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SPECIAL ISSUE ARTICLE

5GEx: Realizing a Europe wide Multi-domain Framework for Software Defined Infrastructures

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ABSTRACT

Market fragmentation has resulted in a multitude of network and cloud/data center operators, each focused on different countries, regions and technologies. This makes it difficult and costly to create infrastructure services spanning multiple domains, such as virtual connectivity or compute resources. In this article we discuss the goals and work being done within the 5GEx project in realizing a Europe-wide multi-domain platform. This platform aims at enabling cross-domain orchestration of services over multiple administrations or over multi-domain single administrations in the context of emerging 5G Networking. The 5GEx vision is based on introducing a unification via NFV/SDN compatible multi-domain orchestration for networks, clouds and services. We describe the motivation and 5GEx vision, the adopted architecture and the next steps in terms of implementation and experimentation.
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1. INTRODUCTION

This article presents the vision and the current achievements within the 5G Exchange (5GEx) European project. The goal of 5GEx is to realize an European wide multi-domain Anything as a Service (XaaS) platform. The platform will host future experimental 5G network service architectures based on technologies such as Network Function Virtualization (NFV) and Software Defined Networking (SDN). We present our detailed vision, architecture, point to the current achievements and identify the gaps that will be bridged within the project beyond the current state of art. To evaluate the efficacy of the architecture, the project presents an experimental plan to show the possibility of implementing various use cases over an European experimental architecture within a matter of minutes. We believe that this capability will soon become relevant to many other 5GPPP projects hoping to deploy and experiment with their solutions over a "real" large scale system, traversing multiple administrative domains [1].

Multi-domain Europe wide telecommunication infrastructures that can be easily deployed will benefit industries across the board. For example: the ability to deploy and pay for a Virtual Private Network (VPN) connecting all your hotel branches across Europe with the same ease as Internet shopping today will not only facilitate existing business operations but will open up the market to new user and newer innovative services. Ideally, a customer would expect a one-stop shop, where such infrastructure services could be purchased, which would in turn subcontract operators to provide the entire service.

To support a novel multi-domain composition of on demand services, the 5GEx project aims at bootstrapping such collaboration between telecommunications operators regarding 5G infrastructure services. Such services and associated resources will play a crucial role in making 5G happen as they provide the foundation of all cloud and networking services apart from the radio interface itself. Such an exchange, not only requires the removal of technical barriers, but also business ones.

The rest of the article is organized as follows. Section 2 provides an overview of key 5G challenges and introduces the vision of the 5GEx project. Based on this vision, a multi-domain orchestrator architecture is described in

Section 3. How this architecture will be evaluated is described in Section 4. Section 5 describes the expected outcome of 5GEx in terms of advances over current state of the art. Finally, Section 6 concludes this article.

2. 5G CHALLENGES AND 5GEX VISION

The communications infrastructure ecosystem is constrained in maximizing usage efficiency and revenue generation capability *stemming* from infrastructure. As a result, *possible Internet service offerings are accordingly wound down*. There are five fundamental challenges to the current Internet marketplace as the industry moves to 5G.

- Weak Service Agility: Traditionally, services are provided as vertically integrated applications (silos) with limited openness, limited interoperability, vendor lock-in, and weak flexibility. This hinders agile service customization, service enhancement, and *ability to seize* new markets. Sequential service design and roll-out is dominant today, with long lead times, high IT costs, and limited utility. This service agility challenge exists within a single network infrastructure domain *as well as* globally across the thousands autonomous systems which comprise the Internet and are run by different administrative domains. To overcome this issue, it is paramount to increase the level of resource accessibility and exploitation in the service delivery chain. The lack of multi-domain infrastructure service alignment and coordination that could speed up service delivery, enable new services, and serve unmet market needs is a key challenge for 5G.
- Over the Top (OTT): The OTT* challenge arises because networks and applications *don't go along* in terms of economic interest and technical structure. Application providers send traffic over the top of the Internet, across multiple networks to end users without any delivery *performance* guarantee.
- Inter-provider Automation: Telcos and application providers cannot efficiently automate resource and information exchange coordination between domains, leading to limited visibility of network conditions and subsequently sub-optimal traffic delivery, higher OPEX, *in the end loss of service creation opportunities*. In the Internet, telcos exchange control information based on the Border Gateway Protocol (BGP) and billing is often based on wholesale megabit/sec/month at the 95% percentile. SIP or SS7 are used to control mobile voice calls and there are wholesale billing functions to enable settlements, based on per minute billing *model*.
- Validated Standards: The absence of service tools and automation between providers is partly related to the absence of standards for inter-domain functions. European operators focusing over countries or regions, find it extremely difficult to create and trade world-wide services with *somehow guaranteed* quality of service or with a low OPEX component, due to the lack of automation and flexibility.
- Trading Limitation: The lack of a services business model means ad hoc, unstructured and unfair trading between the different suppliers. This has resulted in outdated business models, e.g., a walled garden approach with limited collaboration. Market fragmentation (where these models are localized) and time-consuming establishment (following lengthy negotiations) give rise to mutually harmful effects (e.g., hot-potato routing). These models tend to be bi-lateral so they do not scale well.

