeRTIGO [149]	✓	✓	-
			Enhanced FlowVisor [150]	-	-	✓
			Slices Isolator [151]	-	✓	✓
			Double FlowVisor [152]	-	-	-
		Spec. Netw. Types, Sec. V-C	CellVisor [62], [63]	-	✓ (base station)	✓ (radio resources)
			RadioVisor [153]	-	-	✓ (radio link)
			MobileVisor [154]	-	-	-
			Optical FV [155]	-	✓	✓ (optical link)
			Enterprise Visor [156]	-	-	-
		Policy-b., Sec. V-D	Compositional Hypervisor [157]	-	-	-
			CoVisor [158]	✓	✓	-
Distr.	Gen. Comp. Platf., Sec. VI-A		FlowN [159]	✓	-	-
			Network Hypervisor [160]	✓	-	-
			AutoSlice [80], [161]	✓	-	-
			Network Virtualization Platform (NVP) [162]	-	✓	✓
	Gen. Comp. Platf. + Gen.-purp. NE, Sec. VI-B		OpenVirteX [77], [163], [164]	✓	-	-
			OF NV Cloud [165]	-	-	-
			AutoVFlow [166]	-	-	-
	Gen. Comp. Platf. + Spec.-purp. NE, Sec. VI-C		Carrier-grade [167]	-	✓	✓
			Datapath Centric [168]	-	-	-
			DFVisor [169], [170]	-	✓	✓
			OpenSlice [171]	-	-	-
			Advanced Capabilities [172]	-	-	✓
	Gen. Comp. Platf. + Gen.-purp. NE + Spec.-purp. NE, Sec. VI-D		Hyperflex [173]	-	-	-

and buffers. Among the centralized hypervisors that provide topology abstraction, there are a few that go a step further and provide also node and links abstraction, namely VeRTIGO and CoVisor. Other hypervisors provide node and link abstraction; however, no topology abstraction. This is mainly due to the distributed architecture of such hypervisors, e.g., Carrier-grade. The distribution of the hypervisor layer tends to complicate the processing of the entire topology to derive an abstract view of a virtual slice.

As surveyed in Section V-C, hypervisors for special network types, such as wireless or optical networks, need to consider the unique characteristics of the node and link resources of these special network types. For instance, in wireless networks, the characteristics of the wireless link resources involve several aspects of physical layer radio communication, such as the spatial distribution of radios as well as the radio frequencies and transmission time slots).

3) *Summary*: Overall, we observe from Table II that only less than half of the cells have a check mark (✓), i.e., provide some abstraction of the three considered network attributes. Most existing hypervisors have focused on abstracting only one (or two) specific network attribute(s). However, some hypervisor studies have not addressed abstraction at all, e.g., FlowVisor, Double FlowVisor, Mobile FlowVisor, Enterprise Visor, and HyperFlex. Abstraction of the physical network attributes, i.e., the network topology, as well as the node and link resources, is a complex problem, particularly for distributed hy-

pervisor designs. Consequently, many SDN hypervisor studies to date have focused on the creation of the vSDN slices and their isolation. We expect that as hypervisors for virtualizing SDN networks mature, more studies will strive to incorporate abstraction mechanisms for two and possibly all three physical network attributes.

B. Virtual SDN Network Isolation Attributes and Mechanisms

Another differentiation between the SDN hypervisors is in terms of the isolation capabilities that they can provide between the different vSDN slices, as summarized in Table III. As outlined in Section III-C, there are three main network attributes that require isolation, namely the hypervisor resources in the control plane, the physical nodes and links in the data plane, and the addressing of the vSDN slices.

1) *Control Plane Isolation*: Control plane isolation should encompass the hypervisor instances as well as the network communication used for the hypervisor functions, as indicated in Fig. 4. However, existing hypervisor designs have only addressed the isolation of the instances, and we limit Table III and the following discussion therefore to the isolation of hypervisor instances. Only few existing hypervisors can isolate the hypervisor instances in the control plane, e.g., Compositional Hypervisor, FlowN, and HyperFlex. Compositional Hypervisor and CoVisor isolate the control plane instances in terms of network rules and policies. Both hypervisors compose the rules

TABLE III
SUMMARY COMPARISON OF VIRTUAL SDN NETWORK ISOLATION ATTRIBUTES

Classification			Hypervisor	Control Plane Instances	Nodes	Data Plane Links	Virtual SDN Network Addressing
Centr.	Gen. Comp. Platf.	Gen., Secs. V-A, V-B	FlowVisor [9]	–	Flow CPU	Tables, Bandwidth (BW)	Configurable non-overlapping flowspace
			ADVisor [148]	–	Flow CPU	Tables, BW	VLAN, MPLS
			VeRTIGO [149]	–	–	–	–
			Enhanced FlowVisor [150]	–	–	BW	–
			Slice Isolator [151]	–	Flow Tables	BW, queues, buffers	–
			Double FlowVisor [152]	–	–	–	–
		Spec. Netw. Types, Sec. V-C	CellVisor [62], [63]	–	–	Radio (space, time, freq.)	MAC (base station)
			RadioVisor [153]	–	–	Radio (space, time, freq.)	–
			MobileVisor [154]	–	–	–	–
			Optical FV [155]	–	–	Optical (wavelength)	–
			Enterprise Visor [156]	–	–	–	–
		Policy-b., Sec. V-D	Compositional Hypervisor [157]	Rules	–	–	–
			CoVisor [158]	Rules	–	–	–
Distr.	Gen. Comp. Platf., Sec. VI-A		FlowN [159]	Threads	–	–	VLAN
			Network Hypervisor [160]	APIs	–	–	–
			AutoSlice [80], [161]	–	Flow Tables	–	VLAN, MPLS
			Netw. Virt. Platform (NVP) [162]	–	Flow Tables	BW, queues	–
	Gen. Comp. Platf. + Gen.-purp. NE, Sec. VI-C		OpenVirteX [77], [163], [164]	–	Flow Tables, CPU	BW	Configurable overlapping flowspace
			OF NV Cloud [165]	–	Flow Tables	–	MAC
			AutoVFlow [166]	–	–	–	–
			Carrier-grade [167]	–	Flow tables	BW	VLAN, VxLAN, PWE
	Gen. Comp. Platf. + Spec.-purp. NE, Sec. VI-C		Datapath Centric [168]	–	–	–	–
			DFVisor [169], [170]	–	–	–	GRE
			OpenSlice [171]	–	–	Optical (wavel., time)	–
			Advanced Capabilities [172]	–	–	BW, queues	–
	Gen. Comp. Platf. + Gen.-purp. NE + Spec.-purp. NE, Sec. VI-D		Hyperflex [173]	CPU	–	–	–

