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RESEARCH ARTICLE

Analysis of end-to-end multi-domain management and orchestration frameworks for software defined infrastructures: an architectural survey

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ABSTRACT

Over the last couple of years, industry operators' associations issued requirements towards an end-to-end management and orchestration plane for 5G networks. Consequently, standard organisations started their activities in this domain. This article provides an analysis and an architectural survey of these initiatives and of the main requirements, proposes descriptions for the key concepts of domain, resource and service slicing, end-to-end orchestration and a reference architecture for the end-to-end orchestration plane. Then, a set of currently available or under development domain orchestration frameworks are mapped to this reference architecture. These frameworks, meant to provide coordination and automated management of cloud and networking resources, network functions and services, fulfil multi-domain (i.e. multi-technology and multi-operator) orchestration requirements, thus enabling the realisation of an end-to-end orchestration plane. Finally, based on the analysis of existing single-domain and multi-domain orchestration components and requirements, this paper presents a functional architecture for the end-to-end management and orchestration plane, paving the way to its full realisation.

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1. INTRODUCTION

The mounting interest on software defined infrastructures and network functions virtualization is driven by the compelling need of network operators for efficient and flexible utilisation of their infrastructures. The evolution of the telecommunications market in the last decade has highlighted challenges that can be overcome only by lowering the cost of ownership of the infrastructure and improving the agility of deployment of new services. For these reasons, all the 5G white papers issued by industry operators in the last couple of years claim for automated management of the infrastructure, flexible placement of network functions and end-to-end (E2E) quality assurance. The fulfilment of these capabilities is assigned to an *E2E management and orchestration (MANO) plane* which role is, in few words, to perform E2E orchestration of resources and services.

As shown in Figure 1, the management and orchestration plane has an essential role of mediation between the service plane and the infrastructure plane, in order to ensure an efficient utilisation of the infrastructure while fulfilling performance and functional requirements of heterogeneous services. NGMN [1] states that 5G systems shall support flexible and configurable network architectures, adaptable to use cases involving a wide range of service requirements.

Logical architectures, consisting of virtual functions connected by virtual links, shall be hosted by software defined infrastructures.

The role of the infrastructure will not be limited to providing connectivity: it shall offer coordinated allocation networking and cloud resources (connectivity, compute, storage and related connectivity). New services will be 'manufactured by software', hosted in an 'infrastructure factory' where resources and network functions are dynamically and flexibly traded and provisioned.

The aim of this article is twofold. First, it surveys different views issued by industry and standard associations on architecture and roles of the E2E MANO plane. The target is to draw a reference architectural framework comprehensive of all the capabilities that the E2E MANO plane is expected to fulfil. Then, the paper provides an architectural survey of existing orchestration frameworks, mapping them to our reference architectural framework. This framework is the result of an analysis carried out within the scope of the 5G Exchange project [2]. The main objective is to design, implement and test in a large-scale platform a multi-domain MANO framework. Indeed, E2E orchestration can be realised only resolving two fundamental multi-domain issues:

- Multi-domain as multi-technology: currently, several resource MANO frameworks expose resource virtualisation and support automated provisioning of resources to services; it is necessary to unify MANO of heterogeneous resource technology domains in order to realise an E2E software defined infrastructure suitable to host 5G services.
- Multi-domain as multi-operator: the implementation of E2E MANO must deal with the interaction of multiple administrative domains (i.e. different service and/or infrastructure providers) at different levels: resource MANO, service MANO, inter-operator service level agreement (SLA) fulfilment.

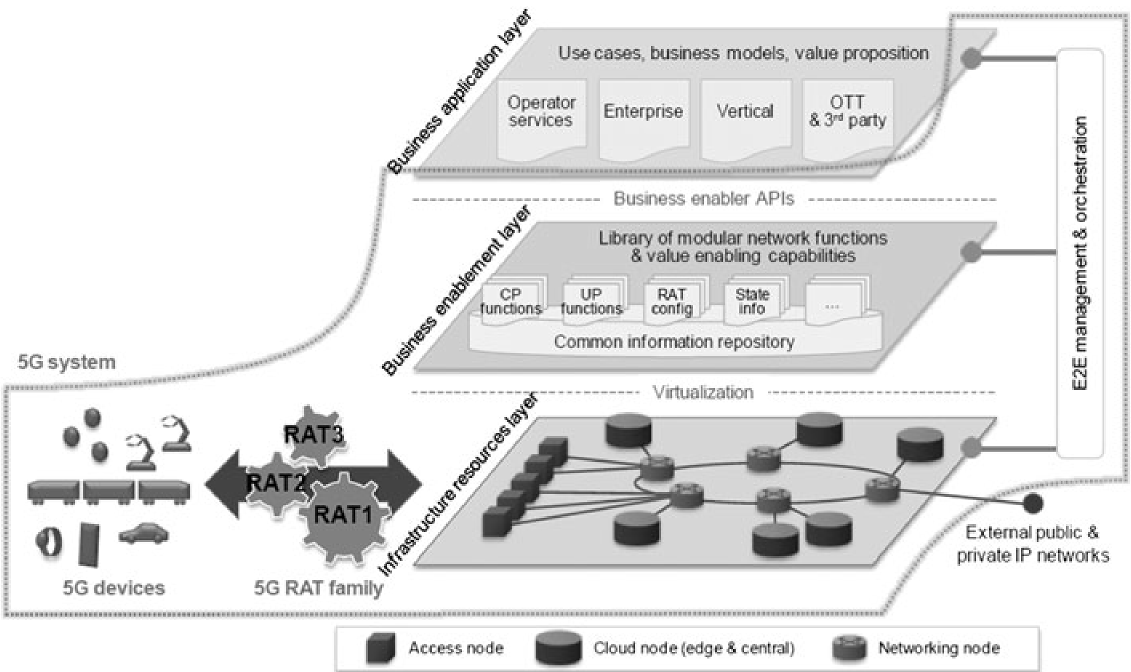

Figure 1. NGMN 5G white paper [1]: 5G architecture. The role of the end-to-end management and orchestration plane spans from the infrastructure layer to the application (service) layer.

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The analysis of existing domain orchestration frameworks advances a functional architecture for the E2E MANO plane. The functional areas covered by this architecture, which is drawn as conclusion of the paper, enable E2E service and resource orchestration in multi-domain environments.

The paper is organised as follows. Section 3 introduces the requirements issued to the E2E MANO plane by various 5G-related white papers, as well as overviews the main related activities in the standardisation arena. Section 2 defines E2E MANO concepts and our reference architectural framework. Section 4 analyses existing virtualisation domain frameworks and their related MANO capabilities as well as current initiatives aiming at developing multi-domain orchestration components. Section 5 introduces a functional architecture for the E2E MANO plane, while Section 6 concludes the paper and elaborates on future work.

2. MULTI-DOMAIN ORCHESTRATION CONCEPTS

This section, introduced by a short dictionary of key terms related to orchestration and slicing of resource and services, describes a reference architectural framework that will be used in the following sections to classify existing single-domain and multi-domain orchestrator (MdO) functionality.

2.1. Key terms and definitions

In Section 3, we highlighted several key words that recur in the discussion on E2E orchestration. In order to elaborate on the vision summarised in Figure 3 and describe a consistent E2E orchestration framework, it is necessary to provide our definitions for these terms. Here, follows a short reference dictionary that starts with resources and their abstraction, continues with the definition of network function and concludes with the concepts of resource and service slices and orchestration.

Resource: physical or virtual network (packet, optical and so on) or cloud (compute and storage) element with given capacity attributes, QoS characteristics and connectivity ports.

Resource domain: a topology of resources exposed as an abstraction.

Abstraction: a representation of an entity in terms of selected characteristics while hiding or summarising characteristics irrelevant to the selection criteria (ONF [3]).

Virtualisation: an abstraction whose selection criterion is dedicated to a particular client or application (ONF [3]).

Network function (NF): in this paper, the term NF is used to refer to any of the following:

- Service function (SF), IETF [4]: function that is responsible for specific treatment of received packets. A service function can be a virtual instance or be embedded in a physical network element.
- Network function, ETSI NFV [5]: a functional block within a network infrastructure that has well-defined external interfaces and well-defined functional behaviour.
- Virtualized network function (VNF): an implementation of an NF that can be deployed on a network function virtualisation infrastructure (NFVI) (according to ETSI NFV).

Orchestration: it is the automated arrangement and coordination of complex networking systems, resources and services. It has an inherent intelligence and implicitly autonomic control of all systems, resources and services.

Network function virtualisation [5] does not define orchestration explicitly. Its meaning may be inferred from the NFVO definition network functions virtualisation orchestrator (NFVO): functional block that manages the network service (NS) life cycle and coordinates the management of NS life cycle, VNF life cycle (supported by the VNFM) and NFVI resources (supported by the VIM) to ensure an optimised allocation of the necessary resources and connectivity, where life cycle management is defined as a set of functions required to manage the instantiation, maintenance and termination of a VNF or NS. NFV [5] orchestration is seen as a single concentrated functional block, without delegation. The NFV orchestrator may consider resource availability and load when it responds to a new demand and may rebalance capacity as needed, including creating, deleting, scaling and migrating VNFs.

Although [6] does not formally define [software defined networking (SDN)] orchestration, the meaning of the concept is apparent from the SDN controller that is expected to coordinate a number of interrelated resources, often distributed across a number of subordinate platforms, and sometimes to assure transactional integrity as part of the process. This is commonly called orchestration. An orchestrator is sometimes considered to be an SDN controller in its own right, but the reduced scope of a lower level controller does not eliminate the need for the lower level SDN controller to perform orchestration across its own domain of control. A provisional definition of (SDN) orchestration might be the continuing process of allocating resources to satisfy contending demands in an optimal manner. The idea of optimal would include at least prioritised customer SLA commitments, and factors such as customer endpoint location, geographic or topological proximity, delay, aggregate or fine-grained load, monetary cost, fate-sharing or affinity. The word continuing incorporates recognition that the environment and the service demands constantly change over the course of time, so that orchestration is a continuous, multi-dimensional optimisation feedback loop. The orchestration process is often discussed as having an inherent intelligence and implicitly autonomic control [7, 8]. Orchestration is also guaranteeing the adequate service

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performance during the service delivery despite concurrent resource usage among users and service outages [9].

Resource orchestration: automated management of resources in one or multiple resource domains to host an NF or a topology of NFs. A resource orchestrator only deals with resource level abstraction and does not understand the service that the NF or topology of NFs deliver.

Resource slice: a set of resources exposing a logically unified control and management interface; the resource slice is deployed and maintained by a resource orchestrator. Resource slices may recursively include other resource slices.

Service slice: a topology of NFs, providing logically unified control and management interfaces and a related service.

Service orchestration: automated management of a service slice that form a service requested by a customer (NS, cloud service, online service ...); a service orchestrator understands the service that the service slice delivers.

Service template: pre-packaged reusable service definition. A service template describes the NFs to be used to provision the intended service, along with their topology, attributes and deployment instructions. The service template includes a descriptor that defines its functioning, architecture, SLA and pricing.

Service: instantiation of a service template into a service slice, implemented by assigning values to NF attributes and connection points, allocating resource slices and deploying software components.

Multi-domain orchestration: automated management of services and resources in multi-technology (multiple domains involving different cloud and networking technology) and multi-operator (multiple administrative domains) environments.

2.2. Reference architectural framework

The pre-condition to realise the E2E vision summarised by Figure 3 is to enable multi-domain orchestration. This section presents the reference architectural framework depicted in Figure 2 for organising the components and interworking interfaces involved in E2E MANO in multi-domain environments.

At the lower layer in Figure 2, there are resource domains, exposing resource abstraction on interface I5. In the middle layer, domain orchestrators perform resource orchestration and/or service orchestration exploiting the abstractions exposed on I5 by resource domains. Interface I4 allows coordination between domain orchestrators.

An MdO coordinates resource and/or service orchestration at multi-domain level, where multi-domain may refer to multi-technology (orchestrating resources and/or services using multiple domain orchestrators) or multi-operator (orchestrating resources and/or services using domain orchestrators belonging to multiple administrative domains). The MdO interacts with domain orchestrators via interface *I3* APIs to orchestrate resources and services within the same administrative domain. The MdO interacts with other MdOs via interface *I2* APIs (business-to-business) to request and orchestrate resources and services across administrative domains. Finally, the MdO exposes

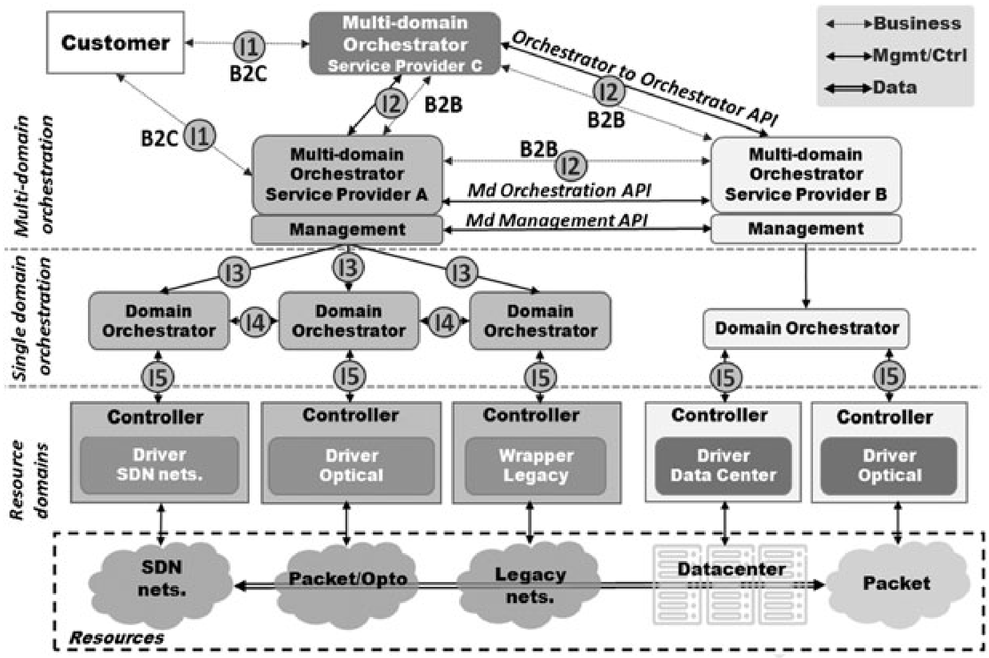

Figure 2. End-to-end management and orchestration: reference architectural framework.

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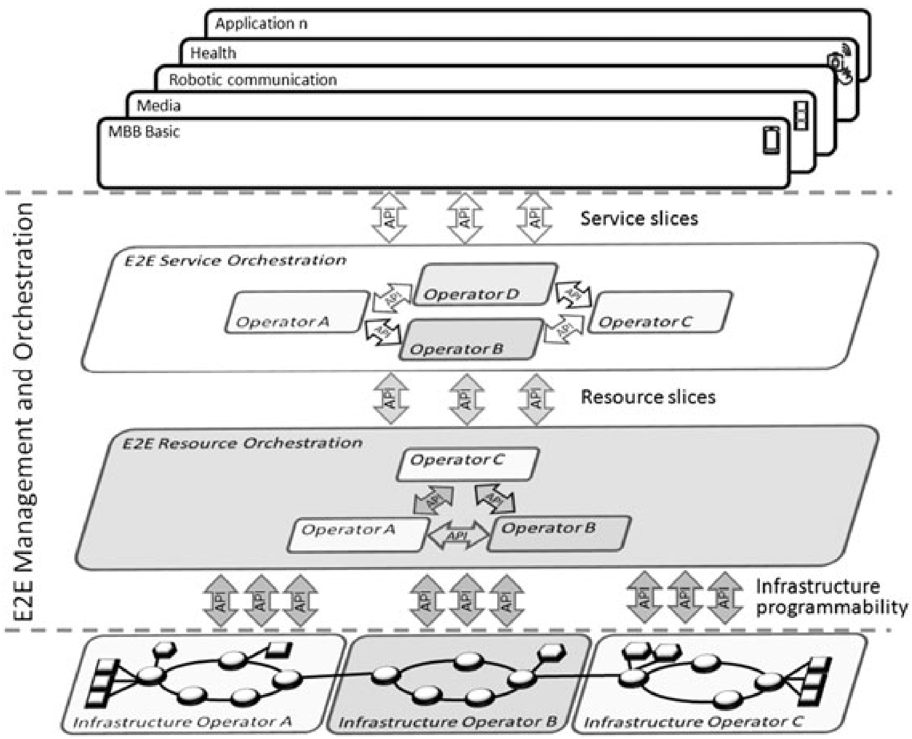

Figure 3. End-to-end (E2E) management and orchestration: multi-domain orchestration of different infrastructure domains belonging to different operators.

on interface *I1* service specification APIs (customer-to-business) that allow business customers to specify their service requirements.

The framework considers also MdO service providers (SPs), such as C in Figure 2, which does not own resource domains but operate an MdO level to trade resources and services.

2.3. Service orchestration models: Multi-operator service level agreement aspects

In a multi-operator environment, the services offered by each operator may require NFs and resources from different locations in several neighbour domains (with different capabilities, requirements, constraints and different administrators) for its deployment. This can be managed by resource and service slicing and a contract becomes necessary between the different providers, including quality assurance by means of an SLA. Operators delivering the service from a service topology can either be a star (customer-facing operator handles all contracts) or a multi-level tree (operators handle contracts in a cascading fashion). These topologies can be realised by means of MdO interface I2 for inter-operator relations and MdO interface I1 for customer to operator relations as depicted in Figure 2. For each resource or service slice, there should be a parent SLA contract that is subdivided in several child SLA contracts, one for each operator that provides resource or service slices for composing the customer demanded service. As resource and KPI monitoring is operator-internal, an SLA aggregator functions for all the contracts that are attached to the parent and aggregates the results of the partial SLA evaluations of each subcontract.

While some of the aforementioned issues have been brought up earlier in the context of cloud federations [10], much challenges remain with regard to SLA handling in a multi-operator, composite service environment. First, today's SLAs in general contain very simple conditions that may not capture all details. When it comes to composite services requesting compute, storage and networking resources at the same time, currently used simplistic SLAs (both in the cloud and telco environment) would probably fail to assure the inherently complex service requirements and the intricate interplay of resources of very different types. In order to mitigate such inefficiency of the contracts, KPIs relevant for composite services should be devised and integrated into SLAs with a holistic view to the service under consideration.

Second, the granularity and amount of internal information shared among operators is key to defining efficient SLAs and estimate the risk of not fulfilling them. In certain cases, operators might want to share finer grain information (e.g. a partial network topology with KPI measurements on the links) with each other to provide high and ASQ, if the end-user is willing to pay for such a service. In other cases, operators like to keep it simple and reveal the least amount of information about their own administrative domain (e.g.

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a totally abstract view of their network, i.e. a 'black box'), provided such a view is adequate for the given service to be delivered successfully. The key observation here is that a flexible information-sharing framework is needed, where any level of details could be shared and incorporated into contracts.

Third, how the parent SLA is subdivided into several partial SLAs, how income is divided based on (un)fulfilled contracts, and how to share the costs of remunerating the customer in case of not meeting KPIs are all important issues to deal with. Note that there are a number of theoretical solutions to this problem published by the research community, drawing on proportional fairness and coalitional game theory [11]; however, a practical, carrier-grade implementation of these mechanisms is still missing. Such computational issues are becoming even more relevant, as the potential for on-demand service negotiation and creation (as opposed to a strictly service catalogue based system) brings with itself the need for calculating (partial) SLA parameters on the fly. Different strategies can be taken under consideration for multi-domain SLA management: (i) a bottom-up strategy that is initiated by providers; (ii) a top-down strategy that is initiated by consumers; and (iii) a mixed/negotiated strategy, which is a combination of strategies 1 and 2 with additional message exchanges. In [12], authors provide a detailed insight on these strategies.

3. END-TO-END MANAGEMENT AND ORCHESTRATION IN 5G NETWORKS

3.1. Existing 5G white papers

5G white papers issued by industry and standard associations (NGMN, IMT-2020) elicit a set of key requirements to the deployment, operation and management of 5G networks. They can be summarised as follows:

- Ease of deployment—5G systems should allow an easy deployment on the existing network infrastructures and furthermore aid the deployment of new services or technologies minimising the impact in the system or the user experience.
- Flexibility, adaptability and scalability—5G networks should be able to change quickly the interconnections between devices and create new nodes to adapt the network to the changing demand services.
- Fixed-mobile convergence—5G should support the fixed and mobile domains unification to claim a better service user experience.
- Operations awareness—5G systems should be able to access a segment of the information to have enough knowledge of the high variety of service requirements and acting accordingly to the situation to optimise the network traffic.
- Innovation—The 5G eco-system is an open eco-system that enables innovations at a fast pace, involving many partners. 5G should provide the capabilities to allow this, with value creation for the operators and the market as a whole. Programmability of the network, availability of 5G value enabling capabilities (e.g. location, QoS, identity and security) and the related APIs are needed to make this happen.

All these requirements imply the realisation of an E2E management plane adapted to flexibly map services to topologies of network functions, dynamically allocate resources to network functions and reconfigure network functions according to changing service demand. In the different 5G white papers, there requirements are variously referred as resource orchestration, resource slicing, service orchestration and service slicing. We hereby provide a review of the most significant statements.

In the 5G white paper (NGMN [1]), the E2E MANO entity is introduced to operate as the contact point that translates the use cases and business models issued by a business application layer into actual network functions and slices. A slice is intended as a managed set of 5G network functions set-up within the 5G system that is tailored to support the communication service to a particular type of user or service.

The E2E MANO entity defines the network slices for a given application scenario, chains the relevant modular network functions, assigns the relevant performance configurations and finally maps all of these entities on the infrastructure resources. The NGMN white paper assigns to the E2E MANO entity the capability to allow for third parties (e.g. mobile virtual network operators and verticals) to create and manage their own network slices, leveraging on APIs and everything-as-a-service principles supported by the underlying infrastructure resource layer. It is also stated that, because of the various tasks of the MANO entity, it will not be a monolithic piece of functionality. Rather it will be realised as a collection of modular functions that integrate advances made in different domains likeNFV, SDN or self-organised networks. Furthermore, it will use data-aided intelligence to optimise all aspects of service composition and delivery.

Fifth-generation mobile communications forum (5GMF) [13] claims that network management in 5G will leverage on SDN/NFV and virtualisation technologies to provide scalable and flexible network management to deal with short service life cycles. Also for 5GMF, the network MANO plane instantiates and maintains E2E virtualised networks including cloud resources. These virtual network slices are instantiated on demand on to the software controlled network domain using APIs exposed by the management plane, which provides dynamic management (i.e. orchestration) for multi-layer and multi-domain mobile networks.

For the IMT-2020 (5G) Group [14], the network orchestration function creates, manages and deletes the network slices. The operator designs the network slice template, including required network functions, interfaces between network functions and the required network resources for

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each network function. The network orchestration function applies the network resources according to the network slice template and instantiates the VNF and their interfaces on the allocated network resources.

NetWorld2020 [15] issues requirements to the MANO plane, which is expected to provide the dynamic allocation of resource containers to network functions, automated management of functions and resources adapted to the functions life cycle, and dynamic support of SLA through additions, reallocations and reconfiguration of network functions.

In addition to the previously introduced white papers, major network manufacturers have also elaborated on the concepts of service and infrastructure slicing and orchestration. We next go through some examples.

According to Ericsson [16], management entities in 5G systems will enable automation of provisioning processes, and they will be capable of coordinating cloud resources for complex dynamic systems that require resource access control and service quality management. Orchestration enables automation across the building blocks of a network through centralised management of network resources. To offer services that draw resources from several building blocks, E2E orchestration is needed to match external business offerings with network efficiency.

In [17], Huawei distinguishes between infrastructure slicing and 5G network slicing; the former meant to isolate portions of the infrastructure and flexibly assign network, compute and storage resources to service overlays; the latter to realise different performance targets issued by heterogeneous, sometime incompatible, service requirements.

Also for Nokia [18], there are several levels and types of orchestration. These include orchestration for services, developed by the operator and offered to users; and the management of cloud services and available resources, performed by the virtualized infrastructure manager domain.

5GMF white paper [19] provides a view on 5G architecture and slice platform and management implementation.

5G white paper on NGFI [20] covers the evolving demand for next generation fronthaul interfaces, design principles, application scenarios, potential solutions and other technical aspects with respect to NGFIs, providing a valid reference for the future evolution of wireless access networks. It is hoped that it will promote the NGFI framework concept while also providing reference indicators for the design of future networks (FNs).

Open network operating system [21] is a SDN operating system facilities for SPs that has scalability, high availability, high performance and abstractions to make it easy to create apps and services. The platform is based on a solid architecture and has quickly matured to be feature rich and production ready.

In conclusion, the scope of the E2E MANO plane involves diverse concepts summarised in Figure 3. *Infrastructure programmability* is a broad concept that refers to infrastructure softwarisation, SDN, NFV and orchestration of network functions. The programmability of the infrastructure is the enabler for E2E orchestration of resources and services. The ‘end-to-end’ requirement implies the capability of realising multi-domain orchestration of different programmable infrastructure domains, possibly belonging to different administrations/operators. In Figure 3, infrastructure operators A, B and C interact at resource orchestration level to expose resource slices to the service layer. These resource slices may involve heterogeneous technologies belonging to different infrastructure operators. At service orchestration level, the operators interact to expose service slices to the SPs. This interaction may involve operators, such as operator D, which does not own an infrastructure (i.e. any resources).

The remainder of this article elaborates on the concepts summarised by Figure 3.

3.2. Standard activities

This section provides an overview of activities in ETSI, ITU-T and BBF related to E2E MANO.

