5GOS: Demonstrating multi-domain orchestration of end-to-end virtual RAN services

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***Abstract*—Despite recent progress in orchestration of Virtual Network Functions (VNFs) and in multi-technology SDN connectivity, the automated provisioning of end-to-end network services composed of virtual functions deployed across distributed compute locations remains an open challenge. This problem is especially relevant to support the deployment of future 5G networks, comprising virtual access and core network functions connected through a potentially multi-domain transport network. In this paper we present and demonstrate the 5GOS, a lightweight end-to-end orchestration framework that enables the automated provisioning of virtual radio access network services. Using an experimental multi-domain testbed we demonstrate that the 5GOS can provision multi-domain virtual Wi-Fi and LTE services in less than three minutes.**

***Index Terms*—Orchestration, multi-domain, cellular network virtualization, SDN, 5G**

I. Introduction

5G networks have been designed with a flexible architecture able to address a plurality of end-user and vertical use cases. This heterogeneity though brings challenges in terms of efficient network deployment and operation. In this regard the ETSI Zero Touch Service Management group [1] is developing solutions to automate the operational processes and tasks of 5G networks, including delivery, deployment, configuration, assurance and optimization.

To achieve the target level of automation it is key to leverage the principles of Network Functions Virtualization (NFV) and Software Defined Networking (SDN), which have been adopted by 3GPP when designing the 5G architecture [2]. Thus, 3GPP defines a *slice* as a concatenation of *network services*, which are in turn composed by a concatenation of physical or virtual network functions (VNFs). VNFs can be used to dynamically instantiate base stations (gNBs), composed of Remote Units (RUs), Distributed Units (DUs) and Centralized Units (CUs), or the core network, which comprises a set of software components communicating through a service based interface [2].

In order to support the dynamic instantiation of the VNFs composing a network service, 5G operators are expected to deploy a distributed compute infrastructure, which may include edge computing facilities, for example collocated with base station or transport nodes, small data-centers collocated with Central Offices (COs), or metro level data-centers [4]. ETSI NFV MANO [5] defines the architectural framework that supports the deployment of VNFs in a given compute location, but no standard solutions exist to deploy network services with VNFs spanning distributed MANO domains. In fact, a 5G operator may not directly own the network infrastructure connecting distributed compute facilities, but rather lease connectivity from a transport provider, which complicates the overall end-to-end service management process.

The 5G-PICTURE project [6] defines new management solutions to orchestrate 5G network services across multi-tenant compute and network infrastructures. The main contribution of this paper is the design and experimental evaluation of the 5GOS, a lightweight management framework that can orchestrate end-to-end 5G services across distributed RAN, compute and transport domains. In particular, leveraging a multi-domain testbed, we demonstrate that the 5GOS can provision end-to-end virtual Wi-Fi and LTE services spanning four domains in different European countries in less than three minutes. To the best of our knowledge this is the first work in the state of the art to provide an experimental benchmark of the deployment time of an end-to-end RAN service across a multi-domain compute and network infrastructure.

This paper is organized as follows. Section III describes the design of the 5GOS and its main interfaces. Section IV describes the implementation of a 5GOS prototype that uses a multi-domain testbed, along with the virtual Wi-Fi and LTE services used in our evaluation. Section V describes the results of our performance evaluation, where we benchmark the provisioning times of the aforementioned services. Finally, Section VI concludes the paper.

II. Related Work

Multi-domain and multi-technology orchestration for integrated network and compute infrastructures has received a lot of attention within the 5GPPP community in Europe. The 5Gex project [25] extends the NFV MANO framework to enable orchestration of multi-operator network services proposing a multi-domain orchestrator (MdO). Operators host an MdO that can gather topology and network services offered by other operators, while serving end customer requests. In a fashion similar to BGP, operators define through bilateral agreements what services to disclose to other operators. The 5G-Crosshaul project [10] proposes a multi-tenant SDN/NFV architecture for transport networks that enables an operator to compose dynamic slices that serve tenant requests. The

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dynamic slices created in 5G-Crosshaul are composed by ETSI NFV network services and by virtual network infrastructures, instantiated as a service, that can be directly controlled by the tenant's control plane. The 5GOS proposed in this paper draws on some of the design principles put forward by the 5Gex and 5G-Crosshaul projects. In particular, the 5GOS features a lightweight MDO, which is however applied to a single operator orchestrating network services through distributed network and MANO technology domains. In addition, like in 5G-Crosshaul, the 5GOS can also control a virtual network infrastructure provisioned as a service by a transit provider. The previous works introduce the general principles of the 5Gex and 5G-Crosshaul architectures, but, unlike this paper, do not include an experimental performance evaluation.

The work in [26] presents the Adrenaline testbