Network Cloudification Enabling Network-Cloud/Fog Service Unification: State of the Art and Challenges

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***Abstract*—The recent developments in networking research leverage the principles of virtualization and service-orientation to enable fundamental changes in network architecture, which forms a trend of network cloudification that enables network systems to be realized using cloud technologies and network services to be provisioned following the cloud service model. On the other hand, the latest progress in cloud and fog computing has made networking an indispensable ingredient for cloud/fog service delivery. Convergence of networking and cloud/fog computing technologies enables unification of network and cloud/fog service provisioning, which has become an active research area that attracts interest from both academia and industry. In this paper, we introduce the notion of network-cloud/fog service unification and propose an architectural framework for unified network-cloud/fog service provisioning. Then we present a survey that reflects the state of the art of research on enabling network-cloud/fog service unification. We also discuss challenges to realizing such unification and identify some opportunities for future research, with a hope to arouse the research community's interest in this exciting interdisciplinary field.**

***Keywords*-network virtualization; network-as-a-service; cloud and fog computing; service-orchestration; network-cloud/fog unification**

I. Introduction

The stunning success of Internet has brought in significant challenges to itself that demand fundamental changes in network architecture in order to utilize infrastructures comprising heterogeneous networking and computing resources to provision services for meeting highly diverse application requirements. A main technical strategy that the networking research community has taken to address the above challenges lies in applying the principles of virtualization and service-orientation in network architecture and service model.

Network virtualization essentially decouples network functions related to service provisioning from the infrastructures for data transport and processing, which is embraced by the latest developments in networking technologies such as the Network Function Virtualization (NFV) architecture. Service-orientation in networking essentially abstracts network resources and capabilities as self-contained entities that can be exposed, accessed, and composed through interfaces that support loose-coupling interactions, which leads to the Network-as-a-Service (NaaS) paradigm. Virtualization and service-orientation have been the key pillars for cloud computing and then recently were adopted by the networking community as key principles for future network design. NFV together with NaaS enable networking systems to be realized based on cloud technologies and network services to be provisioned following the cloud service model. This trend in networking technology development is often referred to as *network cloudification*.

On the other hand, recent developments in the field of cloud computing has made networking more crucial than ever in cloud service delivery. Data center network (DCN) is a core component of cloud infrastructure and networking among data centers is a key enabler for inter-cloud federation. It is the networking performance bottleneck between end users and data centers that motivates deploying cloud-like capabilities at network edge thus leading to the fog computing paradigm. Fog computing, which is essentially an extension of cloud computing with decentralized compute and storage resources embedded in network infrastructures, has made the boundary between networking and computing blurry.

Recent developments in networking and cloud computing are enabling a convergence of these two fields that used to be relatively independent [1]. The latest progress in NFV, NaaS, and fog computing has form a trend toward *unification of network and cloud/fog services* that accelerates network-compute convergence. This trend is becoming an active research area that attracts attention from both academia and industry. Although numerous research works have been conducted on various aspects of network-cloud/fog service unification, they are scattered in different sectors of the literature and there still lacks a big picture that clearly reflects the current status of this promising area.

In this paper, we attempt to provide the research community with a sketch of the state of the art of research on enabling unification of network and cloud/fog service provisioning. We first review the trend of network cloudification

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and the role of networking in cloud/fog computing, then introduce the notion of network-cloud/fog service unification and propose an architectural framework for unified network-cloud/fog service provisioning. We will review representative works that reflect the current status of research toward realizing the network-cloud/fog service unification. We will also discuss open issues and challenges thus identifying some opportunities for future research.

II. Cloudification in Networking

Two fundamental approaches that the research community has leveraged in the past decade for addressing challenges to future networking are virtualization and service-orientation in networking. Virtualization in networking essentially decouples network service provisioning from network infrastructures thus enabling multi-tenant virtual networks with alternative architecture and protocols to be realized upon shared infrastructure for meeting diverse service requirements. Pioneer works that proposed virtualization in networking were presented in [2] and [3]. Then the network virtualization (NV) notion attracted attention of the research community and a wide variety of works have been conducted on different aspects of its architecture and key technologies [4]. It has become a consensus that virtualization should be a key attribute of the future network architecture.

