Network Service Orchestration: A Survey

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***Abstract*—Business models of network service providers are undergoing an evolving transformation fueled by vertical customer demands and technological advances such as 5G, Software Defined Networking (SDN), and Network Function Virtualization (NFV). Emerging scenarios call for agile network services consuming network, storage, and compute resources across heterogeneous infrastructures and administrative domains. Coordinating resource control and service creation across interconnected domains and diverse technologies becomes a grand challenge. Research and development efforts are being devoted on enabling orchestration processes to automate, coordinate, and manage the deployment and operation of network services. In this survey, we delve into the topic of Network Service Orchestration (NSO) by reviewing the historical background, relevant research projects, enabling technologies, and standardization activities. We define key concepts and propose a taxonomy of NSO approaches and solutions to pave the way to the understanding of the diverse ongoing efforts towards the realization of multiple NSO application scenarios. Based on the analysis of the state of affairs, we finalize by discussing a series of open challenges and research opportunities, altogether contributing to a timely and comprehensive survey on the vibrant and strategic topic of network service orchestration.**

I. INTRODUCTION

Modern telecommunication infrastructures consist of a myriad of technologies from specialized domains such as radio, access, transport, core and (virtualized) data center networks. Designing, deploying and operating end-to-end services are commonly manual and long processed performed via traditional Operation Support Systems (OSS) resulting in long lead times (weeks or months) until effective service delivery [1]. Moreover, the involved workflows are commonly hampered by limited built-in infrastructure strongly coupled to physical topologies and hardware-specific constraints.

Technological advances under the flags of Software Defined Networking (SDN) [2] and Network Function Virtualization (NFV) [3] bring new ways in which network operators can create, deploy, and manage their services. SDN and NFV introduce new means for efficient and flexible utilization of their infrastructures through a software-centric service paradigm [4]. However, to realize this paradigm, there is a need to model the end-to-end service and have the ability to abstract and automate the control of physical and virtual resources delivering the service. The coordinated set of activities behind such process is commonly referred to as *orchestration*. In general, orchestration refers to the idea of automatically selecting and controlling multiple resources, services, and systems to meet certain objectives (e.g. a customer requesting a specific network service). Altogether, the process shall be timely, consistent, secure, and lead to cost reduction due to automation and virtualization.

Multiple stakeholders are involved in the development and standardization of enabling technologies for network softwarization and their embodiment into next generation networks (e.g. 5G) based on SDN, NFV, and Orchestration building blocks and reference architectures. The ecosystem includes Standards Developing Organizations (SDOs), as well as industry groups, open source projects, foundations, diverse user-lead groups, and so on. Examples of these players include European Telecommunications Standards Institute (ETSI), Metro Ethernet Forum (MEF), Organization for the Advancement of Structured Information Standards (OASIS), Linux Foundation, and Open Networking Foundation (ONF). Similarly, several (academic and industrial) research and (commercial) development efforts in orchestration, SDN and NFV have been going in recent years, concretized in a number of collaborative endeavors such as Open Source MANO (OSM) [5], OpenStack [6], Open Network Automation Platform (ONAP) [7], 5G-Exchange (5G-Ex) [8], Central Office Re-architected as a Datacenter (CORD) [9], etc.Multiple stakeholders are involved in the development and standardization of enabling technologies for network softwarization and their embodiment into next generation networks (e.g. 5G) based on SDN, NFV, and Orchestration building blocks and reference architectures. The ecosystem includes Standards Developing Organizations (SDOs), as well as industry groups, open source projects, foundations, diverse user-lead groups, and so on. Examples of these players include ETSI, MEF, OASIS, Linux Foundation, and ONF. Similarly, several (academic and industrial) research and (commercial) development efforts in orchestration, SDN and NFV have been going in recent years, concretized in a number of collaborative endeavors such as OSM [5], OpenStack [6], ONAP [7], 5G-Ex [8], CORD [9], etc.Multiple stakeholders are involved in the development and standardization of enabling technologies for network softwarization and their embodiment into next generation networks (e.g. 5G) based on SDN, NFV, and Orchestration building blocks and reference

*This work was supported by UNICAMP and Ericsson.

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architectures. The ecosystem includes Standards Developing Organizations (SDOs), as well as industry groups, open source projects, foundations, diverse user-lead groups, and so on. Examples of these players include ETSI, MEF, OASIS, Linux Foundation, and ONF. Similarly, several (academic and industrial) research and (commercial) development efforts in orchestration, SDN and NFV have been going in recent years, concretized in a number of collaborative endeavors such as OSM [5], OpenStack [6], ONAP [7], 5G-Ex [8], CORD [9], etc.

Unfortunately, broad understanding and practical definitions of Network Service Orchestration (NSO) are still missing –not only across but also inside networking communities. The maturity of ongoing efforts varies largely with the overall technical approach being very much fragmented and showing little consolidation around an overarching notion of network service orchestration. For instance, the work by Rotsos et al. [10] is the first notable attempt to survey the realm of network service orchestration. The authors provide an analysis of the diverse standardization activities around NSO from an operator perspective. The article follows a top-down approach, defining terminologies, requirements, and objectives of a network service orchestrator.

In this survey, our main objectives are to provide a comprehensive review of research, standardization and software development efforts around the overcharged term of Network Service Orchestration. We present an in-depth and up-to-date study on network service orchestration covering some history and context, related enabling technologies, standardization activities, actual solutions, open challenges and research opportunities. In contrast to [10], we propose a view of NSO also from a customer perspective and propose a taxonomy of the main characteristics and features of NSO approaches. We also cover how recent open source platforms and research projects map to the primary characteristics and technical implementations to NSO realization.

Throughout the survey, we distinguish between two types of domains. First, *administrative domains*, which map to different organizations and therefore may exist within a single service provider or cover a set of service providers. In one administrative domain, multiple *technology domains* can exist based the type of technology in scope, for example, Cloud, SDN, NFV, or Legacy. Broadly speaking, we refer to NSO as the automated coordination of resources and services embracing both single-domain and multi-domain contexts.

Figure 1 presents a generic high-level reference model for multi-domain Network Service Orchestration, featuring a Multi-Domain Orchestrator (MDO) per administrative realm and including the notion of a Marketplace for business interactions. MDOs coordinate resources and services in a multiple administrative domain scope covering multiple technology domains [11]. The exchange of information, resources, and services themselves are essential components of an end-to-end network service delivery. The MDO exposes the available services to the marketplace allowing service providers to sell network services directly to their customers or other providers under various possible resources consumption models (e.g. trading resources from each other). The MDO can be seen as a single element with a possible split into two functional components: Service Orchestrator (SO) and Resource Orchestrator (RO). The SO orchestrates high-level services while the RO is responsible for managing resource and orchestrating workflows across technology domains. The Domain Orchestrators (DOs) performs orchestration in each local domain acting on the underlying infrastructures and exposing resources and network functions northbound to the MDO.

The survey is organized as follows. Section II presents essential background and key technologies related to network service orchestration. Concepts, functions, scope, and a taxonomy of NSO are presented in Section III. Section IV focuses on the standardization efforts whereas Section V covers major research projects around NSO. Section VI provides an overview of open source and commercial solutions. Section VII presents some potential scenarios to illustrate the NSO in practice. The discussion in Section VIII points to a series of open challenges and research opportunities. Finally, Section IX concludes the survey.

II. Background

NSO foundations can be rooted back to three enabling technologies, namely Cloud Computing, Software Defined Networking, and Network Function Virtualization. This section presents a brief overview of these topics, as well as an introduction to the historical background and definitions of term "orchestration".

A. Cloud Computing

Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, storage, and services) that can be rapidly and automatically provisioned and released with minimal effort [12]. Thereby, the resources are traded on demand, that is, the customer only pays what to use. Cloud computing becomes one of relevant technology for the 5G networks mainly because it provides high data rate, high mobility, and centralized management [13].

The service models of cloud computing are generally categorized into three classes: Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS). In a cloud IaaS, the infrastructure is offered as a service to the customer. Each customer can have its virtual resources, such as compute, storage, and network. SaaS includes applications such as Facebook, Google Apps, Twitter, and Micrsot Office 365.

PaaS provides services according to a users applications without installing or configuring the operating system. The customers can develop and deploy their applications in the same development environment. The PaaS model includes services such as Microsoft Azure, Google App Engine, RedHat OpenShift, and Amazon Elastic Beanstalk.

In SaaS, in turn, the customer is able to use the providers' applications running on a cloud infrastructure [3]. The softwares are maintained and managed by a cloud provider. IaaS includes applications, for example, OpenStack, CloudStack, Amazon CloudFormation, and Google Compute Engine.

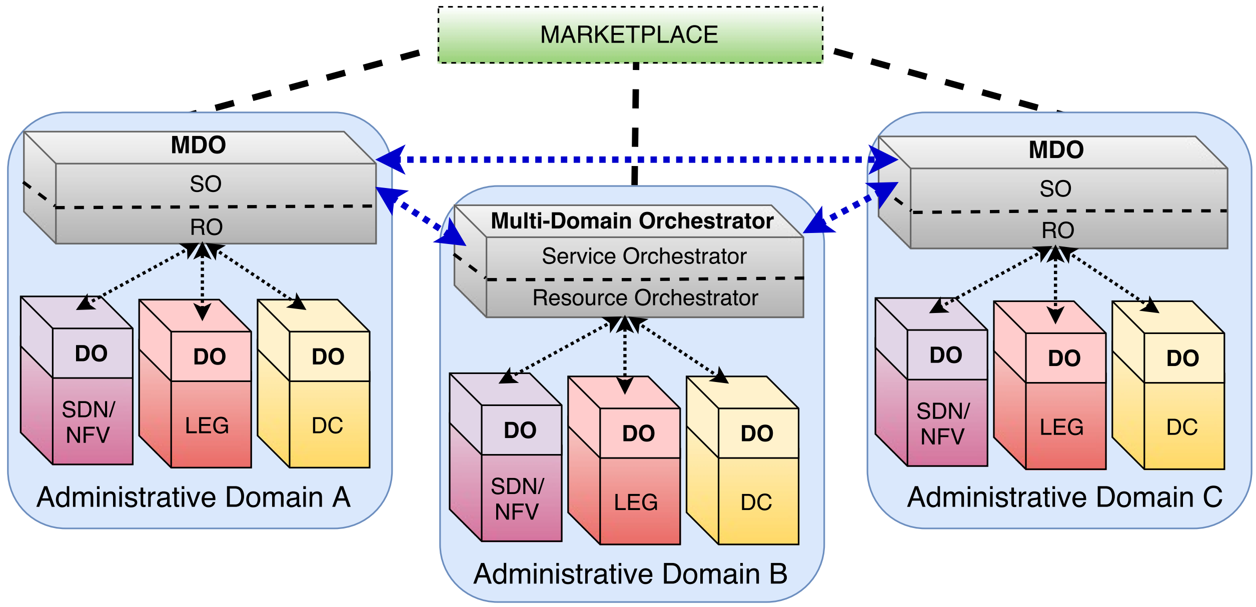


Fig. 1. High-level reference model to illustrate the scope of Network Service Orchestration (NSO) in single-domain and multi-domain environment. The NSO need to have an overview of entire environment to compose the service mainly if the service to use resources of different domains.

In a cloud environment, the notion of orchestration has also been used for integrating basic services [14]. The Orchestration in the cloud involves dynamically deploying, managing and maintaining resource and services across multiple heterogeneous cloud platforms in order to meet the needs of clients. This procedure demands to automatize processes and create a workflow. However, this is not a simple task.

B. Software Defined Networking (SDN)

SDN [2] is an evolving networking paradigm that attempts to resolve the strongly vertical integration of current network environments. To this end, SDN proposals decouple the control plane (i.e. control logic) from the data plane (i.e. data forwarding equipments). With this new architecture, routers and switches become simple forwarding network elements whose control logic is provided by an external entity called SDN controller or Network Operating System (NOS). The SDN controller creates an abstract network view while hiding details of the underlying physical or virtual infrastructure. Running on the top of the SDN controller, software network applications can perform not only traditional functionalities such as routing, load balancing, classification [15], or Intrusion Detection Systems, but also propose novel use cases such as service orchestration across multi-domain and multi-technology in 5G networks [16]. Those applications together with other industry and academy initiatives towards flexible network services over programmable resources are among the main drivers of SDN.

The communication between the SDN controller and the forwarding devices is done through Southbound Interfaces (SBIs), which allow decoupling the control and data plane via open communication protocols (i.e. well-defined APIs). Different SDN SBIs can be considered (e.g., ForCES [17], OVSDB [18], POF [19], etc.), with OpenFlow [20] [21] being the most widely accepted solution available in commercial and open source (hardware and software) devices.

Service orchestrators, OSSes and other network applications can be developed on top of high-level Northbound Interfaces (NBIs) offered by a SDN controller. Indeed, NBIs are crucial components to control and monitor the network services orchestration. Unlike SBIs, where Openflow is a well-known SDN standard protocol, NBIs are still an open issue with different controllers offering a variety of NBIs (e.g., RESTful APIs [22], NVP NBAPI [23], [24], SDMN API [25], etc.). In addition, other type of high-level NBIs category are implemented as NOS management applications [10]. Examples of this category include Virtual Tenant Networks, ALTO, and Intent-based networking (IBN).

The logically centralized SDN controller act in spirit of computer operating systems that provide a high-level abstraction for the management of computer resources (e.g., hard drive, CPU, memory) by playing the network operating system role for network management [26]. As such, it provides a set of services (base network services, management, orchestration) and common interfaces (North/South/East/West) to developers who can implement different control applications and improve manageability of networks. Moreover, such interfaces are used within the Management and Orchestration (MANO) framework to deploy end-to-end connectivity. As today, the most popular open source SDN controllers are Open Network Operating System (ONOS) [27] and OpendayLight [28].

In SDN, the concept of orchestration is vital to automate network operations properly. SDN network domains need single-domain or multi-domain orchestration systems to coordinate end-to-end connectivity services through different network domains controlled by different SDN controller instances, which in turn must communicate directly with the physical network [29].

C. Network Function Virtualization (NFV)

Traditionally, the telecommunication operators have based their networks on a built-in infrastructure strongly coupled to physical topologies and proprietary devices, resulting in network services constrained to the network topology and the physical location of the network appliances. As a consequence, it becomes hard for providers to offer new services with lower cost and more efficiency and agility [3]. Network Function Virtualization has been proposed to solve these problems [30] and change the mode networks are designed and operated by taking a software-centric approached leveraging advances in virtualization technologies and general purpose processors.

According to ETSI Industry Specification Group (ISG) NFV [31], Network Function Virtualization is responsible for separating network functions from the hardware and offering them through virtualized services, decomposed into Virtualized Network Function (VNF), on general purpose servers. With the virtualization of the network functions, NFV promises more flexible and faster network function deployment, as well as dynamic scaling of the VNFs towards providing finer settings. In NFV environment new services do not require new hardware infrastructure, but simply the software installation, i.e. to create VNFs.

Moreover, the NFV can address Network Functions (NFs) in the most appropriate location, providing better user traffic performance. The network service can be decomposed in one or more VNFs, and each one can be constituted in one or more Virtual Machines (VMs). Each VNF is described by a Virtualized Network Function Descriptor (VNFD) which details the behavioral and deployment information of a VNF.

VNFs can be connected or combined as building blocks to offer a full-scale network communication service. This connection is known as service chain. Service chain provides logical connectivity between the virtual devices of NFV architecture. It is worthwhile noting not only connectivity order importance, but also the logical environment interconnection with physical networks.

Within the scope of the ISG NFV [31], service chain is defined as a graph of logical links connecting NFs towards describing traffic flow between these network functions. This is equivalent to the Service Function Chaining (SFC) [32] defined by Service Function Chaining Working Group (IETF SFC WG) of the Internet Engineering Task Force (IETF). An end-to-end network service may cover one or more Network Function Forwarding Graph (NF-FG) which interconnect NFs and end points. Figure 2 describes two examples of end-to-end network services. The first (green line) is composed of virtual Customer Premises Equipment (vCPE) and virtual Firewall (vFW) VNFs and two endpoints (A1 and A2). The second (red line) is composed of vCPE and virtual Deep Packet Inspection (vDPI) VNFs and two endpoints (B1 and B2). Note that NFV allows sharing a multi-tenant VNFs between different network services.

ETSI has developed a reference architectural framework and specifications in support of NFV management and orchestration. The framework focuses on the support VNF operation across different hypervisors and computing resources. It also

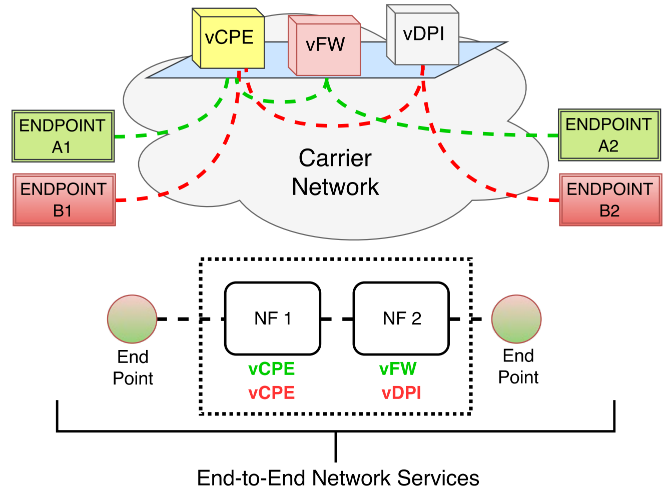


Fig. 2. Example of two end-to-end network services composed of two NFs each. NFV enables the reuse of VNFs, e.g., vCPE.

covers the orchestration and lifecycle management of physical and virtual resources. According to [33], "the framework is described at a functional level and it does not propose any specific implementation." Figure 3 shows the ETSI NFV-Management and Orchestration (MANO) architectural framework with their main functional blocks [34]:

- Operation/Business Support System (OSS/BSS): block responsible for operation and business applications that network service providers use to provision and operate their network services. It is not tightly integrated into the NFV-MANO architecture.
- Element Management (EM): component responsible for the network management functions FCAPS (Fault, Configuration, Accounting, Performance, and Security) of a running VNF.
- VNF: functional block representing the Virtualised Network Function implemented on a physical server. For instance, Router VNF, Switch VNF, Firewall etc.
- NFV Infrastructure (NFVI): representing all the hardware (compute, storage, and networking) and software components where VNFs are deployed, managed and executed.
- Network Function Virtualization Orchestrator (NFVO): it is the primary component, in charge of the orchestration of NFVI resources across multiple Virtualized Infrastructure Managers (VIMs) and lifecycle management of network services.
- VNF Manager (VNFM): performs configuration and VNF lifecycle management (e.g., instantiation, update, query, scaling, termination) on its domain.
- VIM: block provides controlling and managing the NFVI resources as well the interaction of a VNF with hardware resources. For example, OpenStack as cloud platform and OpenDaylight and ONOS as SDN controllers.

The NFV-MANO functional block performs all the virtualization-specific management, coordination, and automation tasks in the NFV architecture including the components NFVO, VNFM, VIM, NFV Service, VNF Catalogue, NFV

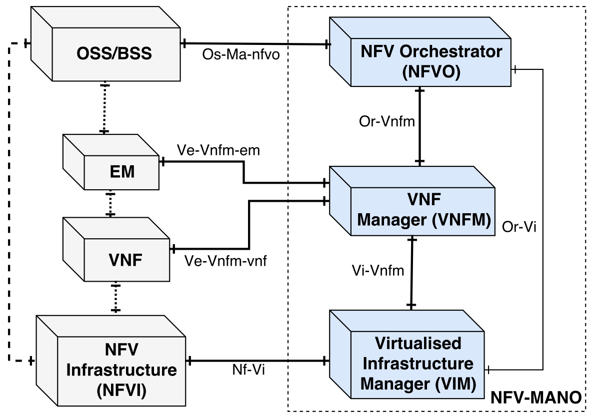


Fig. 3. The NFV-MANO architectural framework. Adapted from [34]

Instance, and NFVI Resource.

The NFV-MANO reference architecture does not specify anything about SDN in its architecture instead it assumes that necessary transport infrastructure is already established and ready to be used. However, in [35], ETSI identifies use cases and the most common options for using SDN in an NFV architectural framework. It also points proof of concepts and recommendations to be fulfilled by the organizations that intend to perform such integration. [36] provides a recent in-depth survey on NFV state of affairs.

D. Orchestration: Historical Overview

The academic community and industry generally require some time to define the real meaning, reach and context of the concepts related to new technology trends as is the case with the term *Orchestration*. The term orchestration is used in many different areas, such as multimedia, music, service-oriented architecture, business processes, SDN, and, more recently, in NFV.

From an end-user perspective, orchestration reminds a symphony orchestra where a set of instruments play together according to an arrangement. The music is arranged and split in small part, after assigns to different musical instruments. When, who, and what will be played, as well as the conducting are essential parts towards achieving the desired effect.

One of the first works in the Information and Communication Technology (ICT) area that cite the term orchestration [37] relate it with coordination and control of multiple media traffics. It distinguishes the orchestration from synchronization and defines an architecture where the orchestration acts in different layers. In the same scope, [38] relates the orchestration with multimedia data. In this work, the orchestration is associated with multimedia presentation lifecycle management. The lifecycle management involves the coordination of stages that constitute all orchestration process.

The use of orchestration is also widely discussed in the scope of web services. In this context, orchestration and automation are considered separate processes. The work in [39] defines orchestration like an executable process that can interact both internal and external services and must be dynamic, flexible, and adaptable the changes. It emphasizes that orchestration describes how web services can act with each other at the message level, including the business logic and execution order of the activities.

More recently in 2009, [40] provides an overview of definition and design of Management and Service-aware Networking Architectures (MANA) for the Future Internet (FI). One of the pillars for the FI pointed by the article is Orchestration. In the envisioned architecture, the orchestration function coordinates the integrated behavior and operations to dynamically adapt and optimize resources in response to changing context following business objectives and policies.

Orchestration is generally related to service automation in cloud [41] and NFV environments. In spite of that, its concepts are not clearly defined in the scope of NFV yet [42] [43].

E. Orchestration: Definitions

Various communities differ with respect to the meaning, assumptions and scope of orchestration functions. Thus, it is helpful begin by reviewing the community understanding to get the main concepts and significance. To this end, we overview the leading organizations and efforts defining the term Orchestration in diverse contexts.

A couple of years ago, the term orchestration was adopted by ETSI in the scope of NFV. In ETSI NFV, the meaning of orchestration is implied, leading to a vague distinction between orchestration and management. Thus, its meaning may just be inferred from the NFVO functions (both resources and services layers). Similarly, the Internet Engineering Task Force (IETF) comes up with an orchestration definition closely aligned with ETSI.

National Institute of Standards and Technology (NIST) [44] was one of the first organizations to define the concept of Service Orchestration. According to NIST vision, orchestration is a process related to the arrangement, coordination, and management of virtualized infrastructure to provide different cloud services to customers.

The ONF [45] has formally defined orchestration as usage and selection of resources by orchestrator for satisfying client demands according to the service level. The meaning of the orchestration is evident given a SDN Controller. ONF mentioned that main functions of Orchestration are two-fold. First, orchestration implies to split heavy-loaded service requests into service components. Moreover, it distributes the aforementioned components among supported platforms, creating an integrated end-to-end solution across multiple domains.

The ITU-T Recommendation Y.3300 [46] describes the framework of software defined networking. This recommendation defines that SDN functions are programming, orchestrating, controlling and managing network resources. Also, it mentions that orchestration provides automated control and management of network resources. Nevertheless, ITU-T does not clarify the difference between SDN functions and orchestration, what causes some confusion.

According to 3GPP Technical Specification 28.801 [47], orchestration is responsible for interpreting and translating a given service request into a configuration of resources (physical and/or virtualized), as needed for service establishment.

The configuration of resources may use resource allocation policies or actual available resources.

In the 5G white paper issued by NGMN [48], there is an end-to-end management and orchestration entity which composes the proposed architecture, and it is in charge of translating the service request (business models) into infrastructure resources, beyond managing tasks such as resource scaling and network functions geographic distribution. It is worthwhile noting this proposal is similar to the one presented by ETSI NFVO.

The MEF [49] proposes Lifecycle Service Orchestration (LSO) as a reference architecture for multi-domain orchestration. LSO, based on network-as-a-service principles, extends the NFV-MANO architecture and creates new capabilities. The orchestration of LSO refers to "automated service management across multiple operator networks that include fulfillment, control, performance, assurance, usage, security, analytics, and policy capabilities."

In addition to all the above-mentioned leading organizations, there are some works in the literature which also define the concept of orchestration. According to [50], orchestration enables programmability for creating and deploying of end-to-end network services and dynamic network control through a single interface. Thyagaturu et al. [51] address orchestration as the coordination of network services and operations in a higher layer, abstracting the underlying physical infrastructure. The work in [52] makes a generic definition of orchestration as automated management of complex systems, middleware, and services.

From the definitions of orchestration presented, we can derive a clear relationship among orchestration, automation, and management. Although the three terms are lumped together, it is necessary an understanding of the differences between them as they are not the same thing. Automation describes a simple and technical task without the human intervention, for example, launching a web server, stopping a server. Management is responsible for maintaining and healthiness of infrastructure. Its role consists of activities such as alarms for event detection, monitoring, backups of critical systems, upgrades, and license management. Orchestration, in turn, is concerned with the execution of a workflow (processes) in a correct order. It controls the overall workflow process from starting the service until it ends. Its objective is to optimize and automate the network service deployment.

Figure 4 illustrates the relationship among the three terms cited. There is a certain hierarchic between them. The orchestration is a high-level plane, below the management, and in the bottom the automation. In our vision, the orchestration depends on tasks performed by management. Both management and orchestration are based on the use of automation in the execution of their tasks. Nevertheless, some activities are only performed by a certain function, optimization, for instance, can not be achieved by simple automation. The optimization is a responsibility of orchestration. There is a difference between them, but, if they work together in the execution of processes, the services deployments will succeed with further accuracy.

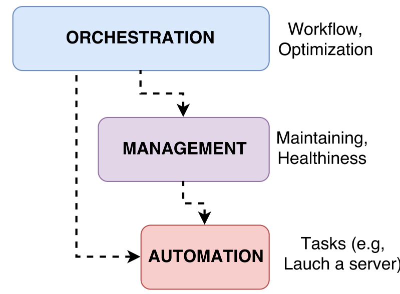


Fig. 4. Relationship among orchestration, management, and automation. Both orchestration and management use automation in their processes.

III. Network Service Orchestration

A. Towards a Practical Definition

We refer to the Network Service Orchestration (NSO) when applied in the services deployment performed by telecommunication operators and service providers. We regard NSO not precisely as a unique technology but a concept to understand network services in detail, relying on multiple technologies and paradigms to achieve such an overarching goal. In a nutshell, network service orchestration comprises the semantics of requested service, and thereby it coordinates specific actions in order to fulfill the service requirements and to manage its end-to-end lifecycle.

The entire orchestration process proposed by NSO involves business and operations that go beyond the delivery of *network services* as defined by ETSI. ETSI NFV-MANO is a platform for management and orchestration required to provisioning VNFs in an NFV domain. The MANO is agnostic and thus has no insight of what is executed within a VNF, restricting its responsibility to the VNF instantiation and lifecycle management.

Based on Figure 1, the MDO understands the operating capabilities of the Network Service (NS) in a broad sense. When a customer demands an NS, firstly it requests the order to a service provider or telecommunication operator through Business-to-Business (B2) interface or a trading platform we refer to as Marketplace. After that, the MDO interacts with any MANO element or other elements (e.g., OSS/BSS, SDN Controllers, Analytic Systems) to create the NS. Thus, a given MANO does not know if the VNFs it is deploying is a load balancer, firewall, or gateway. Meanwhile, the DO just coordinates and manages the orchestration process at a given domain, connecting the involved elements such as network systems, controllers, management software, and IT software platforms.

The NSO works at a higher level in the control and management stack with interfaces to the OSS/BSS. During a network service creation, the orchestration process can exceed the domains boundaries being necessary to use resources and/or services of other providers or operators. Such resources comprised of physical and virtual components. Thus, the NSO is supposed to provide service delivery both within single and/or multi-domain environments (more details in Section III-B). In this sense, different organizations and telecommunication enterprises have developed many open source projects, driving

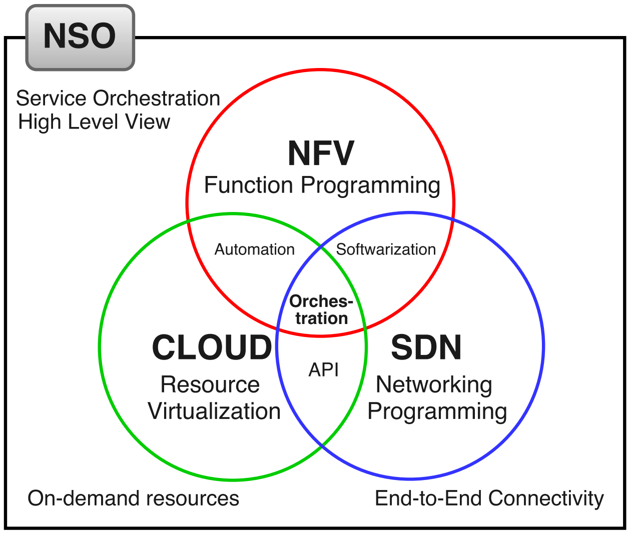


Fig. 5. Overview of the relationships between NSO, NFV, SDN, and Cloud Computing.

orchestration evolution towards open standards that it will permit the implementation of products with a large scale of integration. Section VI addresses some of these projects.