(1) ETSI NFV

The ETSI industry specification group for NFV, with representatives from both telecoms and IT vendors, focuses on defining specifications for the virtualisation of functions within telecommunications networks. One major result of ETSI NFV is the definition of the reference functional architecture (Figure 4) by the MANO working group [3], which focuses on the aspects brought into the operator’s networks by NFV. In its recently started phase 2, ETSI NFV activities include more than 30 new work items and aim at producing normative specifications that define the interfaces related to the main reference points in the NFV-MANO architectural framework.

During phase 1, the MANO working group deliverables briefly discussed the implications of multiple administrative domains for the reference architecture, as required by some of the proposed use cases [22]. According to [3], NFVO is responsible for two major functions:

- Resource orchestration: orchestration of resources across multiple virtualised infrastructure managers (VIM), and
- Network service orchestration: life cycle management of NSs.

The split of these two functions in separated functional blocks is also envisioned to support use cases in which a multi-domain orchestration of services is a requirement [3]. However, further detailed discussions were shifted to ETSI NFV phase 2. Some use cases related to the split of NFVO are currently being discussed in [23]. Especially interesting is the use case entitled ‘Network Services offered by a separate admin domain’, where an operator is offering NSs that span across multiple administra-

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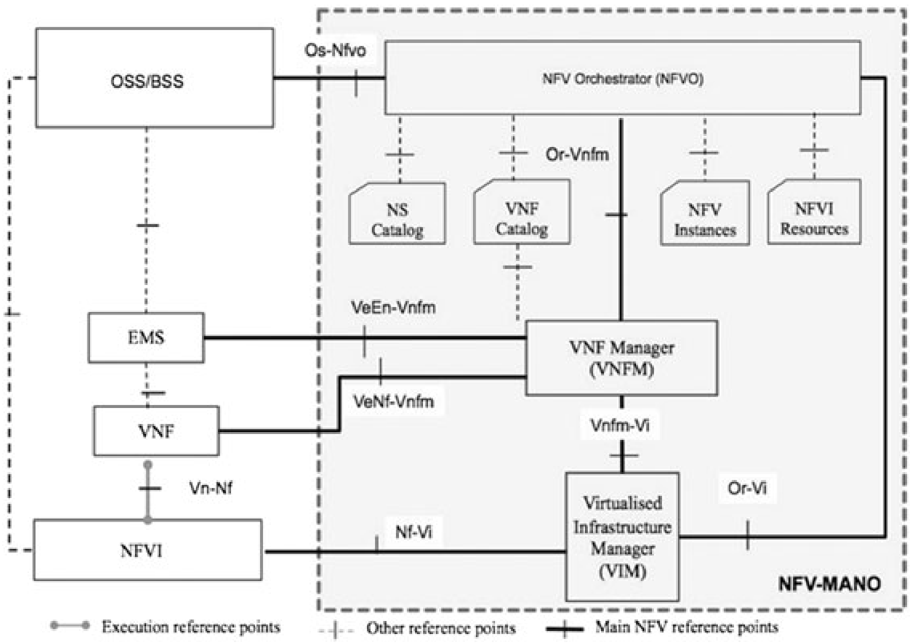

Figure 4. ETSI network function virtualisation (NFV) management and orchestration (MANO) reference architecture.

tive domains using a so-called umbrella NFVO. This use case introduces a new reference point between NFVOs in different domains.

In [23], ETSI NFV ISG provides an overview on typical design patterns, use cases, feedback from proof of concepts and recommendations on using SDN in NFV-MANO architectural framework. Some gaps and recommendations for further studying the applicability of the current reference framework to multiple administrative domain scenarios are also highlighted in this document. Many of them refer to the need of specifying an east-west interface between NFVOs for exchanging information on connectivity, offered services, pricing and so on.

After phase 1, ETSI NFV ISG members, with the support of the Linux Foundation, started an open source project that aims at delivering a de-facto standard NFV platform for the industry, open platform for NFV (OPNFV) [24]. OPNFV looks to realise the ETSI NFV architectural framework by integrating and extending existing open source projects, such as OpenStack, OpenDaylight, KVM and Open vSwitch, among others. While its first two releases (Arno 2015-06, Brahmaputra 2016-02) focus on resource orchestration, building NFV infrastructure and VIM, OPNFV platform is also expected to cover network service orchestration functions (NFVO) in future releases.

(2) ITU-T

Recognising the impact that ‘softwarisation’ is having on ICT industry and what it will mean for the industry of the 5G era, a study group (SG13) dedicated to ‘Future networks including cloud computing, mobile and next-generation networks’ [25] at ITU-T focuses on FNs and SDN within. The group is standardising FNs with the objectives of service (network virtualisation), data, environmental (energy saving for FNs) and socio-economic awareness. Their plans are to develop different facets of the smart ubiquitous network, requirements of network virtualisation for FNs, framework of telecom SDN and requirements of formal specification and verification methods for SDN.

The group also develops standards that detail requirements and functional architectures of the cloud computing ecosystem, covering inter-cloud and intra-cloud computing and technologies supporting everything-as-a-service. This work includes infrastructure and networking aspects of cloud computing models, as well as deployment considerations and requirements for interoperability and data portability. Given that cloud computing relies on the interplay of a variety of telecom and IT infrastructure resources, SG13 develops standards enabling consistent E2E, multi-cloud management and monitoring of services exposed by and across different SPs’ domains and technologies [26]. SG13 published a recommendation in 2015 on resource management in (multi) cloud computing: the recommendation presents general concepts of E2E resource management cloud services, a vision for adoption of cloud resource management in a telecommunication-rich environment [27].

Within SG13, there is a focus group on network aspects of IMT-2020 (international mobile telecommunications) [28] that was established in May 2015 to analyse how emerging 5G technologies will inter-

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act in FNs. The group took an ecosystem view of 5G research of development and published a preliminary study [29] on the networking innovations required to support the development of 5G systems. It has proposed a high level-5G architecture based on the analysis of the 5G requirements, which will be more elaborated in the standardisation phases. It also proposed and elaborated the new concept of Network softwarisation that is represented an overall transformation trend for designing, implementing, deploying, managing and maintaining network equipment and network components by software programming, exploiting characteristics of software such as flexibility and rapidity of design, development and deployment throughout the life cycle of network equipment and components, for creating conditions that enable the redesign of network and services architectures; allow optimisation of costs and processes; and enable self-management. The focus group continues to work on the challenges that telecoms players must overcome in the development of the 5G ecosystem. Specific tasks and areas of work include refining their IMT-2020 network architecture, prototyping (preferably with the open-source community) network softwarisation and information-centric networking, studying network slicing for the fronthaul/backhaul network and defining new traffic models and associated aspects of QoS and operations, administration and management applicable to IMT-2020 networks.

Another study group, SG11 (protocols and test specifications) released a closely related recommendation on the signalling requirements for flexible NS deployments [30]: the recommendation describes the signalling requirements, based on the service platform broadband network gateway (BNG) architecture, needed to achieve outstanding benefits like easy deployment of fine-grained NS. The three aspects the recommendation covers are NS combination/orchestration, service configuration on the BNG, and BNG resources, status and event notification to the service platform.

(3) BBF

There are several ongoing activities within broadband forum (BBF) that is related to the MANO plane of telecommunication networks.

The architecture and migration work area at BBF identifies the relationships between entities to facilitate the transition of networks towards virtualisation while documenting the key functionalities that need to be brought forward to enable a seamless evolution path. The work underpins all the new value-added services and application delivery for fixed and mobile access networks, home and business that can now be deployed at the pace of each market. The models reflect the control, management and data plane aspects of BBF defined architectures and are augmented to subsume new industry directions such as SDN and NFV while carrying forward key aspects of broadband as currently deployed. The work on defining an SDN reference model contains a working text (WT-370) that investigates on the technical aspects associated with fixed access network sharing, addressing the typical infrastructures, topologies and deployment scenarios. It also provides security considerations necessary to support multi-operator access sharing. Besides multi-operator sharing scenarios, this project can be also appropriate for a network operator that wants to slice its access network to offer different services towards customers (e.g. for residential or enterprise markets) and wants to be able to manage it using a vertical organisation structure [31].

The SDN and NFV Work area at BBF focuses on the migration of SDN and NFV, and on the coexistence of physical and virtual elements in the broadband network. The former facilitates agile deployment of new customised distributed broadband services and applications. This, in turn, enables new revenues and provider differentiation while managing OpEx both in the access network and in single-tenant, and multi-tenant residential and business locations. Among other initiatives, the virtual business gateway working text (WT-328) specifies architecture and requirements for the migration of functionalities running on a business gateway to the network SP's infrastructure for enabling network-based features and services. Such migration is expected to simplify the deployment and management of the network and business services [31].