enforced by vSDN controllers to maintain consistent infrastructure control. They also ensure a consistent and non-conflicting state for the SDN physical infrastructure.

FlowN isolates the different hypervisor instances (control slices) in terms of the process handling by allocating a processing thread to each slice. The allocation of multiple processing threads avoids the blocking and interference that would occur if the control planes of multiple slices were to share a single thread. Alternatively, Network Hypervisor provides isolation in terms of the APIs used to interact with underlying physical SDN infrastructures.

HyperFlex ensures hypervisor resource isolation in terms of CPU by restraining the control traffic of each slice. HyperFlex restrains the slice control traffic either by limiting the control traffic at the hypervisor software or by throttling the control traffic throughput on the network.

2) *Data Plane Isolation*: Several hypervisors have aimed at isolating the physical data plane resources. For instance, considering the data plane SDN physical nodes, FlowVisor and ADVisor split the SDN flow tables and assign CPU resources. The CPU resources are indirectly assigned by controlling the OF control messages of each slice.

Several hypervisors isolate the link resources in the data plane. For instance, Slices Isolator and Advanced Capabilities, can provide bandwidth guarantees and separate queues or buffers to each virtual slice. Domain/Technology-specific hypervisors, e.g., RadioVisor and OpenSlice, focus on providing link isolation in their respective domains. For instance, RadioVisor splits the radio link resources according to the frequency, time, and space dimensions, while OpenSlice adapts isolation to the optical link resources, i.e., the wavelength and time dimensions.

3) *vSDN Address Isolation*: Finally, isolation is needed for the addressing of vSDN slices, i.e., the unique identification of each vSDN (and its corresponding tenant). There have been different mechanisms for providing virtual identifiers for SDN slices. FlowVisor has the flexibility to assign any of the OF fields as an identifier for the virtual slices. However, FlowVisor has to ensure that the field is used by all virtual slices. For instance, if the VLAN PCP field (see Section V-A3) is used as the identifier for the virtual slices, then all tenants have to use the VLAN PCP field as slice identifier and cannot use the VLAN PCP field otherwise in their slice. Consequently, the flowspace of all tenants is reduced by the identification

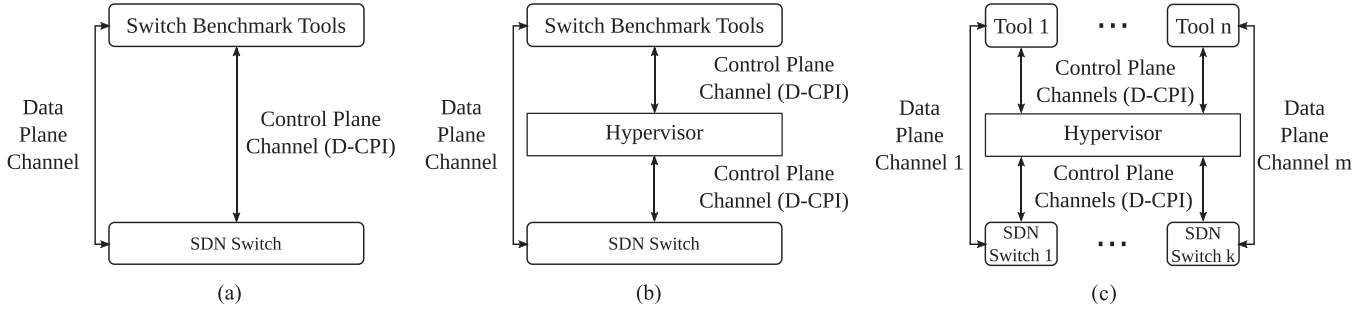


Fig. 7. Conceptual comparison of switch benchmarking setups: switch benchmark (evaluation) tools are directly connected to an SDN switch in the nonvirtualized SDN setup. In the virtualized SDN setups, the control plane channel (D-CPI) passes through the evaluated hypervisor. (a) Nonvirtualized SDN switch benchmarking. (b) Virtualized SDN switch benchmarking: single vSDN switch. (c) Virtualized SDN switch benchmarking: multiple vSDN switches.

header. This in turn ensures that the flowspaces of all tenants are non-overlapping.

Several proposals have defined specific addressing header fields as slice identifier, e.g., ADVisor the VLAN tag, AutoSlice the MPLS labels and VLAN tags, and DFVisor the GRE labels. These different fields have generally different matching performance in OF switches. The studies on these hypervisors have attempted to determine the identification header for virtual slices that would not reduce the performance of today's OF switches. However, the limitation of not providing the vSDN controllers with the full flowspace, to match on for their clients, still persists.

OpenVirteX has attempted to solve this flowspace limitation problem. The solution proposed by OpenVirteX is to rewrite the packets at the edge of the physical network by virtual identifiers that are locally known by OpenVirteX. Each tenant can use the entire flowspace. Thus, the virtual identification fields can be flexibly changed by OpenVirteX. OpenVirteX transparently rewrites the flowspace with virtual addresses, achieving a configurable overlapping flowspace for the virtual SDN slices.

4) *Summary*: Our comparison, as summarized in Table III, indicates that a lesson learned from our survey is that none of the existing hypervisors fully isolates all network attributes. Most hypervisor designs focus on the isolation of one or two network attributes. Relatively few hypervisors isolate three of the considered network attributes, namely FlowVisor, OpenVirteX, and Carrier-grade isolate node and link resources on the data plane, as well as the vSDN addressing space. We believe that comprehensively addressing the isolation of network attributes is an important direction for future research.

VIII. HYPERVISOR PERFORMANCE EVALUATION FRAMEWORK

In this section, we outline a novel performance evaluation framework for virtualization hypervisors for SDN networks. More specifically, we outline the performance evaluation of pure virtualized SDN environments. In a pure virtualized SDN environment, the hypervisor has full control over the entire physical network infrastructure. (We do not consider the operation of a hypervisor in parallel with legacy SDN networks, since available hypervisors do not support such a parallel operation scenario.) As background on the performance evaluation

of virtual SDN networks, we first provide an overview of existing benchmarking tools and their use in non-virtualized SDN networks. In particular, we summarize the state-of-the-art benchmarking tools and performance metrics for SDN switches, i.e., for evaluating the data plane performance, and for SDN controllers, i.e., for evaluating the control plane performance. Subsequently, we introduce our performance evaluation framework for benchmarking hypervisors for creating virtual SDN networks (vSDNs). We outline SDN hypervisor performance metrics that are derived from the traditional performance metrics for non-virtualized environments. In addition, based on virtual network embedding (VNE) performance metrics (see Section II-A), we outline general performance metrics for virtual SDN environments.

A. Background: Benchmarking Non-Virtualized SDN Networks

In this subsection, we present existing benchmarking tools and performance metrics for non-virtualized SDN networks. In a non-virtualized (conventional) SDN network, there is no hypervisor; instead, a single SDN controller directly interacts with the network of physical SDN switches, as illustrated in Fig 1(a).

1) *SDN Switch Benchmarking*: In a non-virtualized SDN network, the SDN switch benchmark tool directly measures the performance of one SDN switch, as illustrated in Fig. 7(a). Accordingly, switch benchmarking tools play two roles: The first role is that of the SDN controller as illustrated in Fig. 1(a). The switch benchmarking tools connect to the SDN switches via the control plane channels (D-CPI). In the role of SDN controller, the tools can, for instance, measure the time delay between sending OF status requests and receiving the reply under varying load scenarios. Switch benchmarking tools are also connecting to the data plane of switches. This enables the tools to play their second role, namely the measurement of the entire chain of processing elements of network packets. Specifically, the tools can measure the time from sending a packet into the data plane, to being processed by the controller, and finally to being forwarded on the data plane.

Examples of SDN switch benchmarking tools are OFTest [210], OFLOPS [144], and FLOPS-Turbo [211]. OFTest was developed to verify the correct implementation of the OF protocol specifications of SDN switches. OFLOPS was

developed in order to shed light on the different implementation details of SDN switches. Although the OF protocol provides a common interface to SDN switches, implementation details of SDN switches are vendor-specific. Thus, for different OF operations, switches from different vendors may exhibit varying performance. The OFLOPS SDN switch measurements target the OF packet processing actions as well as the update rate of the OF flow table and the resulting impact on the data plane performance. OFLOPS can also evaluate the monitoring provided by OF and cross-effects of different OF operations. In the following, we explain these different performance metrics in more detail:

a) OF packet processing: OF packet processing encompasses all operations that directly handle network packets, e.g., matching, forwarding, or dropping. Further, the current OF specification defines several packet modifications actions. These packet modification actions can rewrite protocol header fields, such as MAC and IP addresses, as well as protocol-specific VLAN fields.

b) OF flow table updates: OF flow table updates add, delete, or update existing flow table entries in an SDN switch. Flow table updates result from control decisions made by the SDN controller. As flow tables play a key role in SDN networks (comparable to the Forwarding Information Base (FIB) [212] in legacy networks), SDN switch updates should be completed within hundreds of microseconds as in legacy networks [213]. OFLOPS measures the time until an action has been applied on the switch. A possible measurement approach uses barrier request/reply messages, which are defined by the OF specification [36], [214]. After sending an OF message, e.g., a flow mod message, the switch replies with a barrier reply message when the flow mod request has actually been processed. As it was shown in [143] that switches may send barrier reply messages even before a rule has really been applied, a second measurement approach is needed. The second approach incorporates the effects on the data plane by measuring the time period from the instant when a rule was sent to the instant when its effect can be recognized on the data plane. The effect can, for instance, be a packet that is forwarded after a forwarding rule has been added.

c) OF monitoring capabilities: OF monitoring capabilities provide flow statistics. Besides per-flow statistics, OF can provide statistics about aggregates, i.e., aggregated flows. Statistics count bytes and packets per flow or per flow aggregate. The current statistics can serve as basis for network traffic estimation and monitoring [215]–[217] as well as dynamic adoptions by SDN applications and traffic engineering [218], [219]. Accurate up-to-date statistical information is therefore important. Accordingly, the time to receive statistics and the consistency of the statistical information are performance metrics for the monitoring capabilities.

d) OF operations cross-effects and impacts: All available OF features can be used simultaneously while operating SDN networks. For instance, while an SDN switch makes traffic steering decisions, an SDN controller may request current statistics. With network virtualization, which is considered in detail in Section VIII-B, a mixed operation of SDN switches (i.e., working simultaneously on a mix of OF features) is common. Accordingly, measuring the performance of an SDN

switch and network under varying OF usage scenarios is important, especially for vSDNs.

e) Data plane throughput and processing delay: In addition to OF-specific performance metrics for SDN switches, legacy performance metrics should also be applied to evaluate the performance of a switch entity. These legacy performance metrics are mainly the data plane throughput and processing delay for a specific switch task. The data plane throughput is usually defined as the rate of packets (or bits) per second that a switch can forward. The evaluation should include a range of additional tasks, e.g., labeling or VLAN tagging. Although legacy switches are assumed to provide line rate throughput for simple tasks, e.g., layer 2 forwarding, they may exhibit varying performance for more complex tasks, e.g., labeling tasks. The switch processing time typically depends on the complexity of a specific task and is expressed in terms of the time that the switch needs to complete a specific single operation.

2) SDN Controller Benchmarking: Implemented in software, SDN controllers can have a significant impact on the performance of SDN networks. Fig. 8(a) shows the measurement setup for controller benchmarks. The controller benchmark tool emulates SDN switches, i.e., the benchmark tool plays the role of the physical SDN network (the network of SDN switches) in Fig. 1(a). The benchmark tool can send arbitrary OF requests to the SDN controller. Further, it can emulate an arbitrary number of switches, e.g., to examine the scalability of an SDN controller. Existing SDN controller benchmark tools include Cbench [70], OFCBenchmark [220], OFCProbe [221], and PktBlaster [222]. In [70], two performance metrics of SDN controllers were defined, namely the controller OF message throughput and the controller response time.

a) Controller OF message throughput: The OF message throughput specifies the rate of messages (in units of messages/s) that an SDN controller can process on average. This throughput is an indicator for the scalability of SDN controllers [223]. In large-scale networks, SDN controllers may have to serve on the order of thousands of switches. Thus, a high controller throughput of OF messages is highly important. For instance, for each new connection, a switch sends a OF PCKT_IN message to the controller. When many new flow connections are requested, the controller should respond quickly to ensure short flow set-up times.

b) Controller response time: The response time of an SDN controller is the time that the SDN controller needs to respond to a message, e.g., the time needed to create a reply to a PCKT_IN message. The response time is typically related to the OF message throughput in that a controller with a high throughput has usually a short response time.

The response time and the OF message throughput are also used as scalability indicators. Based on the performance, it has to be decided whether additional controllers are necessary. Furthermore, the metrics should be used to evaluate the performance in a best-effort scenario, with only one type of OF message, and in mixed scenarios, with multiple simultaneous types of OF messages [221]. Evaluations and corresponding refinements of non-virtualized SDN controllers are examined in ongoing research, see e.g., [224]. Further evaluation techniques for non-virtualized SDN controllers have recently been studied,

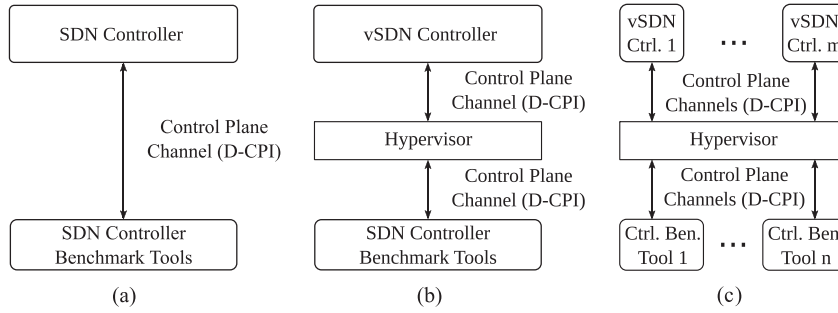


Fig. 8. Conceptual comparison of controller benchmarking setups: in the nonvirtualized setup, the SDN controller benchmark (evaluation) tools are directly connected to the SDN controller. In the vSDN setups, the control plane channel (D-CPI) traverses the evaluated hypervisor. (a) Nonvirtualized SDN controller benchmarking. (b) Virtualized SDN controller benchmarking: single vSDN controller. (c) Virtualized SDN controller benchmarking: multiple vSDN controllers.

e.g., the verification of the correctness of SDN controller programs [225]–[227] and the forwarding tables [228], [229].

B. Benchmarking SDN Network Hypervisors

In this section, we outline a comprehensive evaluation framework for hypervisors that create vSDNs. We explain the range of measurement set-ups for evaluating (benchmarking) the performance of the hypervisor. In general, the operation of the isolated vSDNs should efficiently utilize the underlying physical network. With respect to the run-time performance, a vSDN should achieve a performance level close to the performance level of its non-virtualized SDN network counterpart (without a hypervisor).

1) *vSDN Embedding Considerations*: As explained in Section II-A, with network virtualization, multiple virtual networks operate simultaneously on the same physical infrastructure. This simultaneous operation generally applies also to virtual SDN environments. That is, multiple vSDNs share the same physical SDN network resources (infrastructure). In order to achieve a high utilization of the physical infrastructure, resource management algorithms for virtual resources, i.e., node and link resources, have to be applied. In contrast to the traditional assignment problem, i.e., the Virtual Network Embedding (VNE) problem (see Section II-A), the intrinsic attributes of an SDN environment have to be taken into account for vSDN embedding. For instance, as the efficient operation of SDN data plane elements relies on the use of the TCAM space, the assignment of TCAM space has to be taken into account when embedding vSDNs. Accordingly, VNE algorithms, which already consider link resources, such as data rate, and node resources, such as CPU, have to be extended to SDN environments [230]–[232]. The performance of vSDN embedding algorithms can be evaluated with traditional VNE metrics, such as acceptance rate or revenue/cost per vSDN.

2) *Two-Step Hypervisor Benchmarking Framework*: In order to evaluate and compare SDN hypervisor performance, a general benchmarking procedure is needed. We outline a two-step hypervisor benchmarking framework. The first step is to benchmark the *hypervisor system as a whole*. This first step is needed to quantify the hypervisor system for general use cases and set-ups, and to identify general performance issues. In order to reveal the performance of the hypervisor system

as a whole, explicit measurement cases with a combination of one or multiple vSDN switches and one or multiple vSDN controllers should be conducted. This measurement setup reveals the performance of the interplay of the individual hypervisor functions. Furthermore, it demonstrates the performance for varying vSDN controllers and set-ups. For example, when benchmarking the capabilities for isolating the data plane resources, measurements with one vSDN switch as well as multiple vSDN switches should be conducted.

The second step is to benchmark each *specific hypervisor function* in detail. The specific hypervisor function benchmarking reveals bottlenecks in the hypervisor implementation. This is needed to compare the implementation details of individual virtualization functions. If hypervisors exhibit different performance levels for different functions, an operator can select the best hypervisor for the specific use case. For example, a networking scenario where no data plane isolation is needed does not require a high-performance data plane isolation function. In general, all OF related and conventional metrics from Section VIII-A can be applied to evaluate the hypervisor performance.

In the following Sections VIII-B3 and VIII-B4, we explain how different vSDN switch scenarios and vSDN controller scenarios should be evaluated. The purpose of the performance evaluation of the vSDN switches and vSDN controllers is to draw conclusions about the performance of the hypervisor system as a whole. In Section VIII-B5, we outline how and why to benchmark each individual hypervisor function in detail. Only such a comprehensive hypervisor benchmark process can identify the utility of a hypervisor for specific use cases or a range of use cases.

3) *vSDN Switch Benchmarking*: When benchmarking a hypervisor, measurements with one vSDN switch should be performed first. That is, the first measurements should be conducted with a single benchmark entity and a single vSDN switch, as illustrated in Fig. 7(b). Comparisons of the evaluation results for the legacy SDN switch benchmarks (for non-virtualized SDNs, see Section VIII-A1) for the single vSDN switch (Fig. 7(b)) with results for the corresponding non-virtualized SDN switch (without hypervisor, Fig. 7(b)) allows for an analysis of the overhead that is introduced by the hypervisor. For this single vSDN switch evaluation, all SDN switch metrics from Section VIII-A1 can be employed. A

completely transparent hypervisor would show zero overhead, e.g., no additional latency for OF flow table updates.

In contrast to the single vSDN switch set-up in Fig. 7(b), the multi-tenancy case in Fig. 7(c) considers multiple vSDNs. The switch benchmarking tools, one for every emulated vSDN controller, are connected with the hypervisor, while multiple switches are benchmarked as representatives for vSDN networks. Each tool may conduct a different switch performance measurement. The results of each measurement should be compared to the set-up with a single vSDN switch (and a single tool) illustrated in Fig. 7(b) for each individual tool. Deviations from the single vSDN switch scenario may indicate cross-effects of the hypervisor. Furthermore, different combinations of measurement scenarios may reveal specific implementation issues of the hypervisor.

4) *vSDN Controller Benchmarking*: Similar to vSDN switch benchmarking, the legacy SDN controller benchmark tools (see Section VIII-A2) should be used for a first basic evaluation. Again, comparing scenarios where a hypervisor is activated (vSDN scenario) or deactivated (non-virtualized SDN scenario), allows to draw conclusion about the overhead introduced by the hypervisor. For the non-virtualized SDN (hypervisor deactivated) scenario, the benchmark suite is directly connected to the SDN controller, as illustrated in Fig. 8(a). For the vSDN (hypervisor activated) scenario, the hypervisor is inserted between the benchmark suite and the SDN controller, see Fig. 8(b).

In contrast to the single controller set-up in Fig. 8(b), multiple controllers are connected to the hypervisor in the multi-tenancy scenario in Fig. 8(c). In the multi-tenancy scenario, multiple controller benchmark tools can be used to create different vSDN topologies, whereby each tool can conduct a different controller performance measurement. Each single measurement should be compared to the single virtual controller benchmark (Fig. 8(b)). Such comparisons quantify not only the overhead introduced by the hypervisor, but also reveal cross-effects that are the result of multiple simultaneously running controller benchmark tools.

Compared to the single vSDN switch scenario, there are two main reasons for additional overheads in the multi-tenancy scenario. First, each virtualizing function introduces a small amount of processing overhead. Second, as the processing of multiple vSDNs is shared among the hypervisor resources, different types of OF messages sent by the vSDNs may lead to varying performance when compared to a single vSDN set-up. This second effect is comparable to the OF operations cross-effect for non-virtualized SDN environments, see Section VIII-A1d. For instance, translating messages from different vSDNs appearing at the same time may result in message contention and delays, leading to higher and variable processing times. Accordingly, multiple vSDN switches should be simultaneously considered in the performance evaluations.

5) *Benchmarking of Individual Hypervisor Functions*: Besides applying basic vSDN switch and vSDN controller benchmarks, a detailed hypervisor evaluation should also include the benchmarking of the individual hypervisor functions, i.e., the abstraction and isolation functions summarized in Figs. 2 and 4. All OF related and legacy metrics from Section VIII-A should

be applied to evaluate the individual hypervisor functions. The execution of the hypervisor functions may require network resources, and thus reduce the available resources for the data plane operations of the vSDN networks.

a) *Abstraction benchmarking*: The three main aspects of abstraction summarized in Fig. 2 should be benchmarked, namely topology abstraction, node resource abstraction, and link resource abstraction. Different set-ups should be considered for evaluating the topology abstraction. One set-up is the N -to-1 mapping, i.e., the capability of hypervisor to map multiple vSDN switches to a single physical SDN switch. For this N -to-1 mapping, the performance of the non-virtualized physical switch should be compared with the performance of the virtualized switches. This comparison allows conclusions about the overhead introduced by the virtualization mechanism. For the 1-to- N mapping, i.e., the mapping of one vSDN switch to N physical SDN switches, the same procedure should be applied. For example, presenting two physical SDN switches as one large vSDN switch demands specific abstraction mechanisms. The performance of the large vSDN switch should be compared to the aggregated performance of the two physical SDN switches.

In order to implement node resource abstraction and link resource abstraction, details about node and link capabilities of switches have to be hidden from the vSDN controllers. Hypervisor mapping mechanisms have to remove (filter) detailed node and link information, e.g., remove details from switch performance monitoring information, at runtime. For example, when the switch reports statistics about current CPU and memory utilization, providing only the CPU information to the vSDN controllers requires that the hypervisor removes the memory information. The computational processing required for this information filtering may degrade performance, e.g., reduce the total OF message throughput of the hypervisor.

b) *Isolation benchmarking*: Based on our classification of isolated network attributes summarized in Fig. 4, control plane isolation, data plane isolation, and vSDN addressing need to be benchmarked. The evaluation of the control plane isolation refers to the evaluation of the resources that are involved in ensuring the isolation of the processing and transmission of control plane messages. Isolation mechanisms for the range of control plane resources, including bandwidth isolation on the control channel, should be examined. The isolation performance should be benchmarked for a wide variety of scenarios ranging from a single to multiple vSDN controllers that utilize or over-utilize their assigned resources.

Hypervisors that execute hypervisor functions on the data plane, i.e., the distributed hypervisors that involve NEs (see Sections VI-B–VI-D), require special consideration when evaluating control plane isolation. The hypervisor functions may share resources with data plane functions; thus, the isolation of the resources has to be evaluated under varying data plane workloads.

Data plane isolation encompasses the isolation of the node resources and the isolation of the link resources. For the evaluation of the CPU isolation, the processing time of more than two vSDN switches should be benchmarked. If a hypervisor implements bandwidth isolation on the data plane, the bandwidth

isolation can be benchmarked in terms of accuracy. If one vSDN is trying to over-utilize its available bandwidth, no cross-effect should be seen for other vSDNs.

Different vSDN addressing schemes may show trade-offs in terms of available addressing space and performance. For instance, when comparing hypervisors (see Table III), there are “matching only” hypervisors that define a certain part of the flowspace to be used for vSDN (slice) identification, e.g., FlowVisor. The users of a given slice have to use the prescribed value of their respective tenant which the hypervisor uses for matching. The “add labels” hypervisors assign a label for slice identification, e.g., Carrier-grade assigns MPLS labels to virtual slices, which adds more degrees of freedom and increases the flowspace. However, the hypervisor has to add and remove the labels before forwarding to the next hop in the physical SDN network. Both types of hypervisors provide a limited addressing flowspace to the tenants. However, “matching only” hypervisors may perform better than “add labels” hypervisors since matching only is typically simpler for switches than matching and labeling. Another hypervisor type modifies the assigned virtual ID to offer an even larger flowspace, e.g., OpenVirtX rewrites a set of the MAC or IP header bits at the edge switches of the physical SDN network. This can also impact the hypervisor performance as the SDN switches need to “match and modify.”

Accordingly, when evaluating different addressing schemes, the size of the addressing space has to be taken into account when interpreting performance. The actual overhead due to an addressing scheme can be measured in terms of the introduced processing overhead. Besides processing overhead, also the resulting throughput of different schemes can be measured, or formally analyzed.

IX. FUTURE RESEARCH DIRECTIONS

From the preceding survey sections, we can draw several observations and lessons learned that indicate future research directions. First, we can observe the vast heterogeneity and variety of SDN hypervisors. There is also a large set of network attributes of the data and control planes that need to be selected for abstraction and isolation. The combination of a particular hypervisor along with selected network attributes for abstraction and isolation has a direct impact on the resulting network performance, whereby different trade-offs result from different combinations of selections. One main lesson learnt from the survey is that the studies completed so far have demonstrated the concept of SDN hypervisors as being feasible and have led to general (albeit vague) lessons learnt mainly for abstraction and isolation, as summarized in Section VII. However, our survey revealed a pronounced lack of rigorous, comprehensive performance evaluations and comparisons of SDN hypervisors. In particular, our survey suggests that there is currently no single best or simplest hypervisor design. Rather, there are many open research questions in the area of vSDN hypervisors and a pronounced need for detailed comprehensive vSDN hypervisor performance evaluations.

In this section, we outline future research directions. While we address open questions arising from existing hypervisor

developments, we also point out how hypervisors can advance existing non-virtualized SDN networks.

A. Service Level Definition and Agreement for vSDNs

In SDN networks, the control plane performance can directly affect the performance of the data plane. Accordingly, research on conventional SDN networks identifies and optimizes SDN control planes. Based on the control plane demands in SDN networks, vSDN tenants may also need to specify their OF-specific demands. Accordingly, in addition to requesting virtual network topologies in terms of virtual node demands and virtual link demands, tenants may need to specify control plane demands. Control plane demands include control message throughput or latency, which may differ for different control messages defined by the control API. Furthermore, it may be necessary to define demands for specific OF message types. For example, a service may not demand a reliable OF stats procedure, but may require fast OF flow-mod message processing. A standardized way for defining these demands and expressing them in terms of OF-specific parameters is not yet available. In particular, for vSDNs, such a specification is needed in the future.

B. Bootstrapping vSDNs

The core motivation for introducing SDN is programmability and automation. However, a clear bootstrapping procedure for vSDNs is missing. Presently, the bootstrapping of vSDNs does not follow a pre-defined mechanisms. In general, before a vSDN is ready for use, all involved components should be bootstrapped and connected. More specifically, the connections between the hypervisor and controllers needs to be established. The virtual slices in the SDN physical network need to be instantiated. Hypervisor resources need to be assigned to slices. Otherwise, problems may arise, e.g., vSDN switches may already send OF PCKT_IN messages even though the vSDN controller is still bootstrapping. In case of multiple uncontrolled vSDNs, these messages may even overload the hypervisor. Clear bootstrapping procedures are important, in particular, for fast and dynamic vSDN creation and setup. Missing bootstrapping procedures can even lead to undefined states, i.e., to non-deterministic operations of the vSDN networks.

C. Hypervisor Performance Benchmarks

As we outlined in Section VIII, hypervisors need detailed performance benchmarks. These performance benchmarks should encompass every possible performance aspect that is considered in today’s legacy networks. For instance, hypervisors integrated in specific networking environments, e.g., mobile networks or enterprise networks, should be specifically benchmarked with respect to the characteristics of the networking environment. In mobile networks, virtualization solutions for SDN networks that interconnect access points may have to support mobility characteristics, such as a high rate of handovers per second. On the other hand, virtualization solutions for enterprise networks should provide reliable and secure communications. Hypervisors virtualizing networks that

host vSDNs serving highly dynamic traffic patterns may need to provide fast adaptation mechanisms.

Besides benchmarking the runtime performance of hypervisors, the efficient allocation of physical resources to vSDNs needs further consideration in the future. The general assignment problem of physical to virtual resources, which is commonly known as the Virtual Network Embedding (VNE) problem [47], has to be further extended to virtual SDN networks. Although some first studies exist [230]–[232], they neglect the impact of the hypervisor realization on the resources required to accept a vSDN. In particular, as hypervisors realize virtualization functions differently, the different functions may demand varying physical resources when accepting vSDNs. Accordingly, the hypervisor design has to be taken into account during the embedding process. Although generic VNE algorithms for general network virtualization exist [47], there is an open research question of how to model different hypervisors and how to integrate them into embedding algorithms in order to be able to provide an efficient assignment of physical resources.

D. Hypervisor Reliability and Fault Tolerance

The reliability of the hypervisor layer needs to be investigated in detail as a crucial aspect towards an actual deployment of vSDNs. First, mechanisms should be defined to recover from hypervisor failures and faults. A hypervisor failure can have significant impact. For example, a vSDN controller can lose control of its vSDN, i.e., experience a vSDN blackout, if the connection to the hypervisor is temporarily lost or terminated. Precise procedures and mechanisms need to be defined and implemented by both hypervisors and controllers to recover from hypervisor failures.

Second, the hypervisor development process has to include and set up levels of redundancy to be able to offer a reliable virtualization of SDN networks. This redundancy adds to the management and logical processing of the hypervisor and may degrade performance in normal operation conditions (without any failures).

E. Hardware and Hypervisor Abstraction

As full network virtualization aims at deterministic performance guarantees for vSDNs, more research on SDN hardware virtualization needs to be conducted. The hardware isolation and abstraction provided by different SDN switches can vary significantly. Several limitations and bottlenecks can be observed, e.g., an SDN switch may not be able to instantiate an OF agent for each virtual slice. Existing hypervisors try to provide solutions that indirectly achieve hardware isolation between the virtual slices. For example, FlowVisor limits the amount of OF messages per slice in order to indirectly isolate the switch processing capacity, i.e., switch CPU. As switches show varying processing times for different OF messages, the FlowVisor concept would demand a detailed a priori vSDN switch benchmarking. Alternatively, the capability to assign hardware resources to vSDNs would facilitate (empower) the entire virtualization paradigm.

Although SDN promises to provide a standardized interface to switches, existing switch diversity due to vendor variety leads to performance variation, e.g., for QoS configurations of switches. These issues have been identified in recent studies, such as [143], [233]–[237], for non-virtualized SDN networks. Hypervisors may be designed to abstract switch diversity in vendor-heterogenous environments. Solutions, such as Tango [233], should be integrated into existing hypervisor architectures. Tango provides on-line switch performance benchmarks. SDN applications can integrate these SDN switch performance benchmarks while making, e.g., steering decisions. However, as research on switch diversity is still in its infancy, the integration of existing solutions into hypervisors is an open problem. Accordingly, future research should examine how to integrate mechanisms that provide deterministic switch performance models into hypervisor designs.

F. Scalable Hypervisor Design

In practical SDN virtualization deployments, a single hypervisor entity would most likely not suffice. Hence, hypervisor designs need to consider the distributed architectures in more detail. Hypervisor scalability needs to be addressed by defining and examining the operation of the hypervisor as a whole in case of distribution. For instance, FlowN simply sends a message from one controller server (say, responsible for the physical switch) to another (running the tenant controller application) over a TCP connection. More efficient algorithms for assigning tenants and switches to hypervisors are an interesting area for future research. An initial approach for dynamic (during run-time) assignment of virtual switches and tenant controllers to distributed hypervisors has been introduced in [238]. Additionally, the hypervisors need to be developed and implemented with varying granularity of distribution, e.g., ranging from distribution of whole instances to distribution of modular functions.

G. Hypervisor Placement

Hypervisors are placed between tenant controllers and vSDN networks. Physical SDN networks may have a wide geographical distribution. Thus, similar to the controller placement problem in non-virtualized SDN environments [239], [240], the placement of the hypervisor demands detailed investigations. In addition to the physical SDN network, the hypervisor placement has to consider the distribution of the demanded vSDN switch locations and the locations of the tenant controllers. If a hypervisor is implemented through multiple distributed hypervisor functions, i.e., distributed abstraction and isolation functions, these functions have to be carefully placed, e.g., in an efficient hypervisor function chain. For distributed hypervisors, the network that provides the communications infrastructure for the hypervisor management plane has to be taken into account. In contrast to the SDN controller placement problem, the hypervisor placement problems adds multiple new dimensions, constraints, and possibilities. An initial study of network hypervisor placement [241] has provided a mathematical model for analyzing the placement of

hypervisors when node and link constraints are not considered. Similar to the initial study of the controller placement problem [239], the network hypervisor placement solutions were optimized and analyzed with respect to control plane latency. Future research on the hypervisor placement problem should also consider that hypervisors may have to serve dynamically changing vSDNs, giving rise to dynamic hypervisor placement problems.

H. Hypervisors for Special Network Types

While the majority of hypervisor designs to date have been developed for generic wired networks, there have been only relatively few initial studies on hypervisor designs for special network types, such as wireless and optical networks, as surveyed in Section V-C. However, networks of a special type, such as wireless and optical networks, play a very important role in the Internet today. Indeed, a large portion of the Internet traffic emanates from or is destined to wireless mobile devices; similarly, large portions of the Internet traffic traverse optical networks. Hence, the development of SDN hypervisors that account for the unique characteristics of special network types, e.g., the characteristics of the wireless or optical transmissions, appears to be highly important. In wireless networks in particular, the flexibility of offering a variety of services based a given physical wireless network infrastructure is highly appealing [242]–[247]. Similarly, in the area of access (first mile) networks, where the investment cost of the network needs to be amortized from the services to a relatively limited subscriber community [248]–[251], virtualizing the installed physical access network is a very promising strategy [126], [252]–[255].

Another example of a special network type for SDN virtualization is the sensor network [256]–[259]. Sensor networks have unique limitations due to the limited resources on the sensor nodes that sense the environment and transmit the sensing data over wireless links to gateways or sink nodes [260]–[263]. Virtualization and hypervisor designs for wireless sensor networks need to accommodate these unique characteristics.

As the underlying physical networks further evolve and new networking techniques emerge, hypervisors implementing the SDN network virtualization need to adapt. That is, the adaption of hypervisor designs to newly evolving networking techniques is an ongoing research challenge. More broadly, future research needs to examine which hypervisor designs are best suited for a specific network type in combination with a particular scale (size) of the network.

I. Self-Configuring and Self-Optimizing Hypervisors

Hypervisors should always try to provide the best possible virtualization performance for different network topologies, independent of the realization of the underlying SDN networking hardware, and for varying vSDN network demands. In order to continuously strive for the best performance, hypervisors may have to be designed to become highly adaptable. Accordingly, hypervisors should implement mechanisms for self-configuration and self-optimization. These operations need to

work on short time-scales in order to achieve high resource efficiency for the virtualized resources. Cognitive and learning-based hypervisors may be needed to improve hypervisor operations. Furthermore, the self-reconfiguration should be transparent to the performance of the vSDNs and incur minimal configuration overhead for the hypervisor operator. Fundamental questions are how often and how fast a hypervisor should react to changing vSDN demands under varying optimization objectives for the hypervisor operator. Optimization objectives include energy-awareness, balanced network load, and high reliability. The design of hypervisor resource management algorithms solving these challenges is an open research field and needs detailed investigation in future research.

J. Hypervisor Security

OF proposes to use encrypted TCP connections between controllers and switches. As hypervisors intercept these connections, a hypervisor should provide a trusted encryption platform. In particular, if vSDN customers connect to multiple different hypervisors, as it may occur in multi-infrastructure environments, a trusted key distribution and management system becomes necessary. Furthermore, as secure technologies may add additional processing overhead, different solutions need to be benchmarked for different levels of required security. The definition of hypervisor protection measures against attacks is required. A hypervisor has to protect itself from attacks by defining policies for all traffic types, including traffic that does not belong to a defined virtual slice.

X. CONCLUSION

We have conducted a comprehensive survey of hypervisors for virtualizing software defined networks (SDNs). A hypervisor abstracts (virtualizes) the underlying physical SDN network and allows multiple users (tenants) to share the underlying physical SDN network. The hypervisor slices the underlying physical SDN network into multiple slices, i.e., multiple virtual SDN networks (vSDNs), that are logically isolated from each other. Each tenant has a vSDN controller that controls the tenant's vSDN. The hypervisor has the responsibility of ensuring that each tenant has the impression of controlling the tenant's own vSDN without interference from the other tenants operating a vSDN on the same underlying physical SDN network. The hypervisor is thus essential for amortizing a physical SDN network installation through offering SDN network services to multiple users.

We have introduced a main classification of SDN hypervisors according to their architecture into centralized and distributed hypervisors. We have further sub-classified the distributed hypervisors according to their execution platform into hypervisors for general-purpose computing platforms or for combinations of general-computing platforms with general- or special-purpose network elements (NEs). The seminal FlowVisor [9] has initially been designed with a centralized architecture and spawned several follow-up designs with a centralized architecture for both general IP networks as well as special network types, such as optical and wireless networks.

Concerns about relying on only a single centralized hypervisor, e.g., potential overload, have led to about a dozen distributed SDN hypervisor designs to date. The distributed hypervisor designs distribute a varying degree of the hypervisor functions across multiple general-computing platforms or a mix of general-computing platforms and NEs. Involving the NEs in the execution of the hypervisor functions generally led to improved performance and capabilities at the expense of increased complexity and cost.

There is a wide gamut of important open future research directions for SDN hypervisors. One important prerequisite for the future development of SDN hypervisors is a comprehensive performance evaluation framework. Informed by our comprehensive review of the existing SDN hypervisors and their features and limitations, we have outlined such a performance evaluation framework in Section VIII. We believe that more research is necessary to refine this framework and grow it into widely accepted performance benchmarking suite complete with standard workload traces and test scenarios. Establishing a unified comprehensive evaluation methodology will likely provide additional deepened insights into the existing hypervisors and help guide the research on strategies for advancing the abstraction and isolation capabilities of the SDN hypervisors while keeping the overhead introduced by the hypervisor low.

ACKNOWLEDGMENT

A first draft of this article was written while Martin Reisslein visited the Technische Universität München (TUM), Germany, from January through July 2015. Support from TUM and a Friedrich Wilhelm Bessel Research Award from the Alexander von Humboldt Foundation are gratefully acknowledged.

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