In addition, the customers are demanding full information regarding a given hired network service such as detailed pricing, real-time analytics, and a certain control over the service. NSO can offer more information to the customers and put more control into their hand. Its objective is to understand the service profoundly and to enable that providers/operators attend customer demands.

From an operator and service provider viewpoint, NSO enables to set up new end-to-end services in minutes, keeping those services working and ensuring acceptable performance levels. This process reduces OPEX and provides enhanced services creating new market opportunities and raising the revenues. As well as, it opens up chances for different companies become service providers or provide virtual network functions.

NSO is in charge of all network service lifecycle and delivers an end-to-end connectivity service. To achieve so, orchestration is supported by advances in cloud computing, and technologies such as SDN and NFV, which offer the ability to reconfigure the network quickly as well as programming the forwarding and processing of the traffic. Figure 5 aims at illustrating the relationships between NSO, NFV, SDN, and Cloud Computing.

Each one of these paradigms has different functions: high level orchestration for NSO, function programming for NFV, networking programming for SDN, and resource virtualization for cloud computing. They can work in an integrated pattern to offer advantages such as agility, cost reduction, automation, softwarization and end-to-end connectivity, to enable novel services and applications such as 5G networks.

After this analysis, we can identify the main NSO features as follows:

- *High-level vision of the* NS that permit an overview of all involved domains, technological and administrative.
- *Smart services deployment and provisioning*. These are related to in-deep knowledge about the services, what enable better make decisions.
- *Single and multi-domain environment support* that provide deployment of end-to-end service independently of geographical location.
- *Proper interaction with different MANO and non-MANO elements* which leads to better executed workflows.
- *New markets opportunities*, offering enhanced services and reducing OPEX.

B. Single and Multi-Domain Orchestration

Orchestration in the single and multi-domain environment is different. In a single domain, the orchestrator is in charge of all services and resource availability within its domain as well as has total control over those resources. A domain orchestrator manages the network service lifecycle and interacts with other components not only to control VNFs, but also computing, storage, and networking resources. Its scope is limited by administrative boundaries of the provider. As shown in Figure 1, domain orchestrators can orchestrate heterogeneous technological domains such as SDN, NFV, Legacy, and Data center. Under single domain environment, it is noticeable that the domain orchestrator works as described by ETSI in [34].

However, in a multi-domain environment, local orchestrators do not know the resources and topologies used by other providers. So, multi-domain orchestration is more complex, since it is supposed to provide end-to-end services, which requires cross-domain information exchange features (cf. [53]). Currently, there is not a standard for information exchange process in multi-domain environments, either multi-technology domains or multiple administrative domains. There are some multi-domain orchestration candidates, e.g., T-NOVA FP7 project [54], ONAP [7], Escape [55], and 5G-Ex [16]. All of them will be discussed later in this survey.

ETSI proposes some options regarding multi-domain orchestration. Initially, ETSI NFV Release 2 presents two architectures to address multi-domain scenarios [34]. In the first, the NFVO is split into *Network Service Orchestrator*, manages the network service, and *Resource Orchestrator*, provides an abstract resource present in the administrative domain. A use case for this first option is illustrated in Figure 6(a). A Network Operator offer resources to different departments within the same operator, likewise to a different network operator. One or more Data centers and VIMs represent an administrative domain and provide an abstracted view of its resources. The Service Orchestrator and VNF Manager can or can not be part of another domain. In this use case, a service can run on the infrastructure provided and managed by another Service Provider.

The second architecture does not split the NFVO, but creates a new reference point between NFVOs (See Figure 6(b)) called Umbrella NFVO. This use case requires the composition of services towards deploying a high-level network service. Such service can include network services hosted and offered by different administrative domains. Each domain is responsible for orchestrating its resources and network services. This approach has objectives similar to first, however, an administrative domain is also composed of VNFMs (together with their related VNFs) and NFVO. The NFVO provides standard NFVO functionalities, with a scope limited to the network services, VNFs and resources that are part of its domain.

More recently, the ETSI NFV Release 3 presented others options to support network services across multiple administrative domains [56]. In particular, the use case entitled "Network Services provided using multiple administrative domains" proposes a multi-domain architecture using NFV-MANO. Such architecture introduces the new reference point named "Or-Or" between NFVOs to enable communication and interoperability. Differently of second option (Figure 6(b)), in this approach, there is a hierarchy between the domains. In the example shown in Figure 6(c), NFVO in Administrative Domain C is on-top, using network services offered by Administrative Domains A and B, as well as managing composite NS lifecycle.

In the scope of this paper, end-to-end network services are composed of one or more network functions interconnected by forwarding graphs. Such services might span multiple clouds and geographical locations. Given that, they require complex workflow management, coordination, and synchronization between multiple involved domains (infrastructure entities), which are performed by one (or more) orchestrator(s). Examples of end-to-end services are virtual extensible LAN (VxLAN), video service delivery, and virtual private network.

C. Orchestrator Functions

Section III-A identifies the various areas of term orchestration. Orchestration can be inserted in the context of cloud, NFV, management systems, web services and more recently in the deployment of end-to-end network service in large networks with multiple technologies and administrative domains. In this scope, the orchestrator is the component responsible for automatic resource coordination and control, as well as service provision to customers.

In the NFV context, ETSI NFV-MANO defines the orchestrator with two main functions including *resources orchestration across multiple* VIMs and *network service orchestration* [57]. Network service orchestration functions provided by the NFVO are listed below.

- Management of Network Services templates and VNF Packages. This includes validation of templates and packages with the objective of verifying the artifacts' authenticity and integrity. Besides, the software images are cataloged in involved Points of Presence (PoPs) using the support of VIM.
- Network Service instantiation and management;
- Management of the instantiation of VNFMs and VNFs (with support of VNFMs);
- Validation and authorization of NFVI resource requests from VNF managers (resources that impact NS);
- Management of network service instances topology;
- Policy management related to affinity, scaling (auto or manual), fault tolerance, performance, and topology.

ETSI NFVO functions regarding Resource Orchestration is expressed as follows:

- Validation and authorization of NFVI resource requests from VNF Managers;
- NFVI resource management including compute, storage and network;
- Collect usage information of NFVI resources;

Related to NSO, the orchestrator, in turn, has a more comprehensive function: to decouple the high-level service layer (e.g., marketplace, network slicing) from underlying management and resources layer (e.g., VNFs, Controller, EMS), simplifying innovations and enhancing flexibility in both contexts. The orchestrator allows complex functions to be implemented in underlying technologies and infrastructures. For example, real-time analytics of network services can be deployed through the orchestrator. Another example, the orchestrator can connect the traditional OSS/BSS to the virtualized infrastructure. The Figure 7 represents the significance of the orchestrator in the context of network service.

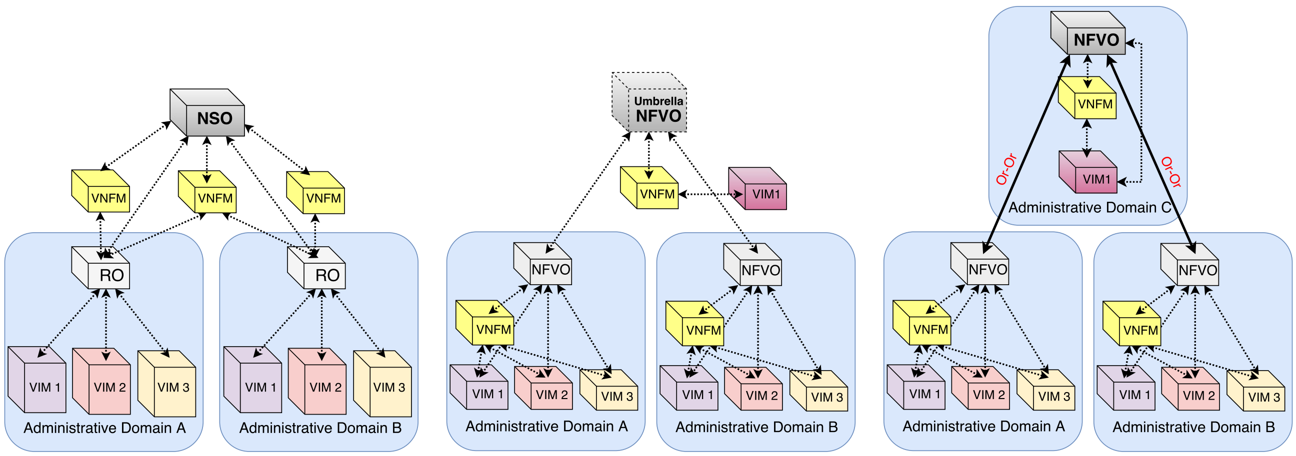
The orchestrator creates an abstraction unified point, enabling to abstract physical and virtual resources, transparently exposing them to service providers and other actors, including marketplace and other orchestrators. It gives service providers further control of their network services and enables developers to create new services and functions.

To accomplish this, the orchestrator must be inserted in each layer of telecommunication network stack, from the application layer down to the data plane. Therefore, different orchestrators can exist in each plane, not being limited to a single orchestrator [43]. Some of the existing orchestration solutions use an orchestrator logically centralized and consider only "softwarized" networks (see Section VI). However, this is impracticable for large and heterogeneous networks.

The orchestrator can be classified according to its function in: Service Orchestration (SO), Resource Orchestration (RO), and Lifecycle Orchestration (LO). Figure 8 illustrates the three primary network service orchestrator functions.

The Service Orchestration is responsible for service composition and decomposition. It can be taken as the upper layer, focused in the interaction with other components such as Marketplace and OSS / Business Support Systems (BSS). The Lifecycle Orchestration deals with the management of workflows, processes, and dependencies across service components. Besides, it maintains the services running according to the contracted Service Level Agreement. Finally, the Resource Orchestration is in charge of mapping service requests to resources, either virtual and/or physical. This mapping occurs across elements such as NFVO, Element Management Systems (EMS), and SDN controllers.

Lifecycle is used to manage a network service with various states (created, provisioned, stopped, etc.). When some action is applied to a network service (e.g., provision a network service), many activities may be needed to apply on the components of this network service. Hence, a workflow is used to execute a bunch of tasks in correct order. Each state of lifecycle can generate one or more activities on workflows. The Figure 9(a) depicts the relationship between lifecycle and workflow of a Network Service.



(a) (b) (c)

Fig. 6. ETSI approaches for multiple administrative domains: (a) approach in which the orchestrator is split into two components (NSO and RO), (b) approach with multiple orchestrators and a new reference point: Umbrella NFVO, (c) approach that introduces hierarchy and the new reference point Or-Or. Adapted from [34] and [56].

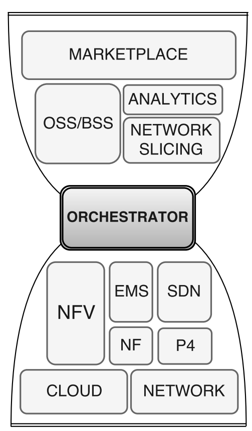


Fig. 7. Strategic role of the Orchestrator as the glue between the actual services and the underlying management of resources.

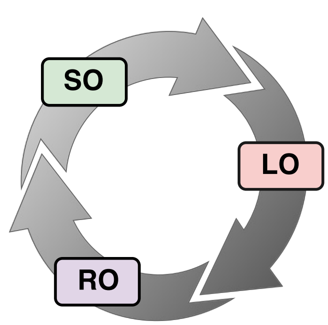


Fig. 8. Different orchestrator functions: Resource Orchestration, Service Orchestration, and Lifecycle Orchestration. There is a relationship of dependency and continuity between the functions.

Figure 9(b) presents an example to improve the real definition of lifecycle and workflow in the context of network service. One of the states in the service lifecycle is the *Created*. In order to achieve such state is necessary to execute four tasks: create Virtual Deployment Unit (VDU)1, create VDU2, configure network and run the application. Therefore, the state only is finished when all those activities are completed.

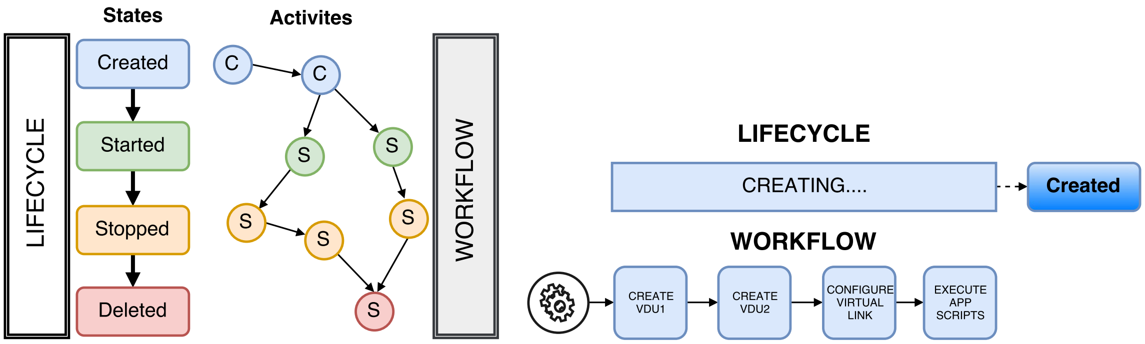
Service lifecycle automation will allow that requested service remains in a desired state of behavior during its lifetime. With the automation, the system responds proactively to changes network and service conditions without human intervention, getting resilience and faults tolerance. These functional aspects of an orchestrator to guarantee the state of a network towawrds a service goal are also being referred to as Intent-based Networking (IBN), cf. [58].

D. Taxonomy

While many aspects of orchestration are under active development and commercial roll-outs, others are still in a preliminary maturity phase. This subsection enumerates central concepts and characteristics related to any NSO approach. It becomes very challenging trying to summarize all concepts related to orchestration in a single work, a challenge exacerbated by the fast evolving pace of so many moving pieces, from standards to enabling technologies. Figure 10 presents the proposed taxonomy as the result of extensive literature research as well as practical experiences with a number of orchestration platforms and research projects.