The vision of the 5GEx project is to create a European platform enabling *a time to market reduction for* various multi-domain services from the current expected time of 90 days to 90 mins (this is one of the key performance indicators, KPIs, identified by the 5GPPP†). The platform should be able to automatically instantiate and *host such services in a balanced way* across itself. Any end user, from a high-end hotel management chain to a individual user developing his own European wide innovative service platform, should be able to request and host services and resources with little more than a button click. Such a platform would significantly reduce both capital expenditure (CAPEX) *and* operational expenditure (OPEX) enabling *a significant cost reduction*.

In order to implement this vision, 5GEx will have to address some technical challenges. One example is the ability to make decisions to orchestrate service components across domains whose details are partially known at best. The challenge has two main parts: *(a)* the correct abstraction *level* at which the domain owners are willing to expose their domain details, *(b)* making efficient service hosting decisions based on the information exposed in the *abstracted data representation*. Some work has already been done on the latter problem in [2] and is expected to be further improved within this project. The 5GEx architecture, introduced in Section 3, is being designed to address this and other additional challenges.

2.1. Use cases

5GEx primarily envisions a set of use case families, covering multiple 5G infrastructure services and verticals. Three different use cases families have been identified:

*Over-the-top is a general term for a service that is utilized over a network that is not offered by that network operator. It is often referred to as "over-the-top" because these services ride on top of the service you already get and don't require any business or technology affiliations with your network operator.

†https://5g-ppp.eu/kpis/

(i) Connectivity, *(ii)* VNF-as-a-Service (VNFaaS), and, *(iii)* Slice-as-a-Service (SlaaS).

Connectivity is a use case family of wholesale connectivity services, including both Core and Value Added Connectivity Services (VACS) over multiple domains and/or providers, capable of supporting next-generation connectivity verticals, such as VPNs and broadcast services.

VNFaaS is a use case family where a customer has access to the VNFs that enable a particular kind of vertical. An example could be the set of VNFs that overall operate a virtual CDN for content delivery of cacheable or streaming content. In this example, an orchestration is needed of the live deployment of CDN virtual caches on different network infrastructure according to, e.g., the perceived real demands. Network slicing is another example of this family of use cases, where the physical infrastructure of one or more network domains is sliced into logical virtual partitions allowing an homogeneous control independently of the ownership of the underlying physical resources.

SlaaS is the widest use case family, building on top of the Connectivity and VNFaaS use case families with the additional requirement and complexity that the customer has full access to the virtual infrastructure resource, and can support additionally more demanding verticals. Infrastructure as a Service (IaaS) is an example use case of this family, in which the end user can request an IaaS service from its cloud service provider. The requested service is a mix of VMs (and associated) storage and connectivity between them from different providers.

2.2. State of the Art

Other efforts are in parallel proposing visions and requirements related multi-domain service operation for the 5G network as well. These include the 5G white papers issued by NGMN [3], 5GMF [4], NetWorld [5] and the IMT-2020 (5G) Promotion group [6]. In the NGMN [3] proposal the E2E Management and Orchestration (M&O) 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. It further states that, due to its various tasks, M&O entity will not be a monolithic piece of functionality. Rather it will be realized as a collection of modular functions that integrates advances made in different domains like Network Functions Virtualization (NFV) or Software Defined Networking (SDN) [7]. 5GMF [4] claims that network management in 5G will leverage on SDN/NFV and virtualization technologies to provide scalable and flexible network management. In their proposal the M&O maintains end-to-end virtualized networks that are instantiated on demand on 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. Requirements have also been issued by the NetWorld [5] to the M&O 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 lifecycle, and dynamic support of SLA through additions, re-allocations and re-configuration of network functions. In the proposal from the IMT-2020 (5G) Promotion Group [6], the network orchestration entity creates, manages and deletes the network slices as designed by the operator. The network orchestration entity applies the network resources according to the network slice template, and instantiates the virtualized network functions and their interfaces on the allocated network resources.