A significant milestone of virtualization in networking is the Network Function Virtualization (NFV) paradigm initially developed by ETSI [5]. NFV decouples network functions from proprietary hardware appliances so that they can run as software instances hosted upon standard commodity servers [6]. NFV embraces the NV principle and offers more specific architecture and mechanisms for virtualizing network functions and managing virtual network functions as well as virtualized network infrastructure.

Another fundamental approach to future networking that has an significant impact on network technology developments is application of the service-orientation principle. In general, the service-orientation principle advocates that a large complex system can be better constructed and managed if it is decomposed into a collection of smaller units called *services*, which exist autonomously but collaborate with each other. A system architecture designed following this principle is called Service-Oriented Architecture (SOA). The concept of *service* in SOA emphasizes its features of being a self-contained platform-independent system module that collaborates with other system modules via loose-coupling interactions; thus should not be confused with the conventional services provisioned by a networking system.

When applied in networking, service-orientation focuses on encapsulating network functionalities and capabilities as services and exposing them through abstract service interfaces. Therefore, such a networking paradigm is often referred to as Network-as-a-Service (NaaS). Earlier efforts toward NaaS include web services in telecommunications [7], next-generation service overlay network (NGSON) [8], and NaaS-based service provisioning in SDN [9]. More recently, the Third Network vision of MEF with its Lifecycle Service Orchestration (LSO) architecture and IETF specifications for Service Function Chaining (SFC) both embrace the NaaS paradigm. NaaS has also been adopted in the NFV architecture in which NFVIaaS, VNFaaS, and VNFPaaS are identified as key use cases. NFV Release 3 is developing TOSCA-based descriptors for network services and functions and RESTful interfaces among NFV orchestrators, VNF managers, and virtualized infrastructure managers.

Virtualization and service-orientation, which are fundamental principles for cloud computing, now have been adopted as key attributes for future networking. Therefore, this trend in networking technology development can be viewed as *Network Cloudification*, which enables networking systems to be realized using cloud technologies and allows network services to be delivered following the cloud service model. Network slicing, as a key feature of 5G networks, aims to construct multi-tenant logical networks that can be offered to different customers on-demand. Network slicing is expected to be realized based on NFV and NaaS therefore is a typical use case of network cloudification.

III. Networking in Cloud/Fog Computing

The recent rapid developments in cloud computing and its evolution have made networking a more indispensable component for cloud service provisioning than ever.

Networking forms a core element of cloud infrastructure. DCNs form the basis of data center infrastructure for supporting cloud applications. Research results have shown that networking performance has a significant impact on cloud service performance [10]. Therefore, management of network resources is integrated in virtually all cloud resource management systems, for example OpenStack Neutron. The recently proposed disaggregated datacenter (DDC) architecture contains separated pools of compute and storage resources that are interconnected using a network fabric. High throughput and low latency networking among disaggregated compute and storage blades is a key enabler for DDC [11].

Large cloud service providers typically deploy multiple datacenters at different geographical sites to enhance service availability, reliability, and flexibility. Such a decentralized cloud infrastructure requires high-performance networking for inter-datacenter cooperation [12]. In addition, the emerging inter-cloud federation paradigm, which allows dynamic coordination and load distribution among datacenters of different service providers, also demands high-performance wide area networking among geo-distributed cloud infrastructures [13].

Networking also plays a crucial role in cloud service provisioning. Cloud services are accessed by end users through networks; therefore, services delivered to end users are essentially composite network-cloud services, in which networking may introduces a performance bottleneck [14]. This performance bottleneck motivated some emerging technologies that aim to bring cloud-like capabilities to network edge in user proximity. We refer to this type of extension of cloud computing as *fog* computing, in which decentralized computing capabilities are deployed across the entire network scale, from access network to transport network to backbone network and cloud data centers [15].

