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Software-Defined Network Virtualization – An Architectural Framework for Integrating SDN and NFV for Service Provisioning in Future Networks

Qiang Duan, Nirwan Ansari, and Mehmet Toy

Abstract

Software-Defined Network (SDN) and Network Function Virtualization (NFV) are two significant innovations in networking. Evolution of both SDN and NFV has shown strong synergy between these two paradigms. Recent research efforts have been made toward combining SDN and NFV to fully exploit the advantages of both technologies. However, integrating SDN and NFV is challenging due to the variety of intertwined network elements involved and the complex interaction among them. In this article, we attempt to tackle this challenging problem by presenting an architectural framework called Software-Defined Network Virtualization (SDNV). This framework offers a clear holistic vision of integrating key principles of both SDN and NFV into unified network architecture and provides guidelines for synthesizing research efforts toward combining SDN and NFV in future networks. Based on this framework, we also discuss key technical challenges to realizing SDN-NFV integration and identify some important topics for future research, with a hope to arouse the research community's interest in this emerging area.

I. Introduction

Rapid advancement in networking and computing technologies has enabled a wide variety of applications with diverse requirements on network services. The highly diverse and dynamic network services demanded by current and emerging applications bring in new challenges to service provisioning in future networks. Software-Defined Networking (SDN) and Network Function Virtualization (NFV) are two significant recent innovations that are expected to address these challenges.

SDN separates network control and data forwarding functionalities to enable centralized and programmable network control [1]. Key components of the SDN architecture include a data plane consisting of network resources for data forwarding, a control plane comprising SDN controller(s) providing centralized control of network resources, and control/management applications that program network operations through a controller. The control-resource interface between the control and data planes is called the southbound interface while the control-application interface is called the northbound interface. Advantages promised by SDN include simplified and enhanced network control, flexible and efficient network management, and improved network service performance.

Network virtualization introduces an abstraction of the underlying infrastructure upon which virtual networks with alternative architecture may be constructed to meet diverse service requirements [2]. More recently, ETSI developed Network Function Virtualization (NFV), a network architecture concept that leverages virtualization technologies to transfer network functions from hardware appliances to software applications [3]. Essentially, NFV embraces the notion of network virtualization and provides more specific mechanisms to decouple service functions from infrastructures. Benefits introduced by NFV include simplified service development, more flexible service delivery, and reduced network capital and operational costs.

Although SDN and NFV were initially developed as independent networking paradigms, evolution of both technologies has shown strong synergy between them. SDN and NFV share common goals and similar technical ideas, and are complementary to each other. Integrating SDN and NFV in future networking may trigger innovative network designs that fully exploit the advantages of both paradigms. Recently, combining SDN and NFV started attracting attention from both academia and industry. However, integrating SDN and NFV is challenging due to the variety of intertwined network elements involved and the complex interaction among them. Currently SDN and

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NFV are still being studied and standardized without sufficient synergy. Therefore, there is an urgent need for a holistic architectural framework in which SDN and NFV principles may be naturally combined.

In this article, we attempt to tackle the challenging problem of integrating SDN and NFV by proposing an architectural framework called Software-Defined Network Virtualization (SDNV). The SDNV framework combines SDN principle of separating data and control planes with NFV principle of decoupling service functions from infrastructures, thus providing a clear holistic vision of SDN and NFV integration. Specifically, we first discuss how SDN and NFV may benefit from each other and present a two-dimensional abstraction model to show the relationship between SDN and NFV principles. Then, we propose the SDNV framework architecture that provides a high-level picture of integrating SDN and NFV. Following this framework, we discuss key technical challenges to realizing SDN-NFV integration and identify some important topics in this area for future research.

II. Integrating SDN and NFV for Service Provisioning in Future Networks

The past few years witnessed exciting progress in SDN technologies and their applications in various networking scenarios [1] including wireless networks [4]. On the other hand, researchers have noticed some issues of the current SDN approach that may limit its ability to fully support future network services [5], [6]. To meet the evolving diverse service requirements, SDN data plane devices need to perform fully general flow matching and packet forwarding, which may significantly increase complexity and cost of SDN switches. On the control plane, current SDN architecture lacks sufficient support of interoperability among heterogeneous SDN controllers, and thus limits its ability to provision flexible end-to-end services across autonomous domains.