In addition to the white papers discussed above, also major network manufacturers have elaborated on the concepts of service and infrastructure slicing and orchestration. In [8], Huawei distinguishes between infrastructure slicing and network architecture slicing; the former meant to isolate portions of the infrastructure and flexibly assign network, compute and storage resources to service overlays; the latter to realize different performance targets issued by heterogeneous, sometimes incompatible, service requirements. This work will be used as a significant input to 5GEx. According to Ericsson [9], management entities will be automatically capable of coordinating cloud resources for complex dynamic systems that require resource access control and service quality management. From Nokia [10] 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.

Some work has been done in ETSI MANO group [11] with respect to orchestration of multiple administrative domains for the reference architecture. According to ETSI phase 1 the Network Functions Virtualization Orchestrator (NFVO) is responsible for Resource and service orchestration across Virtualized Infrastructure Managers (VIMS) along with their life cycle management. Further detailed discussions on the multi administrative part were shifted to phase 2 of the specifications. Currently, the Open Platform for NFV group (OPNFV)[‡] looks to realize the ETSI NFV architectural framework by integrating and extending existing open source projects, such as OpenStack, OpenDaylight, KVM and Open vSwitch, among others. The ITU-T study group 13 (SG13) [12] published a recommendation in 2015 on resource management in (multi) cloud computing: the recommendation presents general concepts of end-to-end resource management for cloud services, a vision for adoption of cloud resource management in a telecommunication-rich environment [13]. Other studies such as Broadband forum [14] and Metro ethernet forum [15] have also addressed orchestration architectures in

[‡] https://www.opnfv.org/

some detail but none has yet focused on the multi-domain orchestration aspects in any particular detail.

The NGSON standard [16] and SDN initiative[§] are working to include SDN and NFV technologies in order to achieve a more powerful multi-domain service composition and orchestration functions, including both application and virtualized network services while dynamically establishing data delivery paths across services [17]. However, neither operational solutions nor testbed deployments are foreseen yet, especially covering multiple network infrastructure technologies.

The requirements and the high level solutions proposed by all such relevant work have already been taken as important input to derive the challenges mentioned earlier. The project will continue to assess, improve, compare as well as when feasible incorporate any and all competent solutions as they are proposed.

3. ARCHITECTURE

5GEx will provide an innovative solution to the challenge of orchestrating services across multi-domain, multi-technology 5G networks. 5GEx means 5G Exchange, and it is an expansion of the IPX concept into 5G networking by enabling the automated provisioning of network services. The term "multiple domain" denotes either multiple network operators or sub-domains or logical slices within a single operator, and "multi-technology" pertains to the multiple technologies of layer 1 to layer 3 back-haul, and core network, combined and complemented with data centers that contain compute and storage resources that can be allocated to services.

3.1. 5GEx key architectural principles

To address our objectives, we need an integration framework capable of accommodating software-defined specifications of networks and of computational and storage resources, as well as all of the modules and components which provide the facilities and functions for the multi-domain operations and business interactions. The main ideas and assumptions of the 5GEx model are based around a three layer holistic techno-economic model. This model includes (A) Multi-operator wholesale relationships, (B) Multi-vendor interoperability and within that, the possibility for Multi-technology, and (C) Resources.

Regarding (A) we expect that a Customer will specify the "Service" they require via an electronic Service Manifest document to a provider. This provider will be the origin provider for that customer. This requires the origin provider to provide a Business-to-Business (B2B) or Business-to-Consumer (B2C) facility to the Customer. In order to deliver the "Service" the origin provider may be able to fulfill all the requirements himself, however for

[§] http://sdn.ieee.org/

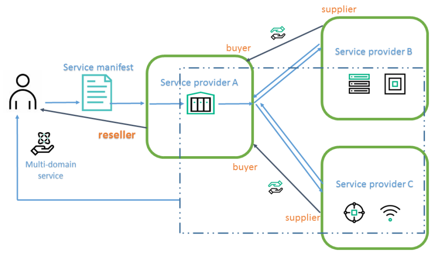

Figure 1. Business relationship models

fully cross-domain service deployments he will need to engage with third parties to procure network resources, or compute resources, or other third party capability, in order to fulfill the full Customer request. From a business / economics viewpoint, the origin provider will become a buyer of wholesale goods from a third party, who is in a fulfiller role. There will be a sub-contract relationship whereby the fulfiller can deliver the wholesale goods to the buyer. Due to the nature of the possible services that may be requested, the origin provider can initiate these buyer/fulfiller requests to many other third parties in order to construct the elements needed for a full service deployment. As any provider can interact with customers, the model can be recursive (i.e., cascading building upon existing trust and business relationships) and stakeholders can have both roles depending on the nature of the request.

The definition of suitable business relationship models supporting the multi-domain service offering is among the key objectives that 5GEx will address. At the current stage, we have performed an initial investigation, and analyzed the possible models along with the technical implications of each. The project has chosen to focus on a decentralized model, without the presence of a "brokering" business role acting as single front-end towards the service customers. We will go for a cascade model, where each provider can act as shop stop to customers. The entry-point provider will check if he can deliver the requested service by its own resources. In case this is not possible, he turns to one or more other providers (which in turn can look for the resources from other providers, creating the service cascade) which to him play the role of *resource suppliers*. The entry-point provider is hence the unique service reseller to the customer, but the service he delivers contain *resource slices* and/or sub-services coming from different providers. The reselling provider procures the resources by searching from a shared catalog, hinting which providers can offer the specific wanted resources. The catalog also exposes the resource pricing from the supplying to the front-end provider. Initially, for the sake of speeding up the first prototyping, the pricing model will be simplified, based on a static price list. The pricing will also include a SLA to properly ensure the availability of third party resources. Then the front-end provider will have

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its own pricing and SLA towards the end customer. In a later phase, more sophisticated pricing models can be considered. Figure 1 gives a graphical view of the above described interactions.

Regarding (B) we consider a model based on orchestrators and controllers. Each orchestrator will be deployed to manage different kinds of technology (core networks, data centers, etc) and will interact with a set of controllers that directly interact with the devices themselves. The controllers accept high-level commands from the orchestrators and each contains different device drivers depending on the technology of the underlying resources, and in this way 5GEx can address multi-technologies.

Resources (C) allocated to the customers are used to implement network services. On the one hand, network services consist of virtual networks that are exposed to the customers using potentially different level of abstractions. Virtual networks span between physical access points and VNFs end-to-end covering all types of networks from access to data centers. Network resources may be of any type, including fix and mobile access networks, IP/MPLS and/or optical transport networks with or without SDN control, OpenFlow controlled SDN networks and also mobile core networks. On the other hand, resources also cover the full set of compute options including virtual machines, storage, bare-metal hosts, or applications.

In order to overcome the traditional separation of network resources from compute and storage resources, 5GEx will be *(i)* fully software driven, *(ii)* allow the combination of networks and compute / storage within a service, *(iii)* define economic enabler components in the architecture and standard interfaces and SLAs that enable the automated trading and orchestration of networks and compute / storage in a service that comprises also an attractive market product.

Within a single domain, the modules and components will have specific well-defined functionality, interacting with the other modules and components using task specific APIs. For the inter-domain activity, there will be a set of these components that support various negotiation, trading and control operations between administrations. The inter-domain activities can be viewed with respect to two major configurations. The first is the operator to operator viewpoint, where the inter-domain activities are between entirely separate administrative domains that are operated by separate organizations, where only certain elements within each domain can interact with each other. The second is the in-operator viewpoint, where the inter-domain activities are within a single operator, and each of the domains may be a partition of or a logical domain within the organizational resources.

3.2. 5GEx framework

Figure 2 highlights the scope of 5GEx by presenting a logical inter-working architecture, showing not only entities but also the different APIs between them. At

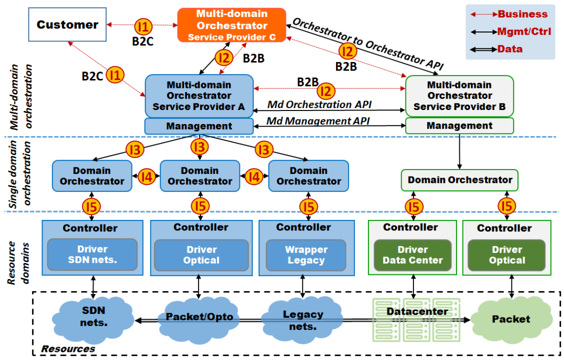

Figure 2. 5GEx architecture framework

the lower layer 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.

A Multi-domain Orchestrator (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 domains. The MdO interacts with other MdO-s via interface I2 APIs (business-to-business, B2B) to request and orchestrate resources and services across administrative domains. Finally the MdO exposes on interface I1 service specification APIs (Customer-to-Business, C2B) that allow business customers to specify their requirements for a service. The framework considers also MdO service providers, such as C in Figure 2, which does not own resource domains but operates a multi-domain orchestrator level to trade resources and services.

The 5GEx approach allows for a clear separation between the multi-domain elements and the local elements, while still ensuring the flexibility to handle both multi-technology and keeping local infrastructure details confidential. The multi-domain orchestrator is in charge of abstracting the underlying infrastructure before it announces what utility and functions the operator is capable of to its neighboring operators. Using such an inter-working architecture for multi-domain orchestration will make possible use-cases that are nowadays hard to tackle due to the interactions of multiple heterogeneous actors and technologies.

3.3. 5GEx functional model and building blocks

We now provide additional details about the 5GEx architecture, by extending the ETSI MANO NFV management and orchestration framework [18] to implement Network Service and resource orchestration across multiple administrative domains, which may belong to different infrastructure operators or service providers, hereby referred as "providers". There are two kinds of multi-provider interworking envisioned:

1. For multi provider Network Service orchestration, a multi domain orchestrator (MdO) offers Network Services by exposing an OSS/BSS – NFV Orchestrator (NFVO) interface to other multi domain orchestrators belonging to other providers.
2. For multi provider resource orchestration, a multi domain orchestrator presents a Virtual Infrastructure Manager (VIM)-like view and exposes an extended NFVO – VIM interface to other multi domain orchestrators.

Figure 3 shows the different functional blocks responsible for service orchestration (SO) and resource orchestration (RO) as currently being also considered by the ETSI Open Source MANO[¶] (OSM). Resource orchestration is provided by the NFV Management and Orchestration, together with Network Service orchestration. On the other hand, service orchestration, which among others is responsible for configuring parameters within Virtualized Network Functions (VNFs), e.g., via element managers, is implemented by an OSS/BSS system.

The functional blocks of the multi domain orchestrator are shown in Figure 4. The Multi Provider MdO 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 network services. Such functions include requesting the instantiation, configuration and interconnection of Network Functions (NFs). Interface I2-S is meant to perform similar operations but between MdOs of different 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.

Interfaces I3-R and I2-R are used to keep 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). The service catalog exposes available services to customers on interface I1-C and to other MdO service operators on interface I2-C. Resource orchestration related interfaces are broken up to I2-RC, I2-RT, I2-RMon to reflect resource control, resource topology and resource monitoring respectively. Furthermore, this notation is generalized and also used for interface I3 and I1. As illustrated by Figure 4, the (left) MdO offers interfaces, such as I2-S or I2-RC, to other MdO-s. In

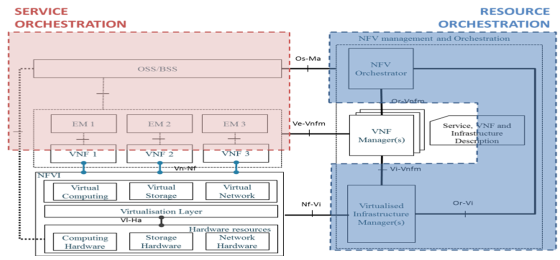

Figure 3. Service and resource orchestration

addition, the (left) MdO may also consume the same interfaces offered by other MdO-s, but for this case the corresponding arrows are not depicted for simplicity.

The multi provider NFVO implements service decomposition by mapping Network Service components on its current resource view. The resource view consists of the inter provider topology, potentially augmented with detailed provider internal topologies and resource locations and capabilities. At first, the multi provider NFVO selects providers that may need to be involved in delivering the Network Service. This decision is policy based or may be calculated based on the advertised inter provider topology and service catalogs on interface I2-RTadvertised (resource topology) and I2-Cadvertised (service catalogs). If needed, the multi provider NFVO may collect further details on charging, offered Network Services, resources and topology from selected providers and may establish bilateral (or direct) business relationship to parts of them if required and not yet done. Then, the Network Service components are mapped on the inter-provider, or optionally on more detailed topology, based on the information collected bilaterally from involved providers. Then, the multi provider NFVO sends the Network Service/resource requests to other providers using the I2-S/I2-RC interfaces.

The multi provider NFVO also implements policy enforcement points on behalf of its administrative domain to profile incoming requests received from other providers. Policy enforcement is needed to allow authorized providers to implement resource orchestration (I2-RC) and/or VNF lifecycle management (I2-F) in their own domain. Administrative domain wide policy enforcement is needed to enforce aggregate resource limits. To assist the multi provider NFVO in Network Service decomposition, there is a need to distribute topology and resource information in two ways:

1. Providers advertise inter provider topology and optionally also their service catalog information to a predefined group of providers. This is done via the I2-RTadvertised and I2-Cadvertise interface.
2. Providers exchange information on a bilateral basis in a consumer provider relation. This is done via the I2-RTbilateral interface.

Providers advertise their basic inter provider topologies to support an initial mapping of the multi provider NFVO

[¶] https://osm.etsi.org/

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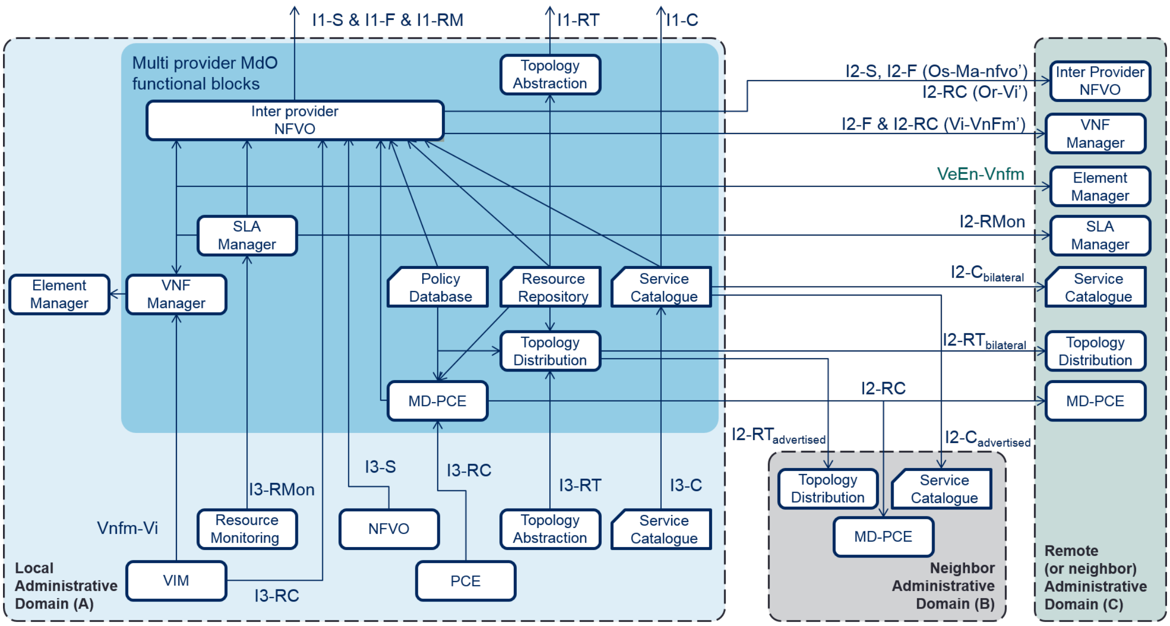

Figure 4. Functional model of multi domain orchestration

orchestration process. Optionally, depending on provider policies, the advertisements may also comprise of more detailed provider internal topology, IT resource capability and location (i.e. compute capacity attached to virtual nodes), as well as access information of the originator provider's orchestration interfaces. Such advertisements may get propagated hop-by-hop, e.g. by BGP-LS, in which case the propagation is subject to the policies of all intermediate providers.