In fog computing, distributed compute and storage resources embedded inside the network infrastructure at various locations collaborate through network connections for service provisioning. Both the ETSI MEC framework [16] and OpenFog architecture [17] not only leverage network systems as the underlying platform but also assume that virtualization and NaaS to be key capabilities of the underlying network infrastructure. Therefore, network cloudification offers key enabling technologies for the emerging fog computing paradigm.

IV. Unification of Network and Cloud/Fog Service Provisioning

We believe that the on-going cloudification in networking and the more crucial role of networking in cloud/fog computing will bring in some significant changes in future service provisioning. The boundary between the data transportation-oriented network services and the data processing-oriented cloud/fog services, which used to be offered by independent service providers, are becoming blurry. The services eventually delivered to end users will be composite network-cloud/fog services in which virtual network, compute, and storage functions are orchestrated for end-to-end service provisioning. The underlying infrastructure comprises heterogeneous networking, computing, and storage resources that are managed by a federated mechanism and utilized by the upper layer virtual functions through resource abstraction.

In this paper, we introduce the concept of *unification of network and cloud/fog services* to reflect such a trend toward composite network-cloud/fog service provisioned through end-to-end orchestration across network, cloud, and fog service domains with federated management of networking, computing, and storage resources. An architectural framework for unified network-cloud/fog service provisioning is depicted in Figure 1.

At the bottom of this architectural framework is the infrastructure layer that comprises heterogeneous networking, computing, and storage infrastructure resources. This layer contains multiple administrative domains operated by different service providers and each administrative domains may be composed of multiple technology domains that comprise some particular types of infrastructures for networking, computing, storage, or their combinations.

The virtualization layer on top of the infrastructure domains provides unified abstraction of heterogeneous infrastructures and exposes the virtualized resources as SOA-

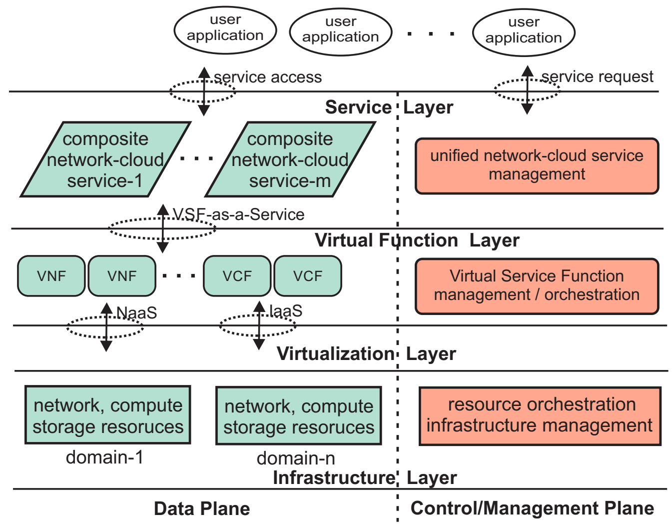

Figure 1. An Architectural Framework for Unified Network-Cloud/Fog Service Provisioning

compliant infrastructure services, for example network infrastructure services and compute infrastructure services, which can be leveraged by the virtual function layer for realizing various virtual network functions (VNFs) and virtual compute functions (VCFs). The VNFs and VCFs then can be selected and orchestrated by the service layer to form composite end-to-end services for meeting the different requirements of end users.

Unification of network-cloud/fog services envisions a service model where the continuum from user devises to access networks, then core networks, and finally data centers forms a unified service delivery environment through a holistic inter-domain approach. The architectural framework shows unification at both service level and resource level. Service-level unification requires unified orchestration across the domains of network, cloud, and fog service providers for end-to-end service provisioning; while resource-level unification calls for federated management of heterogeneous networking, computing, and storage resources, both virtual and physical, to support the service-level unification.