We identify seven key aspects to characterize network service orchestration:

1) ***Service Models***. Relates to the type of services unlocked by the NSO, which may offer new business and relationships and opportunities (e.g., VNF as a Service (VNF), Slice as a Service (SL*aa*S)).
2) ***Software***: Identifies major software-related characteristics of the orchestration solutions, including specificities of the management and standard interfaces.
3) ***Resource***: Refers to the type of underlying resources (e.g., network, compute, and storage) used for the network service deployment.



(a) (b)

Fig. 9. Difference between Lifecycle and Workflow: (a) Lifecycle – sequence of states and workflow – activities in correct order and (b) example of network service lifecycle.

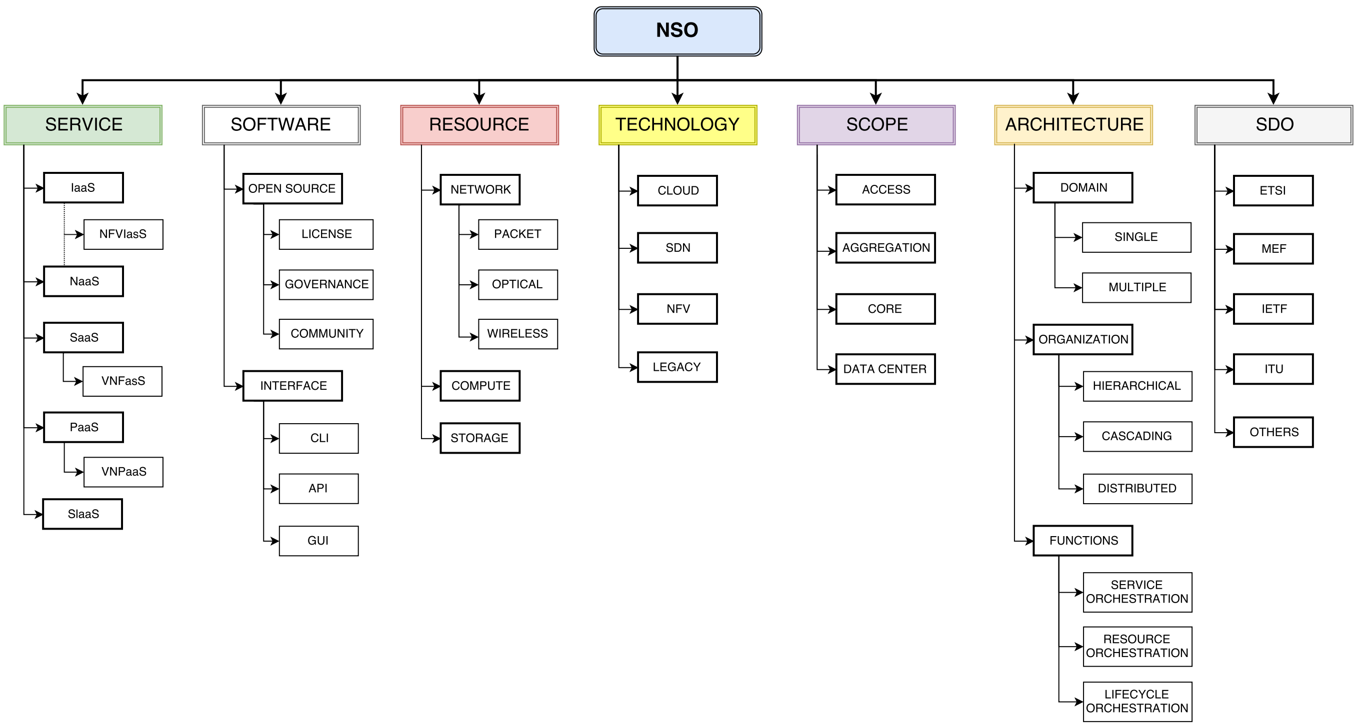


Fig. 10. NSO Taxonomy with seven approach: Service Model, Software, Resource, Technology, Scope of Application, Architecture, and Standards Standards Developing Organization (SDO).

4) ***Technology***: Points to target technologies for NSO (e.g., Cloud, SDN, NFV, and Legacy).
5) ***Scope***: Considers the application domain in terms of network segments embraced by the network service orchestration (i.e., from access network to data centers).
6) ***Architecture***: Unfolds into three relevant architectural dimensions with relate to single- and multi-domain orchestration and functional organization.
7) ***SDO*** *(Standards Development Organization)*: Relates to standardization activities in scope of the NSO.

Additional sub-areas contribute to an in-depth analysis in different contexts, which are further discussed in the following sections.

1) Service Models: This aspect corresponds to the different service models related to orchestration process. Each service is inserted in the context of cloud, SDN, and/or NFV. Cloud computing offers three categories of services such as IaaS, PaaS and SaaS [59]. In IaaS, Cloud Service Provider (CSP) renders a virtual infrastructure to the customers. In PaaS, CSPs provide development environment as a service. Finally, SaaS is a service that furnishes applications hosted and managed in the cloud.

SDN and Network as a Service (NaaS) paradigms can be gathered to provide end-to-end service provisioning. While SDN supply the orchestration of underlying network (switches, router, and links), the NaaS is responsible for private access to the network and customer security [60].

The NFV, in turn, can offer new services including NFVI as a Service (NFVI), VNFaaS, SLaaS and Virtual Network Platform as a Service (VNPaaS). The NFVIaaS provides jointly IaaS and NaaS tailored for NFV. VNFaaS is a service that implements virtualized Network Functions to the

Enterprises and/or end customers. VNPaaS is a platform available by service providers allowing customers to create their own network services. The SLaaS is a concept that the slices are traded and used to build infrastructure services.

All these services can work in parallel to offer higher-level services. Each one acts in a specific area and offers features to customers, enterprises, or other providers.

2) Software: There are many software artifacts related to orchestration covering from a single cloud environment up to more complex scenarios involving multi-domain orchestration. These solutions are outcomes of open source initiatives, research projects or commercial vendors.

Open source approaches significantly accelerate consensus, delivering high performance, peer-reviewed code that forms a basis for an ecosystem of solutions. Open source makes it possible to create a single unified orchestration abstraction. Thus, both research projects and commercial vendors leverage open source technologies to accelerate and improve their solutions. Operators, such as Telefonica, China Mobile, AT&T, and NTT, appear committed to using open source as a way to speed up their development of orchestration platforms [61].

The Open Source Initiative (OSI)[1] defines licenses under Open Source Definition compliance, which allows code and software to be freely used, shared and modified. The more popular open source licenses are Apache License 2.0, Berkeley Software Distribution (BSD), GNU General Public License (GPL), Mozilla Public License 2.0, and Eclipse Public License. Namely, the most important orchestration projects and frameworks (for instance, Aria, Cloudify, CORD, Gohan, Open Baton, Tacker, ONAP, SONATA, and T-NOVA) present a widespread usage of Apache License 2.0.

Another topic related to open source is governance. In short, governance defines the processes, structures, and organizations. It determines how power is exercised and distributed and how decisions are taken. Commonly, a governing board is responsible for the budget, trademark/legal, marketing, compliance, and overall direction, while a technical steering committee is responsible for technical guidance.

An open source orchestration project may be organized as a single community (e.g. vendor-lead) or can be hosted (and eventually integrated with other projects) by a foundation entity [62]. A remarkable example is the Linux Foundation, which among multiple networking related projects is in charge of ONAP, an open source platform aiming at the automation, design, orchestration, and management of SDN and NFV services. Another noteworthy example of an orchestration open source project under the Linux Foundation flagship aiming at delivering a standard NFV/SDN platform for the industry is Open Platform for NFV (OPNFV) [63].

NSO solutions need to perform management tasks such as remote device configuration, monitoring and fault management. Moreover, they require defining interface of communication between various software components. For this, there are diverse types of management and standard interfaces such as Command Line Interface (CLI), Application Programming Interface (API), and Graphical User Interface (GUI). The CLI just is used to execute commands directly in the software using remote access via SSH or Telnet. The API enables the remote management and interconnection with other softwares through specifics commands. The majority of solutions use REST-based API. GUI, in turn, offers a graphic interface that makes it easier its use.

3) Resource: During the creation of a network service, the resource orchestration is responsible for orchestrating the underlying infrastructure. Such infrastructure is composed of heterogeneous hardware and software for hosting and connecting the network services. The resources include compute, storage, and network [64]. In essence, there are three types of networks: packet, optical and wireless (e.g., Wi-Fi, wi-max, and mobile network).

Resources are shared and abstracted making use of virtualization techniques (e.g., para-virtualization [65], full virtualization [66], and containers [67]), defining virtual infrastructures that can be used as physical ones. Sharing and management of resources are much more complex in multi-domain scenarios. The NSO needs to know all the available resources towards the efficient deployment of the NSs.

4) Technology: NSO involves complex workflows and different technologies involved throughout orchestration process: cloud computing, SDN, NFV, and legacy.

The cloud computing paradigm provides resource virtualization and improves resource availability and usage by means of orchestration and management procedures. This includes automatic instantiation, migration and snapshot of VMs, High-Availability, and dynamic allocation of resources [30].

The SDN promotes control across network layers and logical centralization of network infrastructure management. Its main functions is to connect the VNFs and the NFVI-PoPs. In parallel, the NFV technology promotes the network functions programming in order to enable elasticity, automation, and resilience in cloud environments [10]. As illustrated in Figure 5, cloud computing, SDN and NFV are enabler technologies to the NSO. The NSO must also handle legacy technologies such as MPLS, BGP, SONET / SDH, and WDM.

5) Scope: Resources of operators under an orchestration application domain can be part of access networks, aggregation networks, core networks and data centers [11]. The access network is the entry point which connects users to their service provider. It encompasses various technologies, i.e., fixed access, radio access (Wi-Fi, LTE, radio), optical, and provide connectivity to heterogeneous services such as mobile network and Internet of Things (IoT). The core network is the central part of a telecommunications network that connects local providers to each other. The aggregation network, in turn, connects the access network to core network. The data center is the local where are localized the computing and storage resources.

The infrastructure is formed by heterogeneous technologies that may be owned by different infrastructure providers. The network service orchestration in this environment is a challenging task. The NSO must have a view of resources and services since access network until the data center to deploy end-to-end network services. Besides, it is also important to

[1] http://opensource.org

provide consistent and continuous service, independent of the underlying infrastructure [11].

6) Architecture: An NSO architecture can be divided into three sub-categories: (i) *domain*, (ii) *organization*, and (iii) *functions*. The *domain* refers to coverage of the orchestration process in one or more administrative domains: single-domain and multi-domain. In each scenario, the orchestration has its peculiarities.

Single-domain orchestration studies focus on vertical NFV/SDN orchestration within a same administrative domain. In our definition, an administrative domain can have multiple technological domains, such as SDN, NFV, and Legacy. The taxonomy is aligned with ETSI NFV architecture that addresses orchestration for NFV. The multi-domain orchestration involves the instantiation of network service among two or more administrative domains. It is composed of planes (or layers) with different functions and architecture topology. The multi-domain interfaces are not present in original ETSI NFV architecture

The *organization* refers to the different architectural arrangements of a NSO solution. We identified three types of organization: hierarchical, cascading and distributed. The hierarchical approach assumes a high-level orchestrator that has visibility of the entire other domains and capable of configuring services across different domains. The service provider facing the customer as a single entry point will maintain relationships with other providers to complete the requested service. According to [44], the hierarchical approach is impractical because of scalability and trust constraints. Under the cascade model, the provider partially satisfies the service request but complements the service by using resources from another provider. If this provider does not have all the resources, it also can request for another and so on (e.g., a mobile network provider using a satellite provider). In the distributed model, there is not a central actor, and providers request resource and services from each other on a peer-to-peer fashion.

Finally, *functions*,as discussed in Sec. III-C, refers to the main tasks developed by network service orchestrator: service orchestration, resource orchestration, and lifecycle orchestration. These functions can be separated or together in the same component of an orchestration framework. This decision depends on how the orchestrator was developed.

7) Standards Development Organization (SDO): Several Standards Development Organizations, including ETSI, MEF, IETF, and International Telecommunication Union (ITU), are actively working on a collection of standards in order to define reference architectures, protocols, and interfaces in scope of the orchestration domain. Besides, other organizations, academic, vendors and industrial are working in parallel with diverse goals. The main efforts within standardization bodies will be outlined next.

IV. NSO and Standardization

Interoperability and standardization constitute essential factors of the success of a network service orchestration solution. An important design goal for any new networking paradigm relates to openness of interfaces, especially in order to overcome interoperability issues [10]. Several standardization efforts are delivering a diverse collection of norms and recommendations to define an architecture and/or a framework that enables the network service orchestration. This section presents the main standardization bodies at the NSO scope. Table I presents a summary of the main SDOs and organizations related to NSO standardization, as well as the main outcomes produced to date.

A. ETSI

ETSI ISG NFV defines the MANO architectural framework to enable orchestration of VNFs on top of virtualized infrastructures. Since 2012, the group provides pre-standardization and specification documents in different areas, including management and orchestration. NFVO takes a fundamental role in NFV-MANO functional components, as defined in [57] realizing: *(i)* the orchestration of infrastructure resources (including multiple VIMs), fulfilling the Resource Orchestration functions; *(ii)* and the management of Network Services, fulfilling the network service orchestration functions.

Logically composing ETSI NFVO, NSO stipulates general workflows on network services (e.g., scaling, topology/performance management, automation), which consequently reach abstracted functionalities in other MANO components – lifecycle management of VNFs in coordination with VNFM and the consume of NFVI resources in accordance with VIM operational tasks.

Currently, ETSI matures NFV in different areas, such as architecture, testing, evolution and ecosystem. Among ongoing topics approached, network slicing report, multi-administrative domain support [34] [56], and multi-site services (drafting stage) highlight important aspects of evolving the NFV architectural framework, including possible new NSO functionalities. In the upcoming years, ETSI is expected to keep playing a driving role on NFV, what represents a path towards realization of concepts built upon the recommendations/reports, as attested by open source projects such as Open Source MANO.

B. MEF

Metro Ethernet Forum (MEF)'s Third Network [49] approaches NaaS comprising agility, assurance and orchestration as its main characteristics to broach LSO in their defined Carrier Ethernet 2.0 framework. LSO, as a primer component, provides network service lifecycle management when approaching series of capabilities (e.g., control, performance, analytics) towards fulfilling network service level specifications. MEF's LSO provides re-usable engineering specifications to realize end-to-end automated and orchestrated connectivity services through common information models, open APIs, well-defined interface profiles, and attaining detailed business process flows. Therefore, in LSO Service Providers orchestrate connectivity across all internal and external domains from one or more network administrative domains.