A root reason for the limitation of current SDN design to achieve its full potential for service provisioning is the tight coupling between network architecture and infrastructure on both data and control planes. Separation between data and control planes alone in the current SDN architecture is not sufficient to overcome this obstacle. Another dimension of abstraction to decouple service functions and network infrastructures is needed in order to unlock SDN full potential. Therefore, applying the insights of NFV into SDN may further enhance the latter's capability of flexible service provisioning.

On the other hand, many technical challenges must be addressed for realizing the NFV paradigm. Management and orchestration has been identified as a key component in the ETSI NFV architecture. Much more sophisticated control and management mechanisms for both virtual and physical resources are required by the highly dynamic networking environment enabled by NFV, in which programmatic network control is indispensable. Employing the SDN principle – decoupling control intelligence from the controlled resources to enable a logically centralized programmable control/management plane – in the NFV architecture may greatly facilitate realization of NFV.

Recent research efforts toward combining SDN and NFV to enhance network service provisioning have been made from various aspects. Hypervisor and container-based virtualization mechanisms have been applied to support multi-tenant virtual SDN networks. For example, the network hypervisor FlowVisor [7] allows multiple controllers to share an OpenFlow platform and slice data plane infrastructure. FlowN [8] offers a container-based virtualization solution in which each tenant may run its own control application upon a shared SDN controller. Some network system designs have explored utilizing capabilities of both SDN and NFV. For example, Woods *et al.* [9] presented NetVM, a high performance virtual server platform for supporting NFV, and discussed design guidelines for combining SDN controllers with NetVM to provide coordinated network management. Ding *et al.* [10] designed an open platform for service chain as a service by using capabilities of SDN together with NFV. The progressive evolution from SDN-agnostic NFV initiative to SDN-enabled NFV solution was discussed in [11]. Relevant standardization organizations are also actively conducting related study. Open Network Foundation (ONF) recently released a report on the relationship of SDN and NFV [12], and ETSI NFV ISG is currently working on a draft report regarding SDN usage in the NFV architecture [13].

Although encouraging progress has been made toward combining SDN and NFV, research in this area is still at an infant stage. Current works address the problem from various aspects, including hypervisors for virtual SDN networks, usage of SDN controllers in NFV architecture, and SDN/NFV hybrid solutions for service provisioning. It is desirable to have a high-level framework that provides a holistic vision about how SDN and NFV principles may naturally fit into unified network architecture, which may greatly facilitate the research and technical development in this area. This motivates the work presented in the rest of this article.

III. A Two-Dimensional Abstraction Model for SDN and NFV Integration

In this section, we present a two dimensional abstraction model to show how SDN and NFV principles are related to each other and how they may fit in unified network architecture.

Fig. 1. A two-dimensional model of layer-plane abstraction in future networking

As shown in Fig. 1, this abstraction model has *layers* as well as *planes* with clear distinction between these two concepts. Both layer and plane offer abstraction in network architecture but in different *dimensions*. Abstraction provided by layers is in the vertical dimension in the model, starting with underlying hardware and then adding a sequence of layers, each providing a higher (more abstract) level of service. A key property of layering is that the functions of a higher layer rely on the services provided by the lower layers, therefore forming a stack of layers for offering services to applications on the top. On the other hand, plane abstraction is in the horizontal dimension in that functions performed on a plane do not necessarily rely on functions of another plane; therefore, there is no higher or lower plane. Instead, each plane focuses on a particular aspect of the entire network system, such as data transport, network control, and system management. Each plane may comprise multiple layers from physical hardware to application software, and collaborates with other planes for network service provisioning.

Traditional circuit switching-based telecommunication systems embraced plane-dimension abstraction (separating data, control, and management planes) without clear abstraction on the layer-dimension. For example, the Signal System No. 7 was logically separated from voice channels and Intelligent Network (IN) had Service Control Points (SCPs) decoupled from data transportation platform. The IP-based Internet architecture shows clear layer-dimension abstraction but lacks explicitly defined abstraction in the plane-dimension. Packet forwarding, routing, and network management functions are mixed in the same set of IP protocols. Wide adoption of IP-based architecture has made the layer-dimension abstraction dominating in current network designs.