Unification of networking and cloud/fog computing allows provisioning of network, cloud, and fog services converge to a unified service architecture, in which traditional network, cloud, and fog service providers merge to a single role that may obtain a holistic view across service and infrastructure domains for end-to-end service provisioning. End-to-end orchestration across service domains together with federated resource management across infrastructure domains may significantly improve resource utilization as well as enhance service performance.

In addition, virtualization and service-orientation applied across all networking and computing resources in the unified service architecture allow the entire service system be sliced and exposed as services for meeting the various multi-tenant requirements. Therefore, the new service model introduced by network-cloud/fog unification may stimulate innovations in service developments for a wide range of applications and create various new business opportunities.

V. State of the Art of Research Enabling Network-Cloud/Fog Service Unification

Unification of network and cloud/fog service provisioning has attracted attention from both academia and industry and much exciting progress has been made toward this new service paradigm. In this section, we attempt to sketch a big picture about the current status of related research by reviewing representative works in this area.

The architectural framework given in Figure 1 indicates that virtualization and service-orientation in both networking and cloud/edge computing systems form the technical foundation for the unified service architecture. Upon such a foundation, inter-domain orchestration of network and cloud/fog services supported by federated management across networking and computing resources plays a crucial role in enabling network-cloud/edge service unification.

Network service orchestration (NSO) has become an active research area in networking. NSO in general refers to a coordinated set of activities that abstract and automate the control of physical and virtual resources for delivering end-to-end network services. Similar mechanisms for coordinating virtual resources and functions for end-to-end service provisioning are also referred to as service function chaining (SFC).

Currently, ETSI is one of the main driving forces for NSO development. Management and Orchestration (MANO) is a core element in the ETSI NFV architecture, in which the NFV orchestrator (NFVO) is a primary component in charge of orchestration of resources across multiple virtual infrastructure domains and lifecycle management of network services. The basic NFV MANO specification assumes a single administrative domain thus lacking sufficient support for orchestration between network and cloud/fog services.

More recent developments in NFV MANO offer architectural options regarding multi-domain orchestration [18]. One option is to split NFVO to a service orchestrator managing the end-to-end services and multiple resource orchestrators for abstracting and managing the infrastructure resources in different domains. Another option introduces a new element called Umbrella NFVO that composes the services offered by different administrative domains, each of which has its own NFVO for orchestrating its resources and network services within the domain. The option presented in the latest ETSI NFV Release 3 defines a new "Or-Or" reference point between the NFVOs of different domains to enable communications and cooperations among them for end-to-end service provisioning [19] .

IETF has developed the Service Function Chaining (SFC) architecture [20] for enhancing end-to-end network service provisioning. As defined by IETF, a service function chain is an abstracted view of a service that specifies the set of required service functions (SFs) as well as the order in which they must be executed. The IETF SFC architecture comprises a data plane, which handles traffic steering through a series of SFs, and a control plane that is responsible for lifecycle management of service chains and SF instances. Essentially, SFC aims at achieving similar objective as network service orchestration and NFV MANO specification offers an architectural framework for realizing some key components of the IETF SFC architecture. For example, SFs can be implemented as VNF instances and service graphs in SFC architecture may be realized as VNF forwarding graphs managed by MANO.

Enabling technologies for network-cloud service unification have been investigated in various research projects. The NaaS-based architecture developed in the EU FP7 T-NOVA project leverages NFV MANO and supports service orchestration across multiple administrative domains [21]. The FP7 UNIFY project aims to develop a unified platform for composite network and cloud service provisioning. A key mechanism of the UNIFY architecture is service orchestration across network and cloud domains comprising compute, storage, and network resources [22]. The research outcomes of the T-NOVA and UNIFY projects have been utilized in a follow up project 5G Exchange, which has the goal to enable cross-domain orchestration of services over multiple administrations. In this project, NFV MANO architecture is extended with new functional components and interfaces including an inter-provider NFVO [23]. Research outcomes from the aforementioned projects mainly focus on integration between networks and traditional clouds but have not sufficiently investigated the issues brought in by fog computing; for example, distributed compute capabilities scattered across a larger scale network with possible mobility.

Network virtualization, network slicing, and fog computing are key pillars for 5G networks, which will be a representative application case of network-cloud/fog service unification. The 5G end-to-end architecture framework developed by Next Generation Mobile Network (NGMN) Alliance contains end-to-end service management and orchestration as a key component [24]. The on-going 5G-Transformer project is investigating technologies for aggregating and federating transport networks with computing fabrics, from network edge to the core network and cloud data centers, to crete and manage slices throughout a virtualized infrastructure in order to provision composite network-compute services for meeting the diverse requirements of various industry verticals [25].

Various research results toward enabling unified network-cloud/fog service provisioning have been published in the literature. For example, Sonkoly *et al.* [26] designed and implemented a joined network and cloud resource virtualization and programming API that is capable for flexible service chaining control over heterogeneous technology domains. An NFV MANO-based architecture was proposed in [27] to achieve uniform management of IoT services spanning across the continuum from the cloud to the edge of 5G access network. In [28], the authors present an orchestration framework that deploys end-to-end services across OpenStack-managed cloud data centers and SDN networks controlled either by ONOS or OpenDaylight controller. The open-source service platform COMPOSER developed in [29] supports multiple virtualization engines (e.g., virtual machines, containers, native network functions) to instantiate network services and enable joint optimization of network and compute resources.

The currently available works on network service orchestration mainly focus on federated management of network connectivity and network service functions (VNFs). Although encouraging progress has been made for achieving unified control over computing for implementing service functions and networking for steering traffic through the service functions, the service functions considered in this context are mainly network functions, e.g., firewall, NAT, load balancer, etc., instead of functions for provisioning cloud and fog services. Effective mechanisms for fully enabling orchestration across network and cloud/edge service domains still need further research.

Various research efforts have also been made in the fields of cloud and fog computing toward enabling network-cloud/fog service unification. Network resource management has been integrated in typical cloud operating systems. For example, Neutron in OpenStack is an NaaS-based controller that provides APIs for managing networking resources in an IaaS environment. Software-Defined Networking (SDN) provides better support for network programmability through a logically centralized controller; therefore, SDN is often applied in cloud infrastructures to enable cloud OS to manage the underlying network platform. However, currently available works on cloud network management are mainly limited within a single administrative domains and need to be extended for supporting end-to-end network-cloud/fog service unification.

Service composition has been extensively studied in the area of cloud computing and numerous works have been published for cloud resource orchestration [30]. However, most of the existing cloud service composition technologies assume availability of sufficient networking capacities among the compute service components without sufficiently considering the impact of networking on end-to-end service performance. Recently, progress toward network-aware service composition has been reported in the literature. For example, the technology developed in [31] is able to unify the management computing and networking resources inside a datacenter for cloud service provisioning. In [32], the authors formulate the network-cloud service composition problem as a variant of multi-constraint optimal path problem and propose an approximate algorithm to solve it.

The true impact of edge computing relies on the service orchestration capabilities as well as on its interaction with the network architecture. Recent research has suggested alignment of the MEC and NFV architecture, which allows MEC resource management and service orchestration to reuse the mechanisms provided by NFV MANO framework. A double-tier MEC-NFV architecture that aligns and integrates the MEC system with NFV MANO framework was proposed in [33]. ETSI has developed a framework for deploying MEC in an NFV environment that may facilitate orchestration between network and edge services [34].

VI. Challenges and Opportunities

Although exciting progress has been made in both networking and cloud/fog computing fields, unification of network and cloud/fog services is still facing some challenges that are yet to be fully addressed thus offering opportunities for future research.

Heterogeneity across domains is a main challenge to network-cloud/fog service unification. This challenge comes from not only the heterogeneous resources and functions across technology domains but also various control/management mechanisms and policies deployed in different administrative domains. Heterogeneity exists not only in the infrastructure layer comprising network, compute, and storage capabilities but also in the virtual function layer that contains both networking-oriented VNFs and computing-oriented VCFs. Such level of heterogeneity calls for more sophisticated mechanisms for resources federation and service orchestration across both technology and administrative domains. Considering the autonomous domains involved in unified network-cloud/fog service provisioning, which may include mobile access network and backbone network operators, cloud service providers, and third-party fog service providers, effective inter-domain interactions and collaboration for achieving end-to-end service orchestration becomes even more challenging.