A detailed LSO reference architecture [74] presents common functional components and interfaces being exemplified in comparison with ETSI NFV framework and ONF SDN architecture. Internally, a Service Orchestration Functionality

TABLE I
NSO STANDARDIZATION OUTCOMES

SDO	Working Group	Scope	Outcomes
ETSI	NFV ISG (Initial)	NFV	Service Quality Metrics for NFV Orchestration [68]
			Management and Orchestration Framework [33]
			Multiparty Administrative domains [69]
	NFV ISG (Release 2)		VNF Architecture and SDN in NFV Architecture [70]
			Orchestration of virtualized resources [71]
			Functional requirements for Orchestrator [71]
			Lifecycle management of Network Services [71]
			Network Service Templates Specification [72]
	NFV ISG (Release 3)		Policy management [73]
			Report on architecture options to support multiple administrative domains [56]
MEF	The Third Network	NFV, LSO	Lifecycle Service Orchestration Vision [49]
			LSO Reference Architecture and Framework [74]
ONF	Architecture and Framework	SDN	SDN Architecture [75]
			Mapping Orchestration Application to SDN [76]
			Definition of Orchestration [77]
IETF	SFC	SFC, NFV	SFC Architecture [32]
NGMN	Work Programme	5G Network	White Paper: Next Generation Networks [78]
			5G Network and Service Management and Orchestration [79]
TM Forum	Project	SDN, NFV	ZOOM (Zero-touch Orchestration, Operations and Management) [80]
3GPP	S5	5G Network (mobile)	Management and orchestration for next generation network [47]
OASIS	TOSCA	Resource and Service Modeling	TOSCA version 1.0 [81]
			TOSCA for NFV Version 1.0 [82]
			TOSCA in YAML Version 1.2 [83]
ITU	ITU-T SG 13	5G Network (IMT-2020) and network softwarization	Report on Standards Gap Analysis in 5G Network [84]
			Terms and definitions for 5G network [85]
			5G Network management and orchestration requirements [86]
			5G Network management and orchestration framework [87]
			Standardization and open source activities related to network softwarization [88]
	ITU-R	Mobile, radiodetermination, amateur and related satellite services	Framework and overall objectives of the 5G Network [89]

provides to LSO coordinated end-to-end management and control of Layer 2 and Layer 3 Connectivity Services realizing lifecycle management supporting different capabilities. Besides, LSO defines APIs for essential functions such as service ordering, configuration, fulfillment, assurance and billing. A recent example of MEF's use case conceptualization presents an understanding of Software Defined Wide Area Network (WAN) (WAN) managed services in face of LSO reference architecture [90].

C. ONF

At ONF, the SDN architecture defines orchestration as TR-521 [77] states: "In the sense of feedback control, orchestration is the defining characteristic of an SDN controller. Orchestration is the selection of resources to satisfy service demands in an optimal way, where the available resources, the service demands, and the optimization criteria are all subject to change".

Logically, ONF perceives the SDN controller jointly overseeing service and resource-oriented models to orchestrate network services through intents on a client-server basis. From top-to-bottom, a service-oriented perspective relates to invocation and management of a service-oriented API to establish one or more service contexts and to fulfill client's requested service attributes. Such requirements guide the SDN controller in orchestrating and virtualizing underlying resources to build mappings that satisfy the network service abstraction and realization. While in a bottom-up view, a resource-oriented model consists of SDN controller exposing underlying resource contexts so clients might query information and request services on top of them. In accordance, resource alterations might imply in reallocation or exception handling of service behavior, which might be contained in policies specified by client's specific attributes in a service request.

Recursively, stacks of SDN controllers might coordinate a hierarchy of network service requests into resource allocation according to their visibility and control of underlying technological and administrative network domains (e.g., Cross Stratum Orchestration [76]). Thus, SDN controllers might have North-South and/or East/West relationships with each other. At last, a common ground for orchestration concepts is published by ONF as "Orchestration: A More Holistic View" [75], elucidating considerations of its capabilities, among them, employing policy to guide decisions and resources feedback, as well its analysis.

D. IETF/IRTF

At IETF and Internet Research Task Force (IRTF), different working and research groups address NSO from varying angles. Traffic Engineering Architecture and Signaling (TEAS) working group characterizes protocols, methods, interfaces and mechanisms for centralized (e.g., PCE) and distributed path computation (e.g., MPLS, GMPLS) of traffic engineered paths/tunnels delivering specific network metrics (e.g., throughput, latency). Application-based Network Operations (ABNO) sets modular a modular control architecture, standardized by IETF aggregating already standard components, such as Path Computation Element (PCE) to orchestrate connectivity services. SFC Working Group (WG) defines a distributed architecture to enable network elements compute NF forwarding graphs realizing overlay paths. The list of protocols involved in NSO is by far not completed and many new extensions to existing protocols and new ones are expected due to the broad needs of interoperable network service orchestration solutions.

Conceptually, IETF establishes no direct relationship with orchestration, as it concerns majorly the development of protocols. However, the development of protocol-related systems, information models and management interfaces by working groups can enable orchestration of services such as the layer 3 VPN[2]. Even more, as the core network service of the internet, routing detains the capabilities to be managed by orchestration interfaces through the work being performed by the Interface to the Routing System (i2rs) working group. For instance, i2rs facilitates "information, policies, and operational parameters to be injected into and retrieved (as read or by notification) from the routing system while retaining data consistency and coherency across the routers and routing infrastructure, and among multiple interactions with the routing system". As such, RFCs developed by different IETF working groups sit in the scope of SDN, enablers of programmable networks, and therefore, inheriting orchestration capabilities.

[2]https://datatracker.ietf.org/wg/l3vpn/about/

E. NGMN

Next Generation Mobile Networks (NGMN) in [79] provides key requirements and high-level architecture principles of Network and Service Management including Orchestration for 5G. Based on a series of user stories (e.g., slice creation, real-time provisioning, 5G end-to-end service management), the document establishes a common set of requirements. Among them self-healing, scalability, testing and automation, analysis, modeling, etc. Regarding orchestration functionalities, the presented user stories introduce components (e.g., SDN controllers and ETSI NFVO), which execute actions to perform actors goals. For instance, slice creation would be end-to-end service orchestration interpreting and translate service definitions into a configuration of resources (virtualized or not) needed for service fulfillment.

As part of the initially envisioned 5G White Paper [78], NGMN provided business models and use cases based on added values that 5G would bring for future mobile networks. In general, SDN and NFV components are listed as enablers for operational sustainability that will drive cost/energy efficiency, flexibility and scalability, operations awareness, among other factors for simplified network deployment, operation, and management. Such technology candidates highlight the importance of orchestration capabilities besides the evolution of radio access technologies towards 5G realization.

F. TM Forum

TeleManagement Forum (TM Forum) is a global association for digital businesses (e.g., service providers, telecom operators, etc.) which provides industry best practices, standards and proof-of-concepts for the operational management systems, also known as Operations Support Systems (OSSs). One of the biggest TMForum achievements is the definition of a telecom business process (eTOM) and application (TAM) maps, including all activities related to an operator, from the services design to the runtime operation, considering assurance, charging, and billing of the customer, among others. In order to accommodate the SDN/NFV impacts, the TM Forum has created the Zero-Touch Orchestration, Operations and Management (ZOOM) program, which intends to build more dynamic support systems, fostering service and business agility.

As a related research project, SELFNET[3] is, on one side, actively following and aligning its architecture definition with the TM Forum ZOOM and FMO recommendations. Additionally, SELFNET, through one partner of the consortium that is an active member of TM Forum, is also going to actively contribute to the ZOOM working group with respect to the impact that the NFV/SDN paradigm has on the OSS information model (CFS Customer Facing Service, RFS Resource Facing Services, LR Logical Resources, PR Physical Resources). Besides the ZOOM working group, SELFNET will also contribute to the FMO working group by participating in the next generation OSS architecture, which includes the autonomic management capabilities to close the autonomic management loop: 1) Supervision 2) Autonomic 3) Orchestration/Actuation.

[3]https://selfnet-5g.eu/

G. 3GPP

Related to the ongoing specification "Study on management and orchestration architecture of next generation network and service" [91], 3GPP analyzes its existing architectural management mechanisms in contrast with next generation networks and services in order to recommend enhancements, for instance, to support network operational features (e.g., real-time, on-demand, automation) as evolution from Long Term Evolution (LTE) management. Among the item sets contained in the scope, the specification addresses: the scenario in which the applications are hosted close to the access network; end-to-end user services; and vertical applications, such as critical communications. Another ongoing specification, "Telecommunication management; Study on management and orchestration of network slicing for next generation network" [47], presents comprehensive 3GPP views on network slicing associated with automation, sharing, isolation/separation and related aspects of ETSI NFV MANO. In both documents, use cases and requirements cover single and multi-operator services taking into consideration performance, fault tolerance and configuration aspects.

Similar to IETF, 3GPP establishes a relationship with orchestration through management models for network slicing. Related to slicing, the 3GPP TS28 series of documents defines, among other specifications, a network resource model for 5G networks. In a protocol and technology neutral way, such models enable management interfaces for the lifecycle management of 5G networks (e.g., core, access, and radio access technologies). Closely related with NFV, in 3GPP the study of management and virtualization aspects of 5G networks takes places involving the characterization of performance management and fault supervision. For instance, in a first stage, TS 28.545 defines the use cases and requirements for fault supervision of 5G networks and network slicing. Towards sinergy studies of 3GPP systems with NFV, there exists ongoing work to elaborate further on the energy efficiency control framework defined in TR 21.866 and identify potential gaps with respect to existing management architectures, including self-organizing networks and NFV based architectures. Therefore, related to all the major benefits of introducing NFV paradigms into 3GPP, the management of 5G networks and network slices addresses orchestration in its essence, concerning mostly fault and performance.

H. OASIS

OASIS standardizes Topology and Orchestration Specification for Cloud Applications (TOSCA) focused on "Enhancing the portability and operational management of cloud applications and services across their entire lifecycle". TOSCA Simple Profile in YAML v1.0 was approved as standard in 2016 in a rapidly growing ecosystem of open source communities, vendors, researchers and cloud service providers. Looking forward, TOSCA Technical Committee develops a Simple Profile for NFV based on ETSI NFV recommendations.

Logically, TOSCA allows the expressiveness of service to resource mappings via flexible and compoundable data structures, also providing methods for specifying workflows and, therefore, enable lifecycle management tasks. In both Simple and NFV Profiles, TOSCA models service behaviors defining components containing capabilities and requirements, and relationships among them. TOSCA realizes a compliant model of conformance and interoperability for NSOs, enhancing the portability of network services.

TOSCA aims

I. ITU

International Telecommunications Union (ITU) is the United Nations specialized agency for information and communication technologies (ICTs). It develops technical standards that ensure networks and technologies seamlessly interconnected. The Study Groups of ITUs Telecommunication Standardization Sector (ITU-T) develops international standards known as ITU-T Recommendations which act as defining elements in the global infrastructure of ICTs [92].

The ITU is working on the definition of the framework and overall objectives of the future 5G systems, named as IMT-2020 (International Mobile Telecommunications for 2020) systems [89]. The documentation is detailed in Recommendation ITU-R M.2083-0. It describes potential user and application trends, growth in traffic, technological trends and spectrum implications aiming to provide guidelines on the telecommunications for 2020 and beyond.

Besides, the Study Group 13 of ITU-T is developing a report on standards gap analysis [84] that describes the high-level view of the network architecture for IMT-2020 including requirements, gap analyses, and design principles of IMT-2020. Its objective is to give directions for developing standards on network architecture in IMT-2020. In this report also includes the study areas: end-to-end quality of service (QoS) framework, emerging network technologies, mobile front haul and back haul, and network softwarization. The report is based on the related works in ITU-R and other SDOs.

V. Research Projects

This section presents an overview of relevant NSO research projects and positions our taxonomy accordingly as summarized in Table II, providing a single vision of their scope and status. The following subsections are identified by project name and its duration.

A. T-NOVA (2014/01-2016/12)

The focus of the T-NOVA project [54] is to design and implement an integrated management architecture for the automated provision, configuration, monitoring and optimization of network connectivity and Network Functions as a Service (NFaaS). Such architecture includes: (i) a micro-service based NFV orchestration platform–called TeNOR [93], (ii) an infrastructure virtualisation and management environment and (iii) an NFV Marketplace where a set of network services and functions can be created and published by service providers and, subsequently, acquired and instantiated on-demand by customers.

In the T-NOVA architecture, TeNOR is the highest-level infrastructure management entity that supports multi-pop/multi-administration domain, transport network (i.e., MPLS, Optical, Carrier Ethernet, etc.) management between POPs, and data center cloud assets control. The TeNOR Orchestrator is split into two elements: (i) *Network Service Orchestrator* that manages the Network Service Lifecycle, and (ii) *Virtualized Resource Orchestrator* that orchestrates the underlying computing and network resources [94].

T-NOVA leverages cloud management architectures for the provision of resources (compute and storage) and extends SDN for efficient management of the network infrastructure [95]. Its architecture is based on concepts from ETSI NFV model and expands it with a marketplace layer and specific add-on features. All software components produced during the project are available as open source at github[4].

B. UNIFY (2013/11-2016/04)

FP7 Unify [5] project dedicated to approaching multiple technology domains to orchestrate joint network services concerning compute, storage and networking. The primary focus set flexibility as its core concern, especially to bring methods to automate and verify network services.

Unify overall architecture contains components in a hierarchical composition enabling recursiveness. At the bottom, a set of Controller Adapters (CAs) interface technology-specific domains (e.g., optical, radio, data center) to abstract southbound APIs for a typical model of information to define software programmability over a network, compute and storage elements, such as virtualized container, SDN optical controller and OpenStack. Overseeing CAs, Resource Orchestrators (ROs) define ways to manage the abstracted components of technology-domains specifically. For instance, while an RO for a SDN controller orchestrates network flows (e.g., allocating bandwidth and latency), a RO for a cloud orchestrator would be concerned more over orchestrate network jointly with compute and storage resources (e.g., allocating memory and disk). Moreover, managing one or more ROs, a global orchestrator performs network service orchestration in multiple technological domains, understanding the service decomposition and outsourcing specific orchestration tasks to ROs.