Rapid development of the wide spectrum of Internet services requires much more flexible network control and management, which is limited by the tight coupling between control/management and data forwarding in the current Internet architecture. SDN essentially brings in the plane-dimension abstraction by separating the data and control/management planes. Although the TCP/IP stack provides layer-dimension abstraction, the interfaces between layers are not defined flexibly enough to meet the requirement of future network services. A key obstacle lies in the unnecessary coupling between service-oriented functions and transport-oriented infrastructures that limits network design from fully exploiting the benefits of layer-dimension abstraction. The network virtualization notion advocates decoupling service provisioning from network infrastructure and the NFV architecture attempts to leverage standard IT technologies to realize such decoupling through simple yet flexible abstraction of underlying hardware infrastructures.

It is worth mentioning that TCP/IP layer stack is used in Fig. 1 just as an example to show the concept of layer-dimension abstraction. The model is applicable to network architecture with alternative layers. The vertical decoupling highlighted between the network interface and Internet layers in the figure is also for illustration. In fact, position of virtualization in the layer-dimension is a design option for virtualization-based network architecture. Similarly, control and management can be considered either as one plane or two separated planes in the plane dimension.

From the layer-plane abstraction model, we can see that the key principles of both SDN and NFV are based on abstraction but with emphasis on the plane and layer dimensions, respectively. These two abstraction dimensions are orthogonal; that is, network architecture may have abstraction on one dimension but not on the other. Therefore, SDN and NFV in principle are independent – NFV may be realized with or without SDN and vice-versa. On the other hand, the challenging requirements for service provisioning in future networks demand abstraction on both dimensions in order to fully exploit their advantages. Therefore, integrating the software-defined principle and the virtualization notion leads to unified network architecture with key components in four quadrants and abstract interfaces for loose-coupling between them, as shown in Fig. 2.

Fig. 2. Integrating key principles of SDN and NFV in unified network architecture

IV. Software-Defined Network Virtualization for Integrating SDN and NFV

A. Key Components of the SDNV Framework

The SDNV framework is shown in Fig. 3. The infrastructure layer comprises the physical resources of network and compute infrastructures, which may consist of multiple autonomous domains. The virtualization layer realizes abstraction of physical infrastructures into virtual resources and provides mapping between physical and virtual resources. The service layer is responsible for providing service-related functionalities. This layer utilizes the virtual resources made available by the virtualization layer to realize Virtual Service Functions (VSFs), including both Virtual Network Functions (VNFs) and Virtual Compute Functions (VCFs). The service layer selects and orchestrates appropriate VSFs to construct Virtual Networks (VNs) for meeting service requirements of user applications.

Both infrastructure and service layers of the SDNV framework have separated data and control/management planes. The control/management plane on the infrastructure layer consists of controllers for network and compute infrastructures. Heterogeneous SDN controllers and southbound protocols (e.g., OpenFlow and ForCES) may be applied in different domains. We refer to such controllers as Infrastructure Domain Controllers (IDCs). The control/management plane on the service layer is responsible for VSF and VN life cycle management, including construction, instantiation, maintenance, and termination of VSFs/VNs. VNs are constructed by composing appropriate VSFs for meeting service requirements. Each VN has its own controller (called VNC) that controls all the data plane VSFs involved in this VN, just like a SDN controller controls all switches in a physical network domain. The virtualization layer decouples service-oriented control/management from infrastructure domain controlling, while providing a standard interface through which service control/management functions may interact with infrastructure controllers. Such decoupling on the control/managemnt plane enables differentiation between control/management functions associated to transport infrastructures and those related to services, and thus allows them to be provided, maintained, and developed independently following their own evolutionary paths.

Fig. 3. Software-Defined Network Virtualization architectural framework

B. Key Interfaces of the SDNV Framework

The interface provided by the virtualization layer enables high-level abstraction of underlying network and compute infrastructures, including both data plane capabilities and control/management functionalities. This interface decouples the logical topologies, addressing schemes, and routing mechanisms of virtual networks from those of physical infrastructures while maintaining the mapping between virtual and physical objects. In addition, the virtualization layer interface should guarantee isolation between virtual objects to allow multi-tenant VNs to share a common infrastructure substrate.

Another important interface is between the data plane and the control/management plane. This interface decouples control/management functionalities from physical infrastructure resources and virtual network functions, thus realizing the plane-dimension abstraction in the SDNV framework. Since this interface is between controllers and controlled resources/functions, it is referred to as SouthBound (SB) Interface following SDN terminology. Clear separation between the service layer and infrastructure layer in SDNV requires the SB interface to be split to two sub-interfaces. The SB interface on the infrastructure layer provides interactions between IDCs and the physical network/compute devices under their control, and is therefore called Physical SouthBound (P-SB) interface. The SB interface on the service layer allows each VNC to control the data plane VSFs in its VN following the centralized control principle of SDN, and is therefore called Virtual SouthBound (V-SB) interface. SDNV allows multiple independent P-SB interfaces for meeting requirements of different domains coexisting in the infrastructure layer. Similarly, VNs customized for various services may adopt different V-SB interface protocols.

The interface between user applications and service control/management allows applications to program VNs. It plays a similar role as the NorthBound (NB) interface in the SDN architecture but for virtual networks, and therefore is called Virtual NB interface. This interface offers service abstraction through which user applications may access and configure network services via standard APIs. This interface should support isolation among APIs for different VNCs in order to provide independent programmability for individual virtual networks.

C. Key Features of the SDNV Framework

The SDNV framework combines the notion of network virtualization – decoupling service functions from underlying infrastructures – with the core principle of SDN – separating data and control/management planes, and can thus fully exploit the advantages of both paradigms. The layer-dimension abstraction introduced by the virtualization layer allows life cycles of VSFs and VNs to be independent from those of physical infrastructures, thus enabling rapid innovations both above and below the virtualization layer. The plane-dimension abstraction in the SDNV framework separates data forwarding and control/management functions on both the infrastructure layer and the service layer. Such abstraction on the infrastructure layer supports logically centralized programmable control for each infrastructure domain. Similarly, decoupling data and control planes on the service layer allows each VN to have a central programmable VNC that controls all the data plane VSFs involved in this VN for service provisioning.

The SDNV framework naturally supports multi-provider service scenarios in which diverse virtual networks are created upon a physical substrate consisting of heterogeneous network and compute infrastructures in multiple domains. Therefore, SDNV embraces the trend of unified network-Cloud service provisioning. VSFs in SDNV may provide service functions virtuaized from networking systems (VNFs) as well as from Cloud resources (VCFs). End-to-end services delivered by VNs through orchestrating VNFs and VCFs are essentially composite network-Cloud services. Such a converged service ecosystem may introduce new functional roles, such as suppliers of VSFs and providers of composite network-Cloud services, and trigger innovations of new service models.

Comparison between the SDNV framework and the NFV architecture proposed by ETSI shows that the infrastructure layer comprises the hardware resources and their controllers in NFVI; the virtualization layer provides virtual resources of NFVI and the corresponding management (VIM); and the service layer includes the VNF and Management & Orchestration (MANO) components of the NFV architecture. Compared to other frameworks proposed for combing SDN and NFV, for example the ones presented in [12] and [13], the SDNV framework on the one hand makes clear distinction between the plane- and layer-dimension abstraction, which are respectively the emphasis of SDN and NFV; on the other hand, embraces abstraction on both dimensions to integrate the SDN and NFV principles into unified network architecture.

The objective of the SDNV framework is not to replace the current SDN and NFV architecture but to provide an architectural framework showing how these two paradigms may be integrated together for future networking. On the other hand, SDNV is not to simply put current architecture of SDN and NFV together but to combine the key insights of both paradigms into unified network architecture and show how SDN and NFV may cooperate inside such architecture. This framework provides useful guidelines to synthesize research from various aspects toward the common objective of integrating SDN and NFV for supporting service provisioning in future networks.