More thorough study on applying the virtualization and service-orientation principles offers a promising direction to explore for addressing the challenges introduced by heterogeneity across autonomous domains. A general abstract view of virtual resources enabled by unified virtualization of heterogeneous infrastructure resources may facilitate federated inter-domain resource management. Service-oriented resource encapsulation and exposition allows various virtual functions for both networking and computing to be utilized as SOA-compliant services and orchestrated through a unified service composition mechanism for end-to-end service provisioning. In addition, service model and description play a crucial role in abstraction of infrastructure resources as well as virtual functions therefore deserve more thorough investigation in future research.

Scalability has long been a challenge to network and cloud system designs but unification of network-cloud/fog services pushes it to another level. Virtualization of both network and cloud infrastructures allows various functions to be realized as software instances hosted upon VMs or containers and orchestrated to form end-to-end services, which may significantly increase the number of virtual functions involved in service provisioning. On the other hand, the distributed computing infrastructures embedded inside a network may be located in various sites scattered across the network; therefore, end-to-end services typically contains complex network connections among a large number distributed service functions. Due to the limited compute and storage capacities available at fog nodes, lightweight micro-services hosted upon containers fit fog computing better, which then leads to an even larger scale orchestration of finer-grain service components.

The scalability challenges to network-cloud/edge service unification, together with the requirements for elastic service provisioning in a dynamic networking environment, demand more advances in federated resource control and holistic service management. Fully leveraging the emerging software-defined networking (SDN) paradigm combined with network virtualization may significantly enhance system control and management thus offering a promising direction for future research.

We advocate integration of the SDN and NFV principles [35] to fully exploit their advantages beyond the current typical usage of SDN as a traffic steering mechanism for service orchestration in an NFV environment. The SDN principle lies in decoupling resources/functions from their control/management to enable a logically centralized control plane supporting high-level network programmability. By decoupling the data and control planes in all network, compute and storage domains, one may construct a logically centralized control plane with holistic view and global programmability across networking and computing resources, which may greatly facilitate inter-domain resource federation and service orchestration. Following the virtualization principle, the global controller for each unified network-cloud/fog service should be decoupled from infrastructure management.

Another challenge to realizing the notion of network-cloud/fog service unification lies in the complexity of service and resource management required by a large-scale unified architecture supporting dynamic and elastic service provisioning, which is way beyond what manual operations can handle. Therefore, automation in resource and service management becomes a key enabler for the future service architecture, which calls for more advances in higher-level abstraction, effective programmability, and agile system (re-)configuration and (re-)optimization. Big data analytic and machine learning technologies, which recently started receiving attention in networking and cloud computing, offer an approach to achieving agile and adaptive service and resource management that deserves more thorough investigation.

VII. Conclusion

Wide applications of virtualization and service-orientation in networking form a trend of network cloudification and the latest developments in cloud and fog computing lead to a more network-based computing paradigm. Convergence of networking and computing technologies calls for federated resource and service management across the network and cloud/fog domains. In this paper, we introduced the notion of network-cloud/fog service unification and presented an architectural framework for unified network-cloud/fog service provisioning. We then reviewed the representative works that reflect the start of the art research for enabling network-cloud/fog service unification. We also discussed challenges that must be fully addressed before realizing this unified service paradigm and proposed some possible directions for future research. We found that although exciting progress has been made toward unification of networking and cloud/fog computing, this area is still at its early stage thus offering numerous research opportunities. We believe that cross-fertilization among multiple fields such as NFV, NaaS, 5G networks, cloud computing, and fog computing may provide innovative technologies that will significantly enhance the future information infrastructure.

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