In the end, Unify was able to present a common model of information to interconnect different technological domains, CAs, ROs and global orchestrator. Such YANG model was named Virtualizer, and logically defined configurations following the NETCONF protocol. Different demos showcasing joint orchestration of compute and network resources were presented, using the open source orchestrator ESCAPE [6], for instance, modeling VNFs over data centers interconnected via an SDN enabled network domain.

Besides, based on the ONF SDN architecture, Unify was able to demonstrate methods to apply recursiveness across its functional components in order to decompose network services to technological-specific domains.

[4]https://github.com/T-NOVA
[5]http://www.fp7-unify.eu/
[6]https://github.com/hsnlab/escape

C. 5GEx (03/2015-03/2018)

5GEx project aims agile exchange mechanisms for contracting, invoking and settling for the wholesale consumption of resources and virtual network service across administrative domains. Formed by a consortium of vendors, operators, and universities, 5GEx allows end-to-end network and service elements to mix in multi-vendor, heterogeneous technology and resource environments. In such way, the project targets business relationships among administrative domains, including possible external service providers without infrastructure resources.

Architecturally, 5GEx addresses business-to-business (B2B) and business-to-customer (B2C) relationships across multi-administrative domain orchestrator that might interface different technological domains. Basically, 5GEx extends ETSI NFV MANO architecture with new functional components and interfaces. Among its main components, the project defines modules for: topology abstraction; topology distribution; resource repository; Service Level Agreement (SLA) manager; policy database; resource monitoring; service catalog; and an inter-provider NFVO. 5GEx currently utilizes outcome resources mostly from the projects Unify and T-NOVA, especially joining their open source components into already prototyped demonstrations.

D. SONATA (07/2015-12/2017)

With 15 partners representing the telecommunication operators, service providers, academic institutes (among others), the Service Programming and Orchestration for Virtualised Software Networks (SONATA) project [96] addresses two significant technological challenges envisioned in 5G networks: (i) *flexible programmability* and (ii) *deployment optimization* of software networks for complex services/applications. To do so, SONATA provides an integrated development and operational process for supporting network function chaining and orchestration [97].

The major components of the SONATA architecture consist of two parts: (i) the SONATA *Software Development Kit (SDK)* that supports functionalities and tools for the development and validation of VNFs and NS and (ii) the SONATA *Service Platform*, which offers the functionalities to orchestrate and manage network services during their lifecycles with a MANO framework and interact with the underlying virtual infrastructure through Virtual Infrastructure Managers (VIM) and WAN Infrastructure Managers (WIM) [98].

The project describes the use cases envisioned for the SONATA framework and the requirements extracted from them. These use cases encompass a wide range of network services including NFVIaaS, VNFaaS, vContent Delivery Network (CDN), and personal security. One of the use cases consists of hierarchical service providers simulating one multi-domain scenario. In this scenario, Service Programming and Orchestration for Virtualised Software Networks (SONATA) does not address the business aspects, only the technical approaches are in scope. SONATA intends to cover aspects in the cloud, SDN and NFV domains [99].

Moreover, the project proposes to interact and manage with not only VNFs also support legacy [100]. Besides, it describes technical requirements for integrating network slicing in the SONATA platform. The SONATA framework complies with the ETSI NFV-MANO architecture [100]. The results of the project are shared with the community through a public repository[7].

E. 5G-Transformer (06/2017-11/2019)

The 5G-Transformer Project [101] consists of a group of 18 companies including mobile operators, vendors, and universities. The objective of the project is to transform currents mobile transport network into a Mobile Transport and Computing Platform (MTP) based on SDN, NFV, orchestration, and analytics, which brings the Network Slicing paradigm into mobile transport networks. The project will support a variety of vertical industries use cases such as automotive, healthcare, and media/entertainment.

Likewise, 5G-Transformer defines three new components to the proposed architecture: (i) *vertical slicer* as a logical entry point to create network slices, (ii) *Service Orchestrator* for end-to-end service orchestration and computing resources, and (iii) *Mobile Transport and Computing Platform* for integrate fronthaul and backhaul networks. The Service Orchestrator is the main decision point of the system and interacts with others SOs to the end-to-end service (de)composition of virtual resources and orchestrate the resources even across multiple administrative domains. Its function is similar to our definition of NSO. The project architecture is still ongoing and is not clear its organization (hierarchical, cascade, or distributed). Still in an early stage, the project aims to produce open source artifacts, and deliverables in alignment with standardization bodies such as 3GPP and MGMN [102].

F. VITAL (02/2015-07/2017)

The H2020 VITAL project [103] addresses the integration of Terrestrial and Satellite networks through the applicability of two key networking paradigms, SDN and NFV. The main VITAL outcomes consist of (i) the virtualization and abstraction of satellite network functions and (ii) supporting multi-domain service/resource orchestration capabilities for a hybrid combination of satellite and terrestrial networks [104].

The VITAL overall architecture stands in line with the main directions established by the ETSI ISG NFV [33], with additional concepts extended to the satellite communication domains and network service orchestration deployed across different administrative domains. This architecture includes, among other, functional entities (e.g., NFVO, VNFM, SO, Federation Layer) for the provision and management of the NS lifecycle. In addition, a physical network infrastructure block with virtualization support includes SDN and non-SDN (legacy) based network elements for flexible and scalable infrastructure management.

Implementing the relevant parts of the VITAL architecture, X–MANO [105] is a cross-domain network service orchestration framework. It supports different orchestration architectures such as hierarchical, cascading (or recursive) and peer-to-peer. Moreover, it introduces an information model and a programmable network service in order to enable confidentiality and network service lifecycle programmability, respectively.

G. Other Research Efforts

Further architectural proposals and research contributions can be found in the recent literature.

Recent research works have addressed the definition of NFV/SDN architectures. Vilalta et al. [106] present and NFV/SDN architecture for delivery of 5G services across multi technological and administrative domains. The solution is different from the NFV reference architecture. It consists of four main functional blocks: Virtualized Functions Orchestrator (VF-O), SDN IT and Network Orchestrator, Cloud/Fog Orchestrator and SDN Orchestrator. The VF-O is the main component orchestrating generalized virtualized functions such as NFV and IoT. Giotis et al. [107] propose a modular architecture that enables policy-based management of Virtualized Network Functions. The proposed architecture can handle the lifecycle of VNFs and instantiate applications as service chains. The work also offers an Information Model towards map the VNF functions and capabilities.

The work in [108] proposes a novel network slicing management and orchestration framework. The proposed framework automates service network design, deployment, configuration, activation, and lifecycle management in a multi-domain environment. It can manage resources of the same type such as NFV, SDN and Physical Network Function (PNF), belonging to different organizational domains and belonging to the same network domain such as access, core, and transport.

Finally, there still exists a large set of NSO related projects sponsored by the European Union Horizon 2020 research and innovation programme in the 5G Infrastructure Public Private Partnership phases 1, 2, and 3[8]. In different manners those projects relate to orchestration detaining common relationship with open source projects such as the Open Source MANO (OSM) initiative, further described. To quote some of them, for instance: 5GCity[9] aims an infrastructure business model for the 5G city networks; 5G-MEDIA[10] works to integrate media-industry applications with the underlying 5G programmable service platform based on SDN/NFV technologies; and Sat5G[11] intends to establish a plug-and-play satellite infrastructure integrated with 5G connectivity aiming unserved and underserved areas. Such myriad of projects walk towards the consolidation of 5G ideas into live demonstrations of projects, such as the coordination of cross-border corridors for 5G experimental test beds. In essence, all of them were established on ground concepts of NSO, extensively based on and contributing to standardization bodies (e.g., ETSI NFV, ONF, 3GPP).

[7] https://github.com/sonata-nfv/

[8] https://5g-ppp.eu/

[9] https://www.5gcity.eu/

[10] http://www.5gmedia.eu/

[11] http://sat5g-project.eu/

TABLE II
SUMMARY OF RESEARCH PROJECTS RELATED TO NSO

Class	Feature	T-Nova	Unify	5GEx	SONATA	VITAL	5G-T
Service	IaaS/NVFIaaS	○	●	●	●	●	○
	NaaS/NVFIaaS	○	●	●	●	●	○
	SaaS/VNFaaS	●	○	●	●	●	○
	Paaa/VNPaaS	○	○	○	○	○	○
	SlaaS	○	○	●	○	○	●
Open Source		●	●	◐	●	●	◐
Resource/ Network	Packet	●	●	●	●	●	●
	Optical	●	○	●	○	●	○
	Wireless	●	○	●	●	●	●
Resource	Compute	●	●	○	○	●	○
	Storage	●	●	○	○	●	○
Technology	Cloud	●	●	●	●		●
	SDN	●	●	●	●	●	●
	NFV	●	●	●	●	●	●
	Legacy	●	●	●	◐	○	Ø
Scope	Access	○	●	●	●	●	●
	Aggregation	●	●	●	●	●	●
	Core	○	●	●	●	●	●
	Data center	●	●	●	●	○	●
Architecture / Domain	Single	●	●	○	●	●	●
	Multiple	◐	●	●	◐	●	●
Architecture / Organization	Hierarchical	●	●	●	●	●	Ø
	Cascade	○	○	○	○	●	Ø
	Distributed	○	○	○	○	●	Ø
Architecture / Functions	Service Orchestration	●	○	●	●	●	●
	Resource Orchestration	●	●	●	●	◐	●
	Lifecycle Orchestration	●	○	●	●	●	●
SDO	ETSI	●	◐	◐	●	●	○
	MEF	○	○	○	○	○	○
	3GPP	○	○	○	○	○	◐
	MGMN	○	○	○	○	○	◐
	Others	○	◐	○	○	○	○

○ *Outside the Scope,* ◐ *Partial Scope,* ● *Within the Scope,* Ø *Undefined*

VI. Enabling Technologies and Solutions

Some of the existing orchestrating solutions are just tied to a specific networking environment, and moreover, some of them can orchestrate an only limited number of services [42]. In this section, an overview of main orchestration frameworks is presented, including open source, proposed and commercial solutions. The projects cover different technologies and domains. The Table III summarizes the main characteristics of each open source projects with respect to leader entities, resource domains, scope NFV-MANO, VNF definition, Management Interface, and coverage area (single/multi-domain).

A. Open Source Solutions

Open Source Foundations such as the Apache Foundation and the Linux Foundation are increasingly becoming the hosting entities for large collaborative open source projects in the area of networking. The most important projects are ONOS, CORD, Open Daylight, OPNFV and, recently, ONAP, formed by the merger of Open-Orchestrator (OPEN-O) and ECOMP. All the projects are important to create a well-defined platform for service orchestration.

Note that to 5G network, standardization and open source are essential for fast innovation. Vendors, operators, and communities are betting on open source solutions. Even so, existing solutions are still not mature enough, and advanced network service orchestration platforms are missing [109].

In early 2016, the Linux Foundation formed the OPEN-O Project to develop the first open source software framework and orchestrator for agile operations of SDN and NFV. ONOS is also developing an orchestration platform for the CORD project to provide Anything as a Service (XaaS) exploiting SDN, micro-services and disaggregation using open source software and commodity hardware [43].

Many open source initiatives towards network service orchestration are being deployed and this including operators, VNF vendors and integrators. However, these are still in the early stages. We describe next some of these initiatives.

1) Open Source MANO: ETSI Open Source MANO [5] is an ETSI-hosted project to develop an Open Source NFV-MANO platform aligned with ETSI NFV Information Models and that meets the requirements of production NFV networks. The project launched its third release [110] in October 2017 and presented improvements in security, service assurance, resilience, and Interoperability. One of the main goals of this project is to promote the integration between standardization and open source initiatives.

The OSM architecture has a clear split of orchestration function between Resource Orchestrator and Service Orchestrator. It integrates open source software initiatives such as Riftware as Network Service Orchestrator and GUI, OpenMANO as Resource Orchestrator (NFVO), and Juju [12] Server as Configuration Manager (G-VNFM). The resource orchestrator supports both cloud and SDN environments. The service orchestrator provides VNF and NS lifecycle management and consumes open Information/Data Models, such as YANG. Its architecture covers only single administrative domain.

2) Tacker: Tacker [111] is an official OpenStack project building a Generic VNFM and a NFVO to deploy and operate Network Services and VNFs on a Cloud/NFV infrastructure platform such as OpenStack. It is based on ETSI MANO architectural framework and provides a functional stack to orchestrate end-to-end network services using VNFs.

The NFVO is responsible for the high-level management of VNFs and managing resources in the VIM. The VNFM manages components that belongs to the same VNF instance controlling the VNF lifecycle. The Tacker also does mapping to SFC (Service Function Chain) and supports auto scaling and TOSCA NFV Profile (using heat-translator).

The tacker components are directly integrated into OpenStack and thus provides limited interoperability with others VIMs. It combines the NFVO and VNFM into a single element nevertheless, internally, the functionalities are divided. Another limitation is that it just works in single domain environments.

3) Cloudify: Cloudify [112] is an orchestration-centric framework for cloud orchestration focusing on optimization NFV orchestration and management. It provides a NFVO and Generic-VNFM in the context of the ETSI NFV, and can interact with different VIMs, containers, and non-virtualized devices and infrastructures. Cloudify is aligned with the MANO reference architecture but not fully compliant.

Besides, Cloudify provides full end-to-end lifecycle of NFV orchestration through a simple TOSCA-based blueprint following a model-driven and application-centric approach. It includes Agile Reference Implementation of Automation (ARIA) as its core orchestration engine providing advanced management and ongoing automation.

In order to help contribute to open source NFV-MANO adoption, Cloudify engages in and sponsors diverse NFV projects and standards organizations, such as TOSCA specification, ARIA and ONAP.

4) ONAP: Under the Linux Foundation banner, Open Network Automation Platform (ONAP) [7] resulted from the union of two open source MANO initiatives (OPEN-O [113] and OpenECOMP [114]). The ONAP software platform deploys a unified architecture and implementation, with robust capabilities for the design, creation, orchestration, monitoring and lifecycle management of physical and virtual network functions [115]. Also, the ONAP functionalities are expected to address automated deployment and management and policies optimization through an intelligent operation of network resource using big data and Artificial Intelligent (AI) [116].

Two of the biggest challenges to merge two large sets of code are: (i) define a higher-level common information model unifying the predominant data models used by OPEN-O (TOSCA) and OpenECOMP (YANG) and, (ii) create a standard process to the onboarding and lifecycle management of VNFs so that end users can introduce these using an automated process (without requiring core developer teams) [117].