D. A Use Case of the SDNV Framework

In this subsection, we present a use case example of the SDNV framework to illustrate how the framework may guide future network design. End-to-end service provisioning across heterogeneous network domains is challenging in current SDN architecture. The centralized control of a single SDN controller is limited by its network domain boundary, and inter-operation between heterogeneous SDN controllers in different domains is still an open issue. Following the SDNV framework, functions for service provisioning in the SDN architecture may be decoupled from infrastructure domains by a virtualization layer, thus enabling a service delivery platform as shown in Fig. 4. In this platform, the infrastructure resources and control functionalities in each domain are virtualized as VNFs and exposed via an abstract interface (e.g., RESTful API). Upon receiving a service request, the service orchestration module selects and composes the appropriate VNFs to form a forwarding graph that meets the requirement for end-to-end service delivery. Then, the VSF/VN management module instantiates a virtual network to realize this forwarding graph. The controller of this virtual network is also realized through composition of a set of control plane VNFs, each of which virtualizes the control functions of a network domain utilized by this virtual network. In this way, the VN controller orchestrates the VNFs hosted by SDN controllers in heterogeneous domains to achieve end-to-end service delivery. Multiple virtual networks may be constructed upon this platform for meeting the diverse service requirements of different end users. With such a service platform, the uniform abstraction provided by the virtualization layer makes heterogeneous network domains transparent to service management, which may greatly facilitate inter-domain service delivery in SDN.

Fig. 4. Virtualization-based service delivery platform for SDN networks

V. Challenges and Opportunities for Future Research

In this section, we discuss technical challenges to SDN and NFV integration following the SDNV framework and identify some possible topics for future research.

A. Virtualization for Infrastructure Abstraction

Virtualization of physical infrastructures for layer-dimension abstraction plays a significant role in future networking with SDN-NFV integration. Infrastructure virtualization is being extensively studied in cloud computing and networking, but current research pays more attention on data plane infrastructure. The SDNV framework indicates that virtualization on the control/management plane to achieve decoupled control/management for physical and virtual networks is also a research topic that deserves thorough investigation. Another new challenge is to enable unified abstraction of heterogeneous infrastructures (e.g., network, compute, and storage) through a standard platform for supporting composite services across networking and computing domains. XML-based specification language offers a promising approach to providing standard interfaces. However, whether such interfaces should be highly descriptive or simple RESTful interfaces might be more appropriate should be further examined. In addition, infrastructure information must be aggregated to provide a scalable global abstract view while service layer control/management relies on precise infrastructure information to create VNs for meeting service requirements. Therefore, finding an appropriate degree of state aggregation that balances abstraction and precision of logical infrastructure view is also a challenging issue that should be further investigated.

B. Embedding Virtual Service Functions and Virtual Networks

Another key aspect of the virtualization layer in the SDNV framework is to instantiate VSFs and VNs on a shared infrastructure substrate through mapping virtual functions to physical resources. A key objective is to fully utilize infrastructure resources while meeting service requirements. Virtual network embedding is a challenging problem that has been studied for years and various technologies have been proposed [14]. SDNV brings in a new challenge for embedding VNs comprising virtual functions of both networking and computing into heterogeneous infrastructures (networks as well as data centers). This requires federated control and management of network, compute, and storage resources across autonomous domains in an Internet scale, which is still an open issue for future research. Also, current works on VN embedding mainly focus on data plane. SDN-NFV integration calls for more study on distinction and coordination between embedding of data plane objects and their control/mangement functions. Multiple coexisting VNCs, each controlling an individual VN, require effective mechanisms to guarantee isolation between control to different VNs embedded in a shared substrate. In addition, dynamic elastic VN embedding for supporting service scale-up/down and co-migration of VNFs and VCFs are also challenging issues that need more thorough study.

C. Virtual Network Construction

Constructing VNs for meeting user requirements is a core function for future service provisioning, which may be greatly facilitated by integration of SDN and NFV following the SDNV framework. In this framework, the control/management plane on the service layer selects and composes appropriate data plane VSFs to form VNs for meeting service requirements. How to give abstract descriptions of VSF attributes, how to make VSFs available and discoverable, and how to select and compose the optimal set of VSFs are all relevant problems that need more thorough study. Cloud service composition has been extensively studied and may offer some useful techniques for VSF composition to construct VNs [15]. For example, centralized broker-based orchestration schemes and distributed policy-based choreograph mechanisms are both possible approaches to addressing this challenging problem. However, cloud service composition research mainly focused on computing services instead of networking services; therefore, further investigation on VSF composition in the SDNV context, especially composition of VNFs and VCFs across networking and computing domains, offers an interesting topic for future research.

D. Control/Management of Virtual Networks and Virtual Service Functions

Integrating SDN with network virtualization leads to decoupling of data and control/management planes on both infrastructure layer and service layer, thus calling for separate interfaces for controlling and managing physical infrastructure resources and virtual service functions, respectively. Such interface on the infrastructure layer is the physical SB interface between controllers and switches in each infrastructure domain, which has been relatively well studied in the context of SDN (e.g., OpenFlow and ForCES). However, control/management interface on the service layer between virtual networks and their controllers (i.e., the virtual SB interface) has received little research attention and deserves more investigation in the future. Appropriate models for abstracting virtual resources and service functions are required by this interface. Also, such interface should isolate the control/management for different individual VNs to support multiple VNs with customized protocols. In addition, elastic service provisioning requires flexible mechanisms for scaling-up/down VN control capacity and dynamically deploying and migrating VN controllers. These are all open problems for future research.

E. Service Quality Assurance in Virtual Network Environments

Virtualization-based networking environment brings in new challenges to service quality assurance. How can software-based virtual functions achieve comparable level of service quality as what dedicated hardware guarantees is an important issue that must be addressed. The SDNV framework indicates that more diverse functional roles, such as infrastructure providers, VSF suppliers, VN operators, and composite network-cloud service providers, may be enabled by SDN-NFV integration in future networks. These players in the new service ecosystem, who may have conflicting interest, must cooperate for meeting performance requirements of service provisioning. The trend toward network-cloud service convergence particularly calls for new approaches to providing end-to-end QoS guarantees. These challenging problems all offer important topics for future research. In addition, dynamic deployment of virtual service functions enabled by SDN-NFV integration brings in new challenges to traditional performance evaluation methods such as queueing theory-based modeling and analysis, which often assume certain implementations of the analyzed services. Decoupling services from their hosting infrastructures calls for new evaluation approaches that are more agnostic to service implementations.

F. Energy-Aware Network Design

Building environmentally friendly network infrastructure by reducing energy consumption is a very important aspect of future network design. Network resource virtualization together with flexible SDN control and management provides great potential to achieve energy-efficient networking; however, such advantage is yet to be fully exploited. A challenge to energy-aware NFV-SDN integration lies in the variety of intertwined network elements that must be considered in this issue, including both infrastructures and service functions on both data and control/management planes. For example, VSF/VN embedding in network and compute infrastructures should minimize energy consumption while meeting service quality requirements. Energy-aware VSF composition needs to achieve optimal balance among energy consumption, resource utilization, and service performance. Therefore, applying the holistic view of SDN-NFV integration provided by the SDNV framework to facilitate energy-aware future network design will be a very interesting topic for future research.

VI. Conclusion

In this article, we have tackled the challenging problem of integrating SDN and NFV in future networks by presenting an architectural framework that combines the key principles of both paradigms. We first discussed how SDN and NFV may benefit from each other and presented a two-dimensional model to show that both SDN and NFV are based on abstraction but focusing on the plane and layer dimensions, respectively. We then proposed the Software-Defined Network Virtualization (SDNV) framework to provide a clear holistic vision of integrating the SDN and NFV principles into unified network architecture, which allows innovative network designs to fully exploit the advantages of both paradigms. We also discussed key technical challenges to SDN-NFV integration following the SDNV framework and identified some possible topics for future research. We believe that the SDNV framework offers useful guidelines that may facilitate synthesizing research efforts from various aspects toward the common objective of integrating SDN and NFV in future networks.

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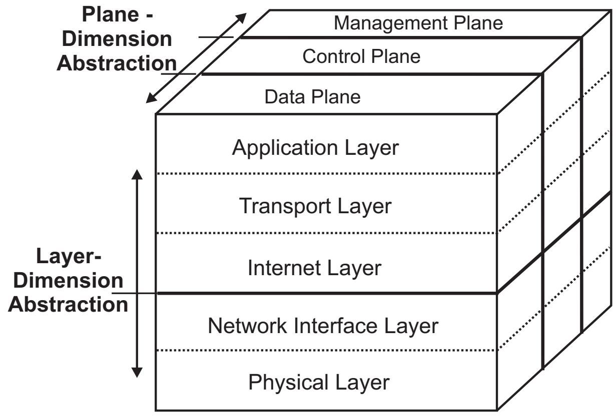