In addition, providers establish bilateral communication between potentially remote, i.e. non-directly connected, inter provider orchestrators in a customer – provider relationship. This is needed to avoid 3rd party involvement in relaying bilateral business information. Furthermore, this also improves scalability by limiting the scope of detailed information distribution to specific providers. Such bilateral communication is supported for all inter provider interfaces.

As part of the Network Service decomposition, the multi provider NFVO must be able to initiate potentially traffic engineered multi-provider connectivity. To be able to manage connectivity constraints, the multi provider NFVO interworks with a potentially external PCE, which has the visibility of inter provider topology (MD-PCE). For example, the PCE may be a consumer of the topology information gathered to support the multi provider orchestration.

Typically, the connectivity data plane is configured by a control plane protocol, such as MP-BGP or PCEP. In this case, the multi provider NFVO programs the control plane to implement resource orchestration, e.g. for allocating and distributing labels on ENNI links. For example, the multi provider NFVO may use the PCEP protocol to ask an active stateful PCE to set up connectivity. Intermediate providers should verify that an incoming connectivity request has the corresponding orchestration state/policy that confirms that the connectivity request is accepted. Such an orchestration state may a priori exist or it may need to be established by the inter provider NFVO.

Alternatively, the inter provider NFVO may configure directly the connectivity data plane along the principles of ONF SDN for OpenFlow controlled administrative domains. In this case coordination for ENNI data plane resource orchestration must be implemented by the inter provider NFVO.

4. PLANNED EXPERIMENTAL EVALUATION

5GEx aims to experiment and validate the devised mechanisms and architecture of the multi-domain orchestrator. The Exchange concept is a set of multi-domain orchestrators dealing with information, control and function exchange for a set of multi-domain resources. Interface I2 in Figure 2, is the dialogue of the exchange. The concept is realized in 5GEx as a sandbox Exchange. In the project we will integrate a set of testbeds using tunnels, from five operators with a set of multi-domain orchestrators to implement the sandbox Exchange. The sandbox Exchange will be used to complement existing peering functions with additional buyer-fulfiller functions. In order to get experiences on wide ranging and large deployments the focus of the experimentation is to: *(i)* determine the feasibility of end-to-end multi-domain orchestration, *(ii)* assess that the solution is of carrier-grade quality, and, *(iii)* verify the pertinence of the technological choices. This experimentation and validation includes the testing of the designed orchestrator and the deployment on a multi-domain, multi-technology testbed to validate and assess the improvement of this system. The experiments will be measured against the various families of use-cases that 5GEx is analyzing: Connectivity, virtual CDN (vCDN) and Anything as a Service (XaaS).

Indeed, the 5GEx project aims at applying several use-cases to the sandbox Exchange in order to orchestrate, test, and prepare commercial deployments of new multi-domain services. Such facilities will allow 5GEx partners to experiment with life-size multi-domain network orchestration. The combination of partner's lab platforms and real networks will form the sandbox Exchange in order to experiment at a large scale with all developed 5GEx technologies. When production networks are not fully available or accessible, the lab platforms will reflect the architecture and engineering rules of production networks in order to provide a sandbox Exchange.

The experimental work that will be conducted will assess the 5GEx solutions and demonstrate the following:

- that the 5GEx system is resilient at a large scale. This demonstrates its scalability by implementing a demonstration across different types of underlying connectivity, computing, and storage resources, participating in a given scenario in the 5GEx platform;
- the ability of 5GEx to support multi-vendor eco-systems and to allow new companies to easily enter the market by producing components, or systems, which can be integrated with existing systems;
- the reduction in complexity and management costs through the introduction of autonomic management and orchestration capabilities.

The sandbox Exchange will act as the platform for the deployment of *(i)* all the software components of the multi-domain orchestrator onto servers, *(ii)* the various controllers needed onto servers, *(iii)* servers to host virtual machines for services, and *(iv)* the network resources for the network service elements. The combination of the software and hardware, in a multi-domain deployment, will provide the necessary results for 5GEx. We believe the "Sandbox mode" is a motivating concept which drives the innovation potential of the project forward and has the potential to overcome some of the challenges in establishing new services. A great challenge in the industry is that NSPs (Network Service Providers) often must collaborate among each other as well as with partner Online Service Providers (OSP) in order to introduce new products and services. However, there are many hurdles, both technical and business wise, and progress is often very slow. Operators are usually very reluctant to "touch" their networks so the sandbox concept could allow the preparation of some massive deployment or configuration by testing it on a network close to the reality without the risk to perform damage on real traffic. In particular, this serves to test new platform releases and verify that new release did not introduce new bugs.