Broadband forum has also produced a white paper on wholesaling network access [32]: the open access principles with respect to the network infrastructure are translated into the support of wholesale services to enable downstream retail SPs to leverage and share the next-generation access investments.

(4) IEEE next-generation service overlay network (NGSON)

IEEE NGSON [33] is a reference framework as presented in Figure 5 for the control and delivery of composite services over diverse IP-based networks with QoS support. As a service overlay network, the NGSON acts as an intermediate layer to support the creation and deployment of composite services across different SPs and over heterogeneous network domains. With respect to prior self-organised networks, NGSON makes progress in the provision of services to end users with better quality of experience by customising and adapting composite services to the dynamic context of users, devices, services and networks while optimising network and computing resources consumption. Cloud technologies for virtualisation of network and computing resources are also expected to enforce this vision.

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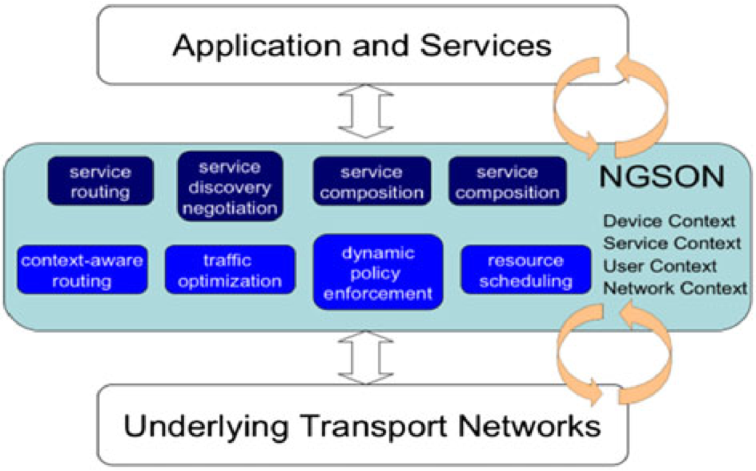

Figure 5. IEEE next-generation service overlay network (NGSON) framework.

The NGSON functional architecture includes service-related functions, transport-related functions, and operation and management functions. The service-related functions include functions that relate to the service control operations, that is, service registry, service discovery, service composition and service routing. The transport-related functions support service data delivery and include network context-aware routing, traffic optimisation, resource scheduling and interworking with underlying networks through dynamic policy enforcement. Operation and management functions are also supported such as service management, life cycle management and service assurance [34]. At service level control, NGSON manages the service information (i.e. functional description and QoS capabilities) published by third-party SPs collected in the service registry. As an end-user requests a service, the service discovery function use the service registry to select and negotiate an appropriate service instance that fulfils the user's demands on the functions and properties of the target service. Based on the binding information of the selected service instance, the service routing function conveys the service request to the selected service and invokes it for service. NGSON also orchestrates a series of the service interactions among one or more component services as specified in the service composition specification. NGSON integrates service-aware technologies supported by service oriented architecture [8] with service components deployed in heterogeneous systems while exploiting context information and adaptation features to dynamically (re-)accommodate service components and their interactions. For the service delivery, NGSON extracts the requirements for service- and transport-related QoS to enforce corresponding QoS control mechanisms across the underlying networks.

Software-defined networking [35] and NFV [36] initiatives can significantly contribute to achieve greater elasticity in NS deployments and accelerate a prominent innovation in NGSON service provisioning and delivery functions. In particular, SDN and NFV allow SPs to create a more powerful service logics based on NGSON that include VNFs handled as service components and participating to the service composition and orchestration process [37]. In this regard, initiatives in IEEE and in NGSON WG have been recently undertaken to identify potential new standards in SDN/NFV and related areas to be developed in IEEE.

4. EXISTING DOMAIN ORCHESTRATION FRAMEWORKS

This section provides an overview of existing single-domain and multi-domains orchestration frameworks. It covers heterogeneous cloud and networking domains, and each provided by a technology specific orchestration framework.

4.1. Resource domains and single-domain orchestrators

This section provides a brief analysis of a set of single-domain orchestrators and their respective resource domains.

(1) *OpenStack heat (OH)* [38] orchestrates cloud resources in the OpenStack framework, managing infrastructure object aggregations (i.e. stacks). The orchestration is performed considering creation, modification and deletion of aggregates of infrastructure objects like virtual machines, virtual volumes and virtual network elements. The infrastructure objects are described in template files, written using the heat orchestration template language, a declarative language in JavaScript object notation format describing all the objects in the aggregate and the relationships among them. Both orchestration and provisioning of infrastructure objects are performed by OH collaborating with other specific components (for compute resources), swift and cin-

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der (for storage resources) and neutron (for connectivity resources). The interface *I3* of OH is based on REST API, and it is used for the management of the stacks. The API, that is available through HTTP(S) protocol, implements both JavaScript object notation data serialisation formats. Software development kits are available for several programming language bindings like Java, Node.js, Python, Ruby, .NET and so on. OH collaborates with keystone (OpenStack project providing identity, token, catalogue and policy services) for authenticating and authorising cloud users.

(2) *Extensible service chain prototyping environment* [39] (ESCAPE) is a general prototyping framework that supports the development of the main functionalities of a service chaining architecture (i.e. VNF implementation, traffic steering, virtual network embedding and so on). EU FP7 *UNIFY* project [40] has proposed a novel SFC (service function chaining [41]) control plane architecture providing unified resource orchestration with joint network and software (compute and storage) virtualisation and programming. In the context of UNIFY, ESCAPE is a proof of concept prototype implementing the relevant parts of this architecture. In particular, it is a realisation of the UNIFY service programming and orchestration framework for both cloud and networking resources. ESCAPE can orchestrate (i) different technology resources directly using domain managers and adapters, (ii) abstract resources exposed by lower level UNIFY compatible domains. Domain managers and technology dependent adapters can be added in a modular way. In particular, the current version supports an SDN domain manager with POX adapter; a local Mininet (emulated network) domain manager with Mininet adapter, POX adapter and NETCONF adapter; an OpenStack domain manager with POX adapter and NETCONF adapter; and a UNIFY domain manager with REST adapter. On the one hand, the former domains are controlled via multiple control channels (e.g. OpenFlow for the networking resources and NETCONF for the compute resources), which can be considered as different realisations of interface *I5*. By this means, minimal (if any) extension is needed from the infrastructure side. On the other hand, the latest UNIFY domain manager implements interface *I3* via the UNIFY Sl-Or interface, which provides the capability of aggregating and managing resources in the form of NF-FG (network function forwarding graphs). This is the joint control API of UNIFY based on a novel resource abstraction combining cloud and networking resources. This approach requires additional components in the infrastructure domain to be able to *speak the UNIFY language*. For this purpose, a dedicated library has been implemented that enables the extension in several domains. Considering that Sl-Or interface has been designed to be recursively chainable, ESCAPE can act as an MdO as well, as explained in Section 4.2.

(3) *Ericsson Harmonizer* [42] aims at providing data centre interconnections crossing heterogeneous networking domains that differ in terms of switching technology (e.g. packet and optical), control system (e.g. SDN and legacy GMPLS) and vendors. The Ericsson Harmonizer provides dynamic and carrier grade E2E transport connectivity combining heterogeneity, elasticity and traffic engineering capabilities in each domain. The solution is based on a hierarchical architecture that guarantees transport resource optimisation minimising the interworking among the domains. An efficient method for abstraction of the resources allows to expose the E2E connectivity in terms of the service parameters while, at the same time, hiding technology specific details. The Harmonizer supports both standard and proprietary protocols as interface to communicate with the resource domains (interface I5). The supported standard interfaces are OpenFlow [43], Path Computation Element Communication Protocol (PCEP) [44] and Border Gateway Protocol—Link State (BGP—LS) [45]. The orchestrator supports both basic version of the protocols and related extensions proposed in the standardisation bodies. More specifically, considering the PCEP, the Harmonizer can manage the following extensions: hierarchical PCEP and stateful/instantiated PCEP.

As interface to communicate with the upper layer, for example, an MdO (interface I3), the Harmonizer supports a proprietary remote procedure call-based interface, but the migration to a NETCONF/YANG interface is planned. Possible candidates that can be used are the Control Orchestration Protocol interface defined in the Strauss project [46] and the UNIFY interface.

(4) *Redzinc VELOX equipment manager* [47] is a component of the VELOX framework that enables the reservation of (abstract) resources for the deployment of virtual path slices. It supports heterogeneous networking resources (i.e. IP/MPLS, SDN and EPC networks) by means of VELOX drivers. The interface I3 of VELOX is based on a TLV-based proprietary northbound API towards the VELOX MdO.

Table I summarises the resource domains considered so far in the E2E MANO framework.