Fig 1. A two-dimensional model of layer-plane abstraction in future networking

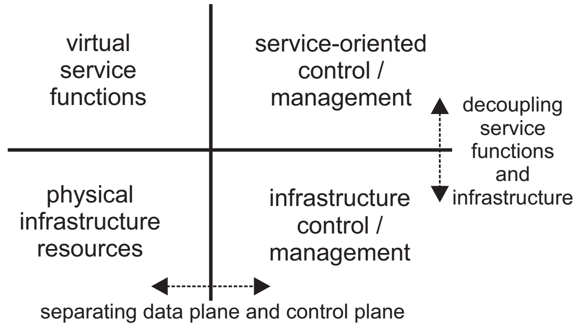

Fig 2. Integrating key principles of SDN and NFV in unified network architecture

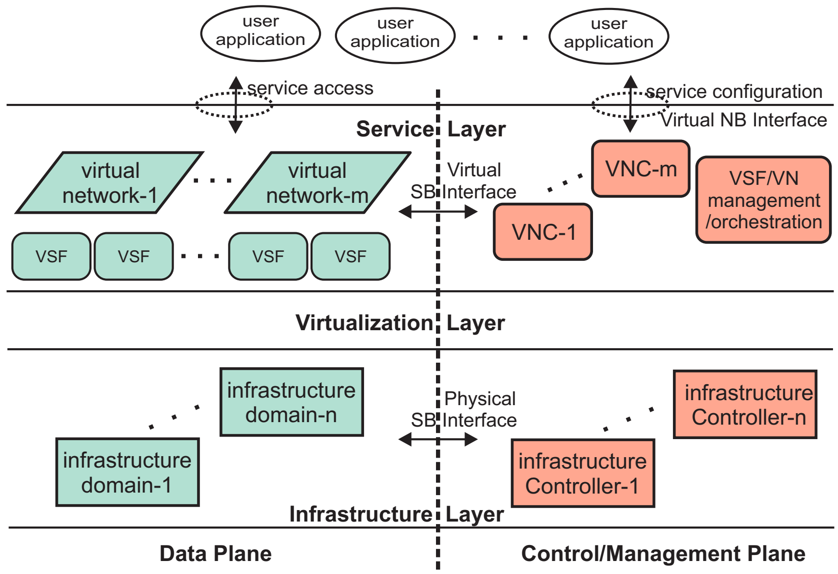

Fig 3. Software-Defined Network Virtualization architectural framework

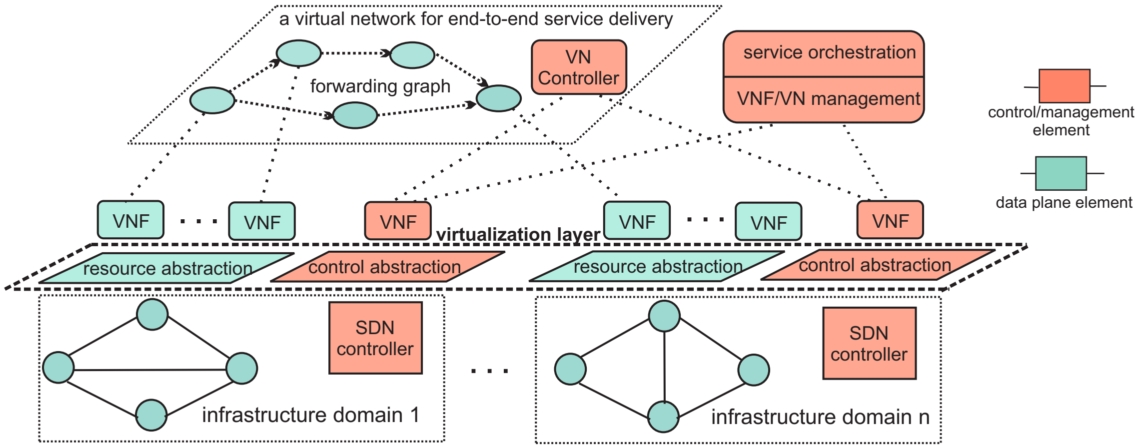

Fig 4. Virtualization-based service delivery platform for SDN networks