5. EXPECTED ADVANCES

5GEx will analyze and define the multi-operator problem by looking at three main dimensions: The first dimension – intra-operator multi-domain scenarios – is the ambition to harmonize in an effective way interworking elements that have different technologies and/or vendors including 5G networks. The second dimension – multi-operator scenarios – is to extend to the multi-operator cooperation to provide an E2E interworking and servicing. In both these dimensions, 5GEx has the ambition to manage multi-domain heterogeneity according to SDN and NFV paradigms where network, compute and storage slicing and suitable virtualization must enable new service models (E2E service level). 5GEx will provide advances beyond the state of the art both in each level separately and in their harmonization in a solution that enables the new service models. The third dimension – business efficiency – is the proposition of new business models and economic mechanisms in the context of 5G for the provision of infrastructure (network, compute and storage) as a service, mitigating the inefficiencies of the current regime and enabling open markets and dynamic resource sharing.

5GEx will have to go beyond the current state of the art to: *(i)* achieve a 90-minute services setup, *(ii)* integrate monitoring instances in the developed multi-operator architecture (i.e., extending and coordinating the existing monitoring capabilities that nowadays are proprietary and restricted to specific domains), *(iii)* optimally solve (i.e., in terms of resource utilization and revenue) the embedding problem of service requests into the set of virtualized resources mapped into multiple operators domains while matching each service SLA requirements.

The 5GEx ambition is to provide harmonic interworking and orchestration among different infrastructure domains including cooperation with both legacy domains and domains implementing new technology in the 5G scenarios. To achieve this, 5GEx aims to extend the current SDN functionality beyond the scope of controlling simple connectivity resources to computation and storage, by creating and demonstrating new abstractions and associated interfaces. We envisage separate control and management planes of distributed nature, which will be able to better react to demand dynamics but also to changing service requirements.

5GEx also aims to build a platform that will be able to co-locate multiple instances of network functions on the same hardware, each running in one or more virtual machines, but also allow the physical distribution of functions in the network. Using this technology we intend

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to enable operators to dynamically instantiate, activate and (re)allocate resources and functions in a flexible and cost effective fashion in multi-domain operator environments.

Furthermore, 5GEx aims to extend existing solutions by developing a two-level orchestration functionality, which will be responsible for the deployment and operation of services across both multiple domains and administrative boundaries. Domain orchestrators will be responsible for coordinating the actions of multiple controllers corresponding to different resources types, whereas a multi-domain orchestrator will supervise the execution of end-to-end services, e.g., running on a distributed set of virtual machines across domains and operators.

The project will also develop an advanced monitoring system, capable of collecting and analyzing data from heterogeneous sources at the physical, virtual and service levels, but also from across administrative domains. By exposing this information to configuration and orchestration architecture components, potential service performance degradation and security breaches can be detected and acted upon with the aim to support secure end-to-end service provisioning.

6. CONCLUSIONS

The main goal of 5GEx is to enable cross-domain orchestration of services over multiple administrations or over multi-domain single administrations in the context of 5G Networking. Such orchestration will allow end-to-end network and service elements to mix in multi-vendor, heterogeneous technology and resource environments. In order to overcome the traditional separation of network resources from compute and storage resources, 5GEx will allow the seamless combination of networks with compute and storage across domains in a single service.

The major outcomes of 5GEx will be: *(i)* a proof-of-innovation multi-domain platform enabling multiple 5G use-cases and realistic scenarios that demonstrate the orchestration of complex end-to-end Infrastructure as a Service (IaaS) across multiple carriers, *(ii)* a set of open source software tools and extensions that can be utilized outside the scope of 5GEx, *(iii)* standardization and contributions pushing for the concepts learned during the development and experimentation of the project, and *(iv)* greatly impacting the telecom and IT market segments by stimulating the industry stakeholders' engagement to actively adopt and extend 5GEx open solutions.

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