The information in the table is organised as follows: resource domain, resource type, resource domain orchestrator(s) options; a brief description of the domain functionalities; and the options currently available for the implementation of interface I5.

In the case of networking resources, a first I5 implementation option relies on both (i) BGP—LS to expose network resource abstraction to domain orchestrator and

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Table I. Existing resource domains and domain orchestrators.

Resource domain		Managed resource type	Reference domain orchestrator	Domain properties and functionalities	Interface/5
Cloud domain	OpenStack		OpenStack heat ESCAPE,	It manages the lifecycle of computing resources (i.e. Virtual	OH: REST API through HTTP(S) protocol ESCAPE: Unify using OpenStack adapter
	Compute(Nova)	Computing		Machines-VSs) implementing functions for spawning,scheduling, and terminating VMs on demand	
	OpenStack block Storage (Cinder)	Block storage	OpenStack heat, ESCAPE	It provides persistent block storage (i.e. virtual Volumes) to VMs running in the cloud, managing the lifecycle and deleting virtual volumes)	OH: REST API through HTTP(S) protocol ESCAPE: Unify using OpenStack adapter
	OpenStack networking (Neutron)	Cloud networking	OpenStack Heat, ESCAPE	It provides network connectivity to the VMs running in the cloud, managing the entire lifecycle (creation, deletion, use and control) of all the involved networking objects (e.g. network trunks, subnets and virtual routers)	OH: REST API through HTTP(S) protocol ESCAPE: Unify using OpenStack adapter
Legacy packet domain		Networking	Harmoniser, VELOX EM	IP/MPLS domain composed of commercially available routers and Linux boxes. Support of Segment Routing, GMPLS control plane or command-line interface (CLI)	Harmoniser: PCEP and BGP-LS VELOX:TLV based proprietary Interface
SDN packet domain		Networking	ESCAPE, Harmoniser, VELOX EM	OpenFlow based network controllable by different OF controllers (i.e. Floodlight, POX, ODL and ONOS) and different OF versions (i.e. 1.0 and 1.3)	ESCAPE: Unify using POX/NETCONF adapters Harmoniser: OpenFlow1.3 VELOX: TLV-based proprietary Interface
Optical domain		Networking	Harmoniser	Optical domain composed of commercially available ROADMs and optical nodes controlled by Linux-based adapters. Supports flexi-grid	Harmoniser: PCEP and BGP-LS
EPC network domain		Networking	VELOX EM	EPC networks with policy and charging rule function (PCRF) exposed via Rx interface	VELOX:TLV based proprietary Interface

ESCAPE, extensible service chAin prototyping environment; SDN, software defined networking.

Trans. Emerging Tel. Tech. 2017;**28**:e3103.

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(ii) PCEP to enable the orchestrator to issue network provisioning requests to the domain controllers. In particular, BGP—LS provides a distribution mechanism for exchanging link-state data either representing the real-physical topology retrieved from routing protocol databases or an abstracted topology including specifically created virtual paths. PCEP, originally designed to provide communication in support of path computations, has been recently extended (i.e. active functionality) to allow the establishment of new NS.

The I5 interfaces will be used to validate the concepts of resource and service slicing on a Sandbox network, a pan-European test bed [2] whose data plane includes domains provided by 13 different partners from industry and academia.

4.2. Multi-domain orchestration candidates

(1) T-NOVA FP7 project [48] implements a NFV orchestration framework compliant with NFV MANO [5].

T-NOVA system builds a business layer or marketplace that facilitates commercial interactions among NFV business stakeholders, such as NF software developers, SPs and customers.

The T-NOVA system architecture is described in Figure 6. T-NOVA marketplace allows SPs to purchase VNFs from software developers in order to compose NS and offer them to their customers, including SLA management, accounting and billing features and the corresponding interfaces with T-NOVA NFV service orchestrator. The T-NOVA marketplace capabilities relevant to the realisation of the reference architectural framework in Figure 2 are as follows:

- A B2C interface based on the ETSI network service descriptor (NSD) information model, which can be mapped to interface I1 in Figure 2 for dispatching service requests to the MdO;
- Service and VNF catalogue that can be directly browsed by the customer;
- Structures to manage service instantiation and monitoring;
- SLA management by means of a component that facilitates SLA specification including definition of penalties or rewards and SLA evaluation.

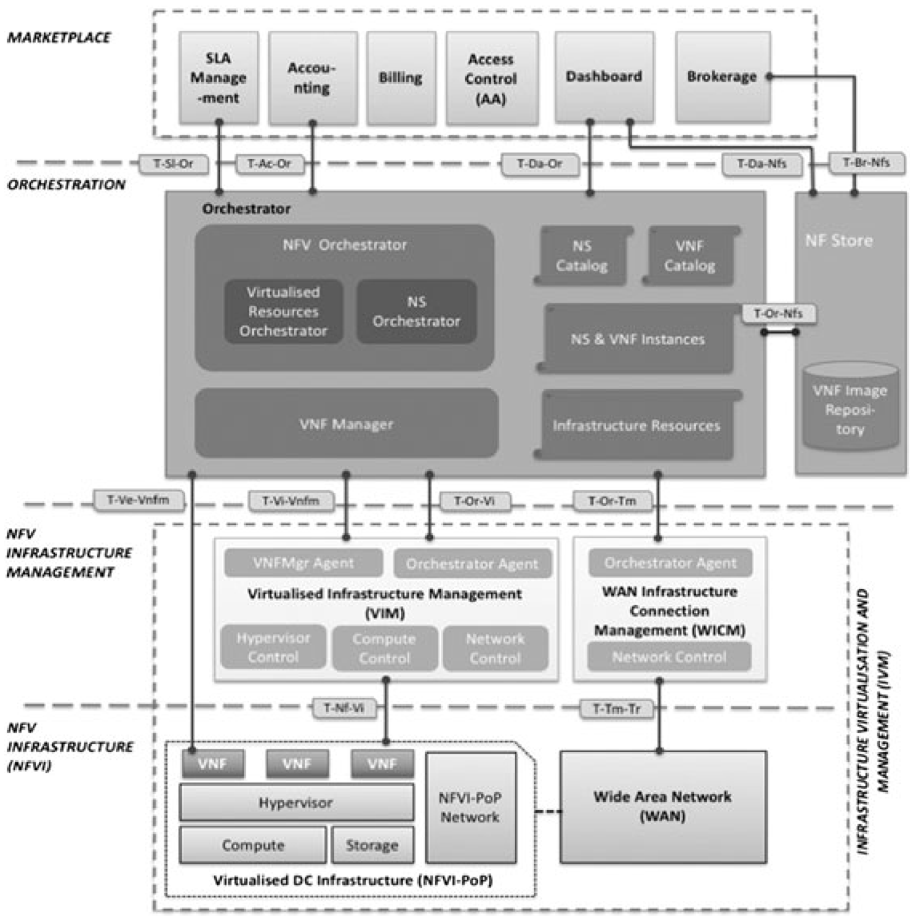

Figure 6. T-NOVA architecture.

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The T-NOVA orchestration layer main capabilities are as follows:

- NS/VNF management and NS/VNF catalogues management, exposing the catalogues to the marketplace;
- Management of networking and cloud resources for NS/VNF hosting;
- Service mapping: resources allocation to NSs;
- NS/VNF instantiation requests management: the T-NOVA orchestrator receives NS/VNF instantiation requests from the marketplace, executes the instantiation and manages the NS/VNF instances repository;
- NS/VNF monitoring: VM-based monitoring data from the lower VIM layer and map it to the corresponding NS/VNF instances.

(2) *ESCAPE* [39], as we have seen in Section 4.1, is a proof of concept prototype of the UNIFY FP7 project [40]. On the one hand, it can operate as a single-domain orchestrator for different technological domains. On the other hand, it is an MdO, thus strictly speaking, it implements the orchestration layer of the UNIFY architecture. However, a simple service layer interacting with clients and an infrastructure layer based on Mininet were also added.

The high-level components and their relations are shown in Figure 7. ESCAPE implements the main interface of UNIFY, namely, the Sl-Or, both at north and south. This enables multiple higher-level orchestrators on top of ESCAPE with corresponding virtual infrastructure views provided by virtualisers. Virtualisers implement the joint resource abstraction for cloud and networking resources proposed by UNIFY. ESCAPE itself constructs and works on a global domain view. The higher-level virtualiser configurations and VNF deployments are multiplexed in this element. The connection towards different infrastructure domains based on legacy or novel technologies are realised via dedicated adapter modules of ESCAPE. The most important one called UNIFY adapter implements the Sl-Or interface that is a candidate for interface I3.