5) X–MANO: X–MANO [105] is an orchestration framework to coordinate end-to-end network service delivery across different administrative domains. X–MANO introduces components and interfaces to address several challenges and requirements for cross-domain network service orchestration such as (i) business aspects and architectural considerations, (ii) confidentiality, and (iii) life-cycle management. In the former case, X–MANO supports hierarchical, cascading and peer-to-peer architectural solutions by introducing a flexible, deployment-agnostic federation interface between different administrative and technological domains. The confidentiality requirement is addressed by the introduction of a set of abstractions (backed by a consistent information model) so that each domain advertises capabilities, resources, and VNFs without exposing details of implementation to external entities. To address the multi-domain life-cycle management requirement, X–MANO introduces the concept of programmable network service based on a domain specific scripting language to allow network service developers to use a flexible programmable Multi-Domain Network Service Descriptor (MDNS), so that network services are deployed and managed in a customized way.

6) Open Baton: Built by the Fraunhofer Fokus Institute and the Technical University of Berlin, Open Baton [118] is an open source reference implementation of the NFVO based on the ETSI NFV MANO specification and the TOSCA Standard. It allows it to be a vendor-independent platform (i.e., interoperable with different vendor solutions) and easily extensible (at every level) for supporting new functionalities and existing platforms.

The current Open Baton release 3 includes many different features and components for building a complete environment fully compliant with the NFV specification. Among the most important are: (i) a NFVO (exposing TOSCA APIs) , (ii) a generic VNFM and Juju VNFM, (iii) a marketplace integrated within the Open Baton dashboard, (iv) an Autoscaling and Fault Management System and (v) a powerful event engine for the dispatching of lifecycle events execution.

Finally, Open Baton is included as a supporting project in the project named Orchestra[13]. This OPNFV initiative seeks

[12]https://www.ubuntu.com/cloud/juju

[13]https://wiki.opnfv.org/display/PROJ/Orchestra

to integrate the Open Baton orchestration functionalities with existing OPNFV projects in order to execute testing scenarios (and provide feedbacks) without requiring any modifications in their projects.

7) ARIA TOSCA: Under the Apache Software Foundation, Agile Reference Implementation of Automation (ARIA) [119] is a framework for building TOSCA-based orchestration solutions. It supports multi-cloud and multi-VIM environments while offering a Command Line Interface (CLI) to develop and execute TOSCA templates, and an easily consumable Software Development Kit (SDK) for building TOSCA enabled software. By taking advantage of its programmable interface libraries, ARIA can be embedded into collaborative projects that want to implement TOSCA-based orchestration. For example, Open-O [113] is using the ARIA TOSCA codebase to create its SDN & NFV orchestration tool [120].

8) XOS: Designed around the idea of Everything-as-a-Service (XaaS), XOS [121] unifies SDN, NFV, and Cloud services (all running on commodity servers) under a single uniform programming environment. The XOS software structures is organized around three layers: (i) a Data Model (implemented in Django[14]) which records the logically centralized state of the system, (ii) a set of Views (running on top of the Data Model) for customizing access to the XOS services and (iii) a Controller Framework (from-scratch program) is responsible for distributed state management.

XOS runs on the top of a mix of service controllers such as data center cloud management systems (e.g., OpenStack), SDN-based network controllers (e.g., ONOS), network hypervisors (e.g., OpenVirtex), virtualized access services (e.g., CORD), etc. This collection of services controllers allows the mapping to XOS onto the ETSI NFV Architecture playing the role of a VNFM. Using XOS as the VNFM facilitates unbundling the glsnfvo and enable to control both a set of EMs and the VIM [122].

9) TeNOR: Developed by the T-NOVA project [54], the main focus of this Multitenant/Multi NFVI-PoP orchestration platform is to manage the entire NS lifecycle service, optimizing the networking and IT resources usage. TeNOR [93] presents an architecture based on a collection of loosely coupled, collaborating services (also know as micro-service architecture) that ensure a modular operation of the system. Micro-services are responsible for managing, providing and monitoring NS/VNFs, in addition to forcing SLA agreements and determining required infrastructure resources to support a NS instance.

Its architecture is split into two main components: *Network Service Orchestrator*, responsible for NS lifecycle and associated tasks, and *Virtualized Resource Orchestrator*, responsible for the management of the underlying physical resources. To map the best available location in the infrastructure, TeNOR implements service mapping algorithms using NS and VNF descriptors. Both descriptors follow the TeNOR's data model specifications that are a derived and extended version of the ETSI NSD and VNFD data model.

[14]https://www.djangoproject.com/

10) Gohan: NTT's Gohan [123] is a MANO-related initiative for SDN and NFV orchestration. The Gohan architecture is based on micro-services (just as the TeNOR implementation) within a single unified process in order to keep the system architecture and deployment model simple. A Gohan service definition uses a JSON schema (both definition and configuration of resources). With this schema, Gohan delivers a called schema-driven service deployment, and it includes REST-based API server, database backend, command line interface (CLI), and web user-interface (WebUI). Finally, a couple of applicable use cases for the NTT's Gohan include to use it (i) in the Service Catalog and Orchestration Layer on top of Cloud services and (ii) as a kind of NFV MANO which manages both Cloud VIM and legacy network devices.

11) ESCAPE: Based on the architecture proposed by EU FP7 UNIFY project [124], ESCAPE (Extensible Service ChAin Prototyping Environment) is a NFV proof of concept framework which supports three main layers of the UNIFY architecture: (i) service layer, (ii) orchestrator layer and, (iii) infrastructure layer [125]. It can operate as a Multi-domain orchestrator for different technological domains, as well as different administrative domains. ESCAPE also supports remote domain management (recursive orchestration), and it operates on joint resource abstraction models (networks and clouds) [126].

In the current implementation of the process flow in ESCAPE, it receives a specific service request on its REST API of the Service Layer. It then sends the requested Service Function Chains to the Orchestration Layer to map the service components to its global resource view. As a final step, the calculated service parts are sent to the corresponding local orchestrators.

B. Commercial Solutions

The commercial orchestration solutions market is rising and will be formed by diverse types of companies including new startups, service provider IT vendors, VNF vendors, and the traditional network equipment vendors [127].

Some software and hardware vendors already offer network orchestration solutions. Below are presented the major commercial products that we consider as mature and robust solutions. All information about the products was got through the vendor's site and technical reports.

Cisco offers a product named Network Services Orchestrator enabled by Tail-f [128]. It is an orchestration platform that provides lifecycle service automation for hybrid networks (i.e., multi-vendors). Cisco NSO enables to design and deliver services faster and proposes an end-to-end orchestration across multiple domains. The platform deploys some management and orchestration functions such as NSO, Telco cloud orchestration, NFVO, and VNFM.

The Blue Planet SDN/NFV Orchestration platform [129] is a Ciena's solution that provides an integration of orchestration, management and analytics capabilities. It aims to automate and virtualize network service across physical and virtual domains. The platform supports multiple use cases, including SD-WAN service orchestration, NFV-based service automation, and CORD orchestration.

TABLE III
SUMMARY OF OPEN SOURCE NSO IMPLEMENTATIONS

Solution	Leader	VNF Definition	Resource Domain				MANO			Interface Management			Domain	
			Cloud	SDN	NFV	Legacy	NFVO	VNFM	VIM	CLI	API	GUI	Single	Multiple
ARIA TOSCA	Apache Foundation	TOSCA	✓							✓	✓		✓	
Cloudify	GigaSpace	TOSCA	✓		✓		✓	✓		✓	✓	✓	✓	
ESCAPE	FP7 UNIFY	Unify	✓	✓	✓		✓		✓	✓	✓		✓	✓
Gohan	NTT Data	Own	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	
ONAP	Linux Foundation	HOT, TOSCA, YANG	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Open Baton	Fraunhofer / TU Berlin	TOSCA, Own	✓		✓		✓	✓		✓	✓	✓	✓	
OSM	ETSI	YANG	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	
Tacker	OpenStack Foundation	HOT, TOSCA	✓		✓		✓	✓		✓	✓	✓	✓	
TeNOR	FP7 T-NOVA	ETSI	✓	✓	✓		✓				✓	✓	✓	
X-MANO	H2020 VITAL	TOSCA			✓		✓				✓	✓		✓
XOS	ON.Lab	-	✓	✓	✓			✓			✓	✓	✓	✓

Another commercial solution is the HPE Service Director of the Hewlett Packard Enterprise. The product is a service orchestration OSS solution that manages end-to-end service and provides analytics-based planning and closed-loop automation using declarations-based service model. It supports multi-vendor VNF, multi-VIM, various OpenStack flavors and multiple SDN controllers.

The Oracle Communications Network Service Orchestration solution [130] orchestrates, automates, and optimizes VNF and network service lifecycle management by integrating with BSS/OSS, service portals, and orchestrators. It has two environments to deploy the network services: one design-time environment to design, define and program the capabilities, and a run-time execution environment to execute the logic programmed and lifecycle management. In essence, it plays the roles of the NFVO, Telco cloud orchestration, and end-to-end service.

Ericsson offers some solutions in the scope of the cloud, SDN and orchestration. One of them is the Ericsson Network Manager [131] that provides a unified multi-layer, multi-domain (SDN, NFV, radio, transport and core) management systems and plays various roles such as VNFM, network slicing, and network analytics.

Many of the above-mentioned products are often extensions of proprietary platforms. There are few details publicly available, mostly marketing material. The list of commercial solutions is not exhaustive and will certainly become outdated. However, the overview should serve as a glipmse on the expected rise of commercial NSO solutions in the near future as enabling open source technologies and standards mature.

VII. APPLICATION SCENARIOS

NSO is envisaged to support diverse use case scenarios. This section aims at providing a brief practical view on a number of application domains and the main benefits provided by NSO in each scenario, delivering a sample of the expected potential of NSO in operation.

A. *Next Generation Mobile Telecommunication Networks*

The fifth generation of mobile communication systems (5G) is expected to meet diverse and stringent requirements that are currently not supported by current mobile telecommunication networks, like ubiquitous connectivity (connectivity available anywhere), zero latency (lower than few milliseconds) and high-speed connection (10 times higher than 4G).

An efficient realization of 5G requires a flexible and programmable infrastructure covering transport, radio, and cloud resources [79]. SDN and NFV are considered key enabling technologies to provide the required flexibility in processing and programmability, whereas end-to-end orchestration is regarded fundamental to improve the mobile service creation and resource utilization across the all network segments, from radio access to transport [132]. Furthermore, end-to-end orchestration should tackle a significant challenge in mobile telecommunication networks, namely, the integration of different technologies, including radio, SDN and NFV, so that network services may be dynamically created and adapted across the domains (wireless, aggregation and core).

Finally, mobile management and orchestration solutions are expected to enable (i) congestion handling per subscriber or traffic, (ii) dynamic allocation of resources according to traffic variation and/or service requirements, and (iii) load reduction on transport networks and central processing units [133].

B. *Transport Networks*

Optical networks evolved from statically assigned single and multi-mode fiber channels to highly flexible modulation schemes using separate wavelengths. Nowadays, optical equipments allow prompt wavelength conversion and flexible packet-to-optical setups. Given that agility increase, more programmability is being added to optical networks, for instance through PCE-based architectures for application-based network operations (ABNO) [134].

Under the flag of Software-Defined Optical Networks [135], such as those based on OpenFlow extensions, different use cases target transport networks to deliver new approaches on wavelength-based routing and virtualization of optical paths. Like PCE, different forms of SDN abstractions in optical networks come with a logically centralized entity to program network elements encompassing optical paths. In a wider perspective, logical services are implemented through central controllers as part of a NSO workflow. Optical transport of traffic across long-range areas, from data centers to end customers as Fiber-to-the-X (e.g., houses FTTH, curbs FTTC, Nodes FTTN), involve different intermediate elements requiring packet-optical conversions and vice-versa. An NSO envisioned in this scenario of packet-optical integration can take advantage of the knowledge about topology and equipments status, therefore optimizing traffic forwarding according to optical and packet-oriented capabilities. For instance, an NSO could optimize and aggregate Multi-Protocol Label Switching (MPLS) Label Switching Paths (LSPs) inside optical transport networks as part of higher-level service lifecycle goals.

Ongoing work at MEF aims to standardize SD-WAN [90] as the means to flexibly achieve programmable micro-segmented paths – based on QoS, security and business policies – across sites (public or private clouds), using overlay tunnels over varied underlay technologies, such as broadband Internet and MPLS. A service orchestrator is needed to tailor and scale paths on-demand to assure application policies by interfacing a controller that manages programmable edge SD-WAN routers, spanning multiple provider sites. WAN traffic can flow through non-trusting administrative domains in heterogeneous wired/wireless underlay networks with varying performance metrics.

C. Data Centers

Data Centers have long been upgraded with network virtualization for traffic forwarding and scaling L2 domains, such as VXLAN. Current technologies realize hypervisor tunneling for north-south and east-west traffic in data centers. More importantly, with the advent of operating system-level virtualization (a.k.a containers), even more flexible methods of end-host network virtualization have been deployed in data centers – there are examples already available in commercial products (e.g., VMWare NSX). In addition, computer virtualization platforms also contain networking extensions/plugins for dynamic networking between servers (e.g., Kubernetes and OpenStack). Those logically programmable network fulfillments derive the properties that concern a NSO.

The orchestration of cloud resources [136] has been a longstanding topic of research and actual commercial solutions. NSO programmability has been increasingly important to keep isolation in-network and at servers for heterogeneous customers that inhabit public clouds (e.g., Azure, AWS and Google Cloud). For instance, Kubernetes, using kube-proxy, defines networking in Google Cloud via a set of dynamic routes associations between service addresses and bridges' addresses in PODs (servers) hosting containers; ideally, a service is maintained independently of the associated containers host location. Container-based orchestration is a production reality but many challenges remain open [137], a number of them related to the seamless integration with network services inside the data centers and across data centers.

Similar concepts of NSO characteristics already exist to program paths optimizing traffic workloads, high throughput and low latency across data centers and to edge CDNs – best examples being Google B4 and Andromeda SDN projects. Therefore, NSO already plays an essential role in data center networking as it became a pioneer in direct application of SDN concepts.

Lately, research topics in this domain concern integration of multiple cloud environments envisioning different guarantees of SLA for distinct classes of traffic. As more mobile applications evolve towards accomplishing customers requirements for low latency and high throughput (e.g., virtual and augmented reality), NSO will play an important role addressing issues originated from those requirements.

D. Network Slicing

Future mobile/5G and fixed networks scenarios with diverse service requirements represent a growing and more complex challenge at the time of managing network resources. Network Slicing is being widely discussed in standard organizations as a key mechanism to provide flexibility in the management of network resources [79]. Network Slicing enables operators to create multiple network resources and (virtual) network functions isolated and customized over the same physical infrastructure [138]. Such dedicated networks, built on a shared infrastructure can reduce the cost of the network deployment, speeds up the time to market and offer individual networks customizations according to customer requirements so that operators can introduce new market services [108].

Increased flexibility introduces higher complexity in design and operation of network slices. Keys to avoid the CAPEX and OPEX increase is to automate the full lifecycle phases of a slice: (i) preparation phase, (ii) instantiation, configuration and activation phase, (iii) runtime phase and (iv) decommissioning phase [139]. Besides the automation, other management and orchestration use cases of network slicing are fault management, performance management, and policy management. It is also expected multi-operator coordination management in order to create end-to-end network slices across multiple administrative domains and some level of management to be exposed to the network slice tenant [140].

E. Intelligent Transport System

The Intelligent Transport System (ITS) is composed of diverse components, including smart infrastructures, radio and core networks, and connected vehicles/transports. The main users are automotive and transport companies, governments, and vehicle users. The system consists of sensors embedded in roads and cities to communicate with each other and/or with smart vehicles and other networks. Such system focuses on massive communication among involved elements and provides benefits of sustainability, security, and mobility in cities, roads, and railways [133].

Smart vehicles, transport, and infrastructure are some of the fields where the network service orchestration can contribute largely. The main difficulty arises from the fact that components such as Evolved NodeB (ENB) [141], Roadside

Unit (RSU) [142], and core network need to operate towards offering integrated services and with fine-tuning configurations harmonically. Another problem is the dynamism of the network traffic with the significant amount of data and constant changes in the network.

The orchestration can handle a big amount of data, contexts, and interfaces under an automatic and agile way. It demands for an overview of all the infrastructure and connected devices to enhance decision making process. With the adoption of NSO, the elements of the network architecture can be exposed as VNFs and new elements, e.g., telemetry and analytics, may be introduced. As a result, issues as scalability and location can be solved. Besides, NSO using SDN can handle the inter-system handover that consists of a switch among different networks (WCDMA, LTE, WI-FI) due to the fast movement of the transports. Many challenges need to be overcome and orchestration is regarded as a key factor to the success of ITS.

F. Internet of Things

According to Gubbi et al. [143], IOT is a network of sensing and actuating devices providing the ability to share information through a unified platform. Such devices or "things" may transmit a big amount of data over a network without requiring human-to-human or human-to-computer interaction. Its application areas include homes, cities, industry, energy systems, agriculture, and health. Due to the amount of generated-data and its dynamic and transient operational behavior, IOT will lead to scalability and management issues in the process of transport, processing, and storage of the data in real time [3]. Besides, the various entities involved need to be orchestrated to convert the data into actionable information [144].

NSO along with NFV and SDN allow network services to be automatically deployed and managed. In this scenario, SDN is responsible for establishing the network connections, NFV provides the management of the network functions, and NSO govern all deployment process of the end-to-end network service. Such paradigms can help to process and manage significant amounts of IoT-generated data with better network efficiency. The separation between resources and services provided by such technologies enables the isolation and lower impact risks of IOT on other infrastructures. Also, they can reduce the human intervention in the operation of the network, feature that is essential to the achievement of Internet of Things.

The authors in [145] propose an orchestrator for Internet of Things that manages all planes of an IOT ecosystem. The orchestrator selects resources and deploys the services according to security, reliability, and efficiency requirements. This approach enables an overall view of the whole environment, reducing costs and improving the user experience. Thus, orchestration allows the creation of more flexible and scalable services, reducing the probability of failure correlation between application components.

VIII. Challenges and Research Opportunities

NSO promises to improve efficiency when instantiating (day 1) and operating (day 2) network services, but the path ahead is not without challenges. This section provides a discussion on the main challenges and research opportunities for NSO, including scalability, security, resource modeling, performance, and interoperability.

A. Scalability

Some researches assume that 5G network might connect 50 billion devices until 2020 [146], [147]. This growth is due to the emergence of vertical industries such as Internet of Things, Smart Cities, and Sensor Networks. In this scenario, orchestration process requires the ability to handle the growth of networks and services to support the huge amount of connected nodes.

In addition, the network services can be deployed over different domains managed by third parties, infrastructure covering large geographical space and diverse type of resources such as access, transport, and core networks. This environment demands high scalability of the components involved, including orchestrators, controllers, and managers.

Most current NSO use cases are just based on deploying a network service in a controlled scenario. Just a use case is not able to check the scalability of the solution. In a production environment, the NS orchestrator is responsible for orchestrating millions of customers and services at the same time. Hence, scalability is an important feature for NSO success.

Some orchestration solutions mainly focus on centralized solutions, which pose scalability issues. The works [43] and [148] suggest different orchestrators involved in the orchestration process of end-to-end network services, not being limited to a single orchestrator. However, there are several particularities on each layer that could be better explored with specific orchestrators, instead of adopting a global orchestrator approach. In this way, we argue that the whole orchestration process can experience better results if split among different actors.

A key challenge is therefore to develop an orchestration process that is massively scalable. This process could involve one or more orchestrators, becoming open and flexible enough to address future applications and enable the integration with external components. The orchestration must avoid the congestions and bottlenecks in the management and orchestration plane to handle the requests for network services.

B. Security and Resiliency

Softwarized networks modify the way how services are deployed replacing the hardware-based network service components with software-based solutions [98]. Through technologies such as SDN and NFV, such network can provide automation, programmability, and flexibility. Generally, it depends on centralized control, which leads to risks to security and resiliency [149]. Thus, new protection capabilities need to be put in place, including advanced management capabilities such as authentication, access control, and fault management.

Security and resiliency must be considered both in design and operation stages of network services. Typically, the services are deployed first, prior to any efforts regarding security development. However, security must be a mandatory issue, mainly in a highly connected and virtualized environment.

Service instantiation involves automated processes that add and delete network elements and functions without human intervention. A critical problem is the addition of a malicious node that can perform attacks, catch valuable information and even the disruption of the entire services.

An essential requirement for a multi-domain orchestration platform is the capability to hide specific details of each domain. This ensures privacy and confidentially of the domains, preserving capabilities and resources to an external component [105].

Resilience in main NSO components such as orchestrators, controllers, and managers is also a critical problem because it can impact directly in overall service operation. Besides, open interfaces that support network programmability and NSO components communication with other external elements such as OSS and other orchestrators are an open issue and a hot topic in research [64], [149],[150]. In the same direction, the 5G-PPP published a white paper [151] suggesting that the orchestration platform must be secure, reliable and flexible.

C. Resource and Service Modeling

Network services need to be efficiently modeled towards deploying resource requirements, configuration parameters, management policies, and performance metrics. Service modeling will enable abstraction of resources and capabilities of underlying layers. It simplifies the understanding of functions and provides a generic way to represent resource and service.

However, it is a major challenge to translate higher-level policies, which are generated from the resource allocation and optimization mechanisms, into a lower level configuration. Templates and standards should be developed to guarantee automated and consistent translation [152]. Besides, the standardization can enable the interoperability and integration of network services templates and addresses limitations arising in the deployment of services in heterogeneous landscape.

There are templates and data modeling languages for Network Function Virtualization (NFV) and Network Service (NS) such as TOSCA, YANG, and HOT. In addition, some organizations propose their own approaches to the definition of Network Services, e.g., Open Baton and Gohan.

ETSI NFV MANO proposes VNF and Network Service descriptors as templates for the definition of functions and services. According to ETSI, NS is defined as a set of VNFs and/or PNFs interconnected by Virtual Links (VLs) and one or more VNF Forwarding Graph.

On the other hand, ETSI NS specifies lowest level resources such as CPU, memory, and network, but it does not extend the resource modeling and does not define a data model to the descriptors [153]. Thus, its approach is driven to single domain environment [148].

On the other hand, the IETF SFC provides the ability to define an ordered list of network services, or service functions (e.g., firewalls, load balancers, DPI) connecting them in a virtual chain. However, SFC does not describe the underlying resource, since its primary focus is service operation, apart from the forwarding topology. As opposed to ETSI, SFC scope covers multi-domain connections.

Resource and service modeling in softwarized networks including multi-domain scenarios need further work. This evolution will enable interoperability of network services and the correct mapping between the high-level configuration and the underlying infrastructure. Currently, the interoperability among the diverse orchestration platforms does not exist.

D. Performance and Service Assurance

The changes that orchestration technology brings to the telecommunication infrastructures make them increasingly virtualized and software-based. So, performance is a constant challenge in a highly dynamic environment of virtual functions and services.

This change reflects on enabling technologies. For instance, the NFV should meet performance requirements to support, in a standard server, the packet processing, including high I/O speed, fast transmission, and short delays [152]. The VNFs must achieve a performance comparable to specialized hardware. According to [3], some applications require specific capabilities, but virtualization can degrade their performance. This generates a trade-off between performance and flexibility. However, recent advances in CPU and virtualization technologies are overcoming these challenges include Data Plane Development Kit (DPDK) [154] – libraries and drivers for fast packet processing, NetVM [155] – enabling high bandwidth network functions to operate at near line speed, and ClickOS [156] – minimalist operating that supports high throughput, low delay, and isolation. Likewise, the document [157] of the ETSI provides a set of recommendations on the minimum requirements that the hardware and virtualized layer should have to achieve high performance.

Another question is performance monitoring coupled with Network Services maintenance. Both require a global view of the resources and a unified control and optimization process with various optimization policies running in it. The monitoring is required to avoid the violation of SLAs in the Service layer. In the order to keep NS performance, it is demanded that the system equally performs in different layers. In multi-domain scenarios, this becomes more complex because it is necessary the exchange of information and resources between different organizations/domains [53]. VNF benchmarking [158] and NS chain profiling [159] coupled to NSO lifecycles and run-time MANO resource allocation and management decisions are potential techniques towards service guarantees and SLA compliance.

In addition, a better composition between the traffic forwarding and NF placement is required towards optimizing the NS deployment. The first steps to provide service performance guarantees are to avoid heavily loaded service nodes and to identify bottleneck links. Algorithms and machine learning techniques can archive better results in this composition.

Thus, how to achieve high performance is an important problem in the research and development of NSO solutions. Projects within the 5G Infrastructure Public Private Partnership (5G-PPP) [151] are targeting enhanced performance towards better user experience.

E. Multi-tenancy and Interoperability

Typically, operators infrastructures are organized in several domains that differ in geographical locations, management (e.g., legacy or SDN), administrative boundaries, and technologies. One of the challenges for service providers is to create and to manage services across unique and proprietary interfaces, making integration and startup difficult tasks to be achieved, as well as increasing the operational costs.

In this scenario, interoperability is essential to enable the deployment of end-to-end network services. Few end-to-end services will be confined within the boundaries of a single domain. They normally encompass a multi-domain orchestration environment composed of providers and vendors with different incentives and business models [109]. There is no consensus about how would be the exchanging process between the multiple actors in deployment end-to-end network services. In fact, ETSI MANO architecture does not bring any provisioning for this kind of exchange. [31].

A number of orchestration solutions based on the ETSI MANO architecture have emerged with the objective of proposing a complete orchestration framework. Table III shows notable solutions. Although the progress made by ETSI in defining architecture and interfaces, each solution uses a particular implementation and data model, which makes interoperability difficult to achieve (cf. [160]). As a result, chaining network functions leveraging different solutions for a single network service deployment and operation is currently a very costly proposition in terms of development efforts and time-to-market.

Standardization is a path to enable interoperability of network services between operators and address limitations that arise in the deployment of services, as explained in Section IV. Another parallel track towards interoperability is a broad adoption of software components and broad agreements on APIs along data and information models fueled by re-usable open source artifacts.

F. Network Service Lifecycle Management

Network service lifecycle consists in all process for deployment, execution, and termination of a network service. The Network Service Lifecycle Management is fundamental to ensure the correct operation of the service.

Nevertheless, the network services can have specific lifecycle management requirements. For example, an NS can use specific resources as Single Root I/O Virtualization (SR-IOV) [161] and DPDK or need resources across various domains. This type of requirements becomes harder the service deployment.

One possible solution is service lifecycle automation. It enables lifecycle management without human intervention. Automation can be obtained through heuristic algorithms and machine learning techniques. ONAP is working on new close control loops (e.g., CLAMP - Closed Loop Automation Management Platform)[15] towards providing automation, performance optimization and Service Lifecycle Management, eventually leveraging network analytics and machine learning assisted decisions. Nevertheless, many aspects of run-time (day 2) workflow modeling and implementation remain open, with TOSCA extensions and BPMN/BPML approaches [162] undergoing improvements to meet the needs of NSO-based lifecycle automation.

[15] https://github.com/onap/clamp

IX. CONCLUSIONS

The traditional telecommunication industry is facing multiple challenges to keep competitive and improve the mode network services are designed, deployed and managed. Architectures and enabling technologies such as Cloud Computing, SDN and NFV, are providing new paths to overcome these challenges in a software-driven approach. Network Service Orchestration (NSO) is a strategic element in this process of evolution. NSO aims at converging various technologies by providing a broader and comprehensible view of network services.

In this comprehensive survey on network service orchestration, we aim at highlighting its importance and trying to contribute to a common understanding of the concept and diverse approaches towards practical embodiments of NSO. We present enabling technologies, clarify on the definition of term orchestration, review standardization advances, research projects, commercial solutions, and list a number of challenges such as resource and service modeling, multi-tenancy and interoperability, multi-domain orchestration, scalability, security and resiliency, performance, and lifecycle management.

The application of NSO in some scenarios was also presented, where it is possible to sense its potential and understand the motivation behind so much ongoing work. We also observe a growing trend towards the use of open source components or solutions in orchestration platforms; however, the platforms require to evolve until become suitable for production. An important contribution of this work was the definition of a taxonomy that categorizes the leading characteristics and features related to network service orchestration.

Despite the fast pacing issues of this vibrant topic, we expect this survey to serve as a guideline to researchers and practitioners looking into an overview of network service orchestration fundamentals, a reference to relevant related work and pointers to open research questions.

ACKNOWLEDGMENT

This research was supported by the Innovation Center, Ericsson S.A., Brazil, grant UNI.62. The authors would also like to express their gratitude to review contributions from David Moura, Lucian Beraldo, Nazrul Islam, and Suneet Singh (in alphabetical order) funded by the EU-Brazil NECOS project under grant agreement no. 777067.

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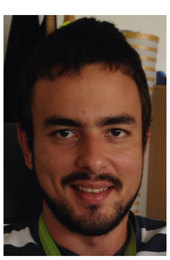

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