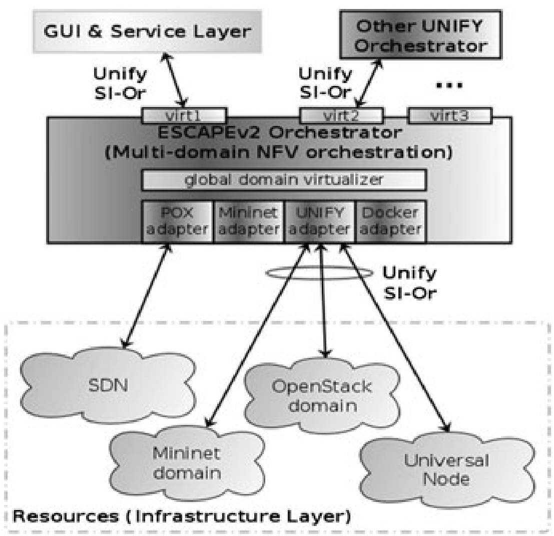

Figure 7. Extensible service chain prototyping environment (ESCAPE) architecture.

The most relevant capabilities provided by ESCAPE relevant to the realisation of the reference architectural framework in Figure 2 are as follows:

- A service layer, which receives service requests in form of service graphs according to ESCAPE interface U-Sl;
- Service mapping into domains based on abstract virtualiser/NFFG splitting;
- Network functions configuration and monitoring;
- Resource control and monitoring for the resource domains supported in the UNIFY framework.

(3) *ETICS FP7 project* [49] although is not proposing, an MdO is aimed at investigating technical solutions, which can assure E2E connectivity with guaranteed characteristics while proposing new business models favouring a more fair distribution of revenues among actors delivering E2E assured quality services. Internet allows to connect people and devices but in a service and quality agnostic manner. Quality of service (QoS) is controllable within each operator's network but is unpredictable across the Internet (congestion of peering points, lack of coordination amongst operators, tussles between content and application providers and operators). These results in unmet market expectations for (i) end-users to choose for different service quality levels and predictable quality of experience; (ii) network operators to differentiate their product offerings beyond their networks reach with better monetisation of their infrastructure; and (iii) content providers which are limited on their product offerings because of the lack of true E2E guarantees

By studying existing limitations and proposing jointly new business models and a flexible architecture capable to adapt to a QoS interconnection market gaining in maturity, ETICS has set-up important pillars for the future of the network interconnection and Internet challenging current practices for network interconnection and E2E QoS assurance.

ETICS defined a new type of product, called assured service quality (ASQ) path to (i) ensure an E2E coherent data flow treatment in multiple domains according to negotiated characteristics for the service (E2E and per-segment); (ii) agree on financial compensations to transport the traffic with defined level of assurance (availability, delay, packet loss rate and so on) and routing policies (e.g. geo-

Trans. Emerging Tel. Tech. 2017;**28**:e3103.

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graphic constraints) and (iii) complement existing best effort traffic exchanges to ensure an additional source of revenue.

Instead of re-architecting the Internet, ETICS acknowledged the technological diversity among operators and defined a new network service and business plane on top of the IP infrastructure. It enables the exchange of macro information on operators' quality capabilities and maintains the confidentiality on operators' infrastructures and their liberty to implement a preferred technology in their domain. Main building blocks have been implemented in a test-bed interconnecting five laboratories networks across France, Germany, Italy and Spain. It demonstrates the feasibility of the network service and business plane over realistic control and data planes comprising commercial routers from multiple vendors and representing a realistic use case.

Taking the opportunity of the multi-operator environment within the project, ETICS discussed possible business models that could make the ASQ concept viable, as well as how operators can exchange such products among them. Finally, ETICS pioneered and disseminated:

- the sending party network pays principle as main model for ASQ traffic exchanged between operators at the wholesale level
- additional business models at the retail level, for the end-users' application charging

An evolutionary collaboration framework capable to cope with an increasing trust among operators and the maturity of the ASQ market: from bilateral (eventually cascading) relations between operators as a bootstrapping scenario to alliances of operators in a more collaborative and dynamic market allowing global business and technical optimisations.

5. MULTI-DOMAIN ORCHESTRATOR ARCHITECTURE PROPOSAL

The analysis of the candidate software components presented in the previous section results in the identification and definition of a set of functional requirements that are expected to be fulfilled by the MdO. Figure 8 depicts the component-based MdO architecture, including its functional blocks and interfaces to local domain orchestrators and to MdO modules in other administrative domains. MdO modules are grouped in four major functional areas: exchange of information and control (EoIC), catalogues, exchange of functions (EoF) and exchange of resources (EoR).

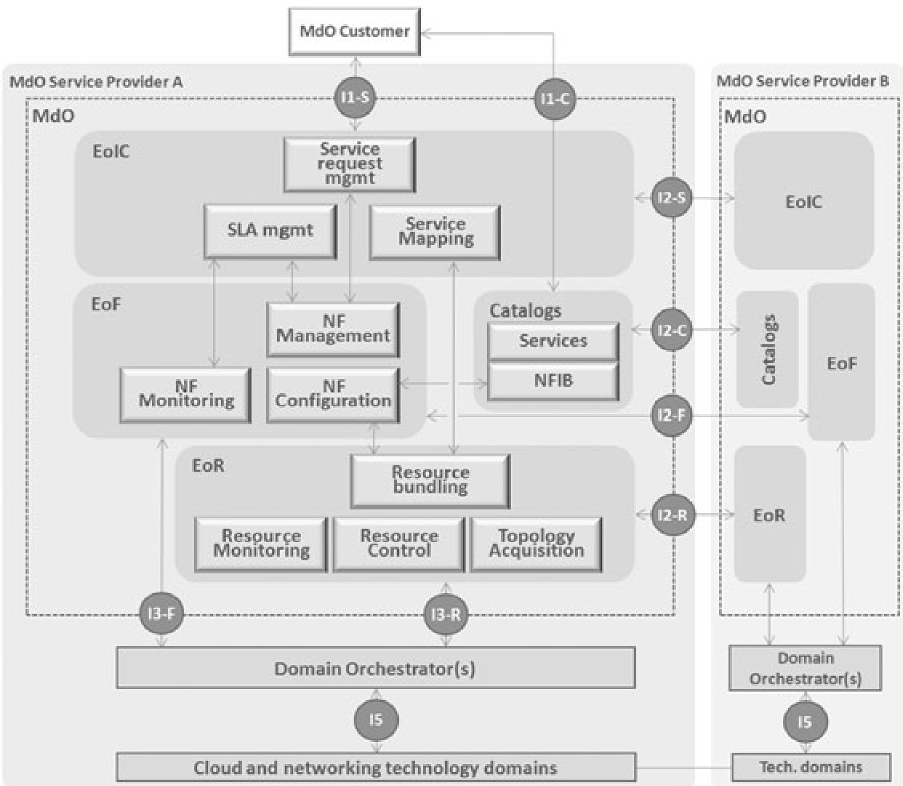

Figure 8. Multi-domain orchestration (MDO) functional architecture proposal.

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The following sections describe the role of the MdO modules, functions and interfaces per functional area. The collection of MANO functions represents an assembly of various plug-ins for different tasks. Further analysis and evaluation of the MdO functionalities are planed as part of the next-work stage in the context of the 5G Exchange project [2].

5.1. Exchange of information and control

The EoIC comprises functional modules that operate buyer-supplier operations at service level, both for customers on interface I1 and for MdOs belonging to other administrative domains on interface I2. Moreover, the EoIC includes the modules that perform service mapping to topologies of NFs, or service slices, and SLA management.

The service request management module exposes a northbound interface (I1-S) through which an MdO customer sends the initial request for services. It handles command and control functions to instantiate service slices. Such functions include requesting the instantiation, configuration and interconnection of NFs, as specified by the service graph created by the service mapping module, to other MdO modules in the EoF functional area. It is also responsible for providing SLA templates and SLA management instructions to the SLA management module in order to assess if the requested service SLA is fulfilled. Finally, it is also acknowledging the result of the service instantiation request to the MdO customer.

Interface I2-S is meant to perform among EoIC belonging to different MdOs (i.e. to other MdO SPs) operations similar to those described for I1-S. EoIC modules coordinate using interface I2-S when the instantiation of the E2E service involves multiple administrative domains. Both for I1-S and I2-S the service management operations imply the establishment of a business contract among the entities: customer to MdO service operator—interface I1-S and MdO operator to MdO operator—interface I2-S.

5.2. Catalogues

The modules exposing repositories of available services and available NFs to customers and to MdOs in other administrative domains are part of the catalogues functional area.

The service catalogue exposes available services to customers on interface I1-C and to other MdO service operators on interface I2-C. Services are described by service templates, which include a service graph (SG) of NFs, service SLA options, price information and deployment instructions. NFs could either be a basic service component, as described in the NF information base (NFIB), or recursively refer to services in the service catalogue. The pricing information of a service can be described as a function of the requirements on the overall graph (i.e. number and location of the end devices) and the functional and non-functional requirements of its component NFs. Service templates are advertised across MdOs in different administrative domains using interface I2-C. For instance, the MdO SP A in Figure 8 can request services and/or NFs offered by the MdO SP B and exposed over interface I2-C to provision a certain service to its customers.

Network function information base is a repository of NFs, including references to the abstract resources required to implement them, similar to the VNF catalogue in ETSI NFV specification [50]. It contains descriptors for available physical and virtual NFs, for example, ETSI NFV VNF descriptor and PNF descriptor. Such descriptors specify the interfaces that the NF exposes, dependencies with other NFs, infrastructure resource requirements as a function of NF expected performance (i.e. CPU requirements as a function of the average traffic rate), deployment artefacts, supported life cycle operations and offered NF SLA options (i.e. reliability SLAs/class).

5.3. Exchange of functions

The EoF functional area includes modules that deal with the instantiation, management, configuration and monitoring of NFs.

The NF management module performs life cycle management operations on individual NFs, which are listed in the NFIB, over interfaces I3-F and I2-F. Performing a life cycle operation on a given NF may imply reconfigurations of the abstract resources on which it is deployed and/or changes in its operational status (active, inactive, terminated and so on). Fault management tasks are also handled by this module, such as collecting alarms and notifications from the NF monitoring module. Fault management diagnoses failures in NFs and attempts to repair them. The NF management module provides support for service re-orchestration, performing operations like scaling in/out and migration on individual NFs over interface I3-F and interface I2-F for NFs deployed by other MdO.

During the service orchestration process, the NFs may be programmed and/or configured according to the given service specification and orchestration decisions. The NF configuration module derives the necessary NF configuration instructions from the service and NFIB and from the orchestration decisions conducted by the service mapping module in the EoIC functional area. Any updates of the specification of the service instance or of its implementation may also trigger the reconfiguration of several NFs. Service configuration instructions may apply to MdOs in other administrations over interface I2-F.

The NFs need to be monitored during their life cycle to assure that domains controlled by different MdO instances provide enough resources to satisfy the required service specification, for example, keeping under a given threshold the latency of a virtual path connecting two endpoints in different administrative domains. The SLA requested for a NF, which is agreed between the MdO and its customer throughout the whole service life cycle, specifies key quality indicators values together with a set of expected non-functional requirements, such as resource

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security, availability, reliability and rules of compliance. The NF monitoring module obtains the monitoring configuration instructions from the NF management module, implements the required probes at the NF level, collects key performance indicators (KPI) and determines key quality indicators compliance with the SLA expected by the customer.

5.4. Exchange of resources

The EoR modules perform resource orchestration, exposing resource slices to modules in EoIC and EoF. Four modules fall in this functional area, dealing with abstract resources and interfacing with underlying domain orchestrators for their realisation.

The resource topology acquisition module keeps an updated global view of the underlying infrastructure topology exposed by domain orchestrators using interface*I3-R* for its own domain and interface *I2-R* for resources in other administrative domains (collected by the respective EoR modules through the corresponding *I3-R* interface). The topology information provided by the domain orchestrator, or by EoR in other MdOs, is an abstract and limited view of the domain infrastructure resources. For instance, the global view of the infrastructure resources topology gathered by this module may only contain information on aggregates of resources by type, for example, cloud computing, networking, storage and geographical location. The topology information is consumed by the service mapping module in EoIC in order to derive a service deployment plan (what are the domain orchestrators chosen to deploy the requested service and what resources are required from them) and accurate pricing information.

The resource bundling module aggregates resources belonging to different resource domains, implementing resource slices that may include abstract resources exposed by multiple domain orchestrators, even belonging to other administrative domains. Figure 9 shows a resource slice that aggregates abstract resources belonging to two different infrastructures belonging to SP A and SP B. Each MdO is in charge of controlling the abstract resources in its own domain, while the resource bundling module provides a unified view of the aggregate to the upper layers. The resource bundling module of SP A coordinates with local (SP A) and remote (SP B) resource control modules to execute actions on the resource slice as a single entity and expose it to EoF modules of Service Provider A.

The resource control modules interface with the different underlying domain orchestrators in the same administrative domain to perform resource level control operations as required by NFs, for example, releasing infrastructure resources during the service shutdown process, scaling up/down computing resources and so on. These control operations are agnostic of the NF logic deployed on the resource slice. For instance, in order to perform a graceful shutdown of a given NF instance, NF management

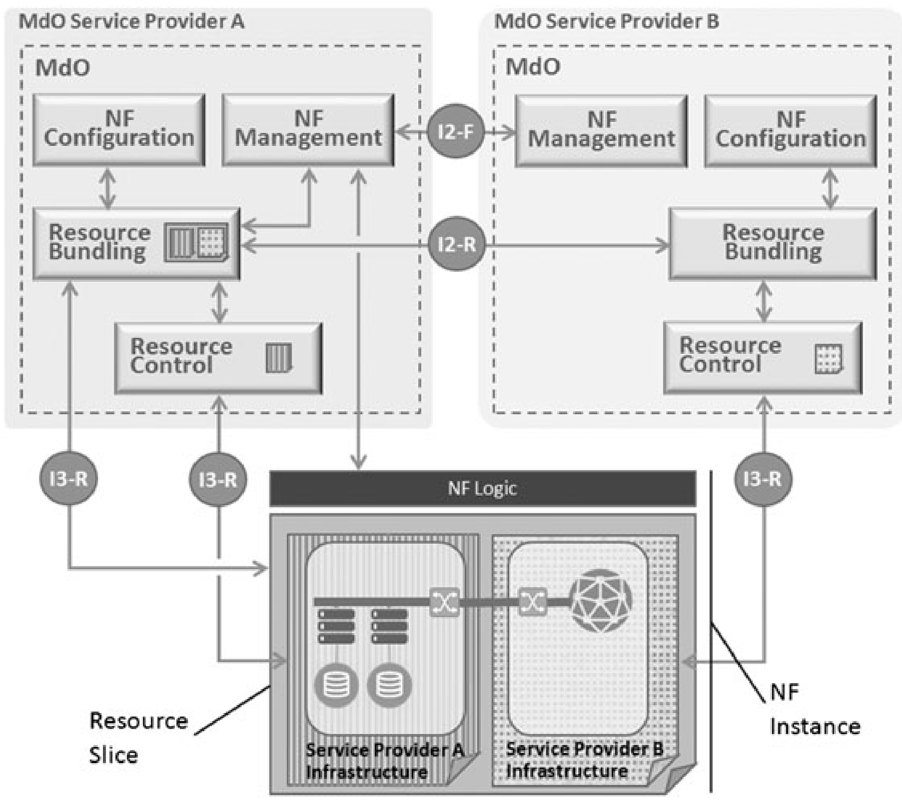

Figure 9. Resource bundle across administrative domains.

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modules send a shutdown signal to the NF logic via its management interface. After the NF logic stops, NF management requests the release of the resource slice to the resource bundling module. The first command stops the software implementing the NF, while the second one triggers the termination of underlying virtual infrastructure resources and/or the release of physical resources. The resource bundling module requests all the resource control modules involved in the resource slice to release their resources.

The resource monitoring module collects and analyses key parameters required for evaluating the status of the system considering both performance and availability of the resources. By relying on ad-hoc designed tasks, a monitoring function is in charge also to activate and coordinate specific measurement devices (probes) to retrieve the required information at resource level.

6. FUTURE WORK AND CONCLUSION

This article presented an architectural survey of key requirements, concepts and methods relevant to an E2E MANO for software defined infrastructures. We argue that usage of logical resources (connectivity, compute and storage) and resource and service slicing, resource orchestration, slice orchestration and service orchestration should be central architectural components of an E2E reference framework which exhibits the key functional and non-functional requirements applicable to 5G environments including: (i) flexibility, adaptability and scalability; (ii) operations awareness; and (iii) fixed-mobile convergence—requirements issued by industry operators association and standardisation bodies. Existing or under development domain orchestrators were mapped into the overall proposed E2E reference framework. A full description of the modules, functions and interfaces per functional area in the E2E reference framework is presented in this paper. The collection of E2E MANO functions represents an assembly of various plug-ins for different tasks and paving the way to its full realisation [2].

We plan to develop and evaluate a full MdO prototype for multi-domain orchestration and management of software defined infrastructures as far as uniform coordination and automated management of resources, network functions and services, fulfilling multi-domain requirements. We also plan to perform an in-depth testing and evaluation of the MdO prototype on the previous mentioned Sandbox network, distributed across different European Organizations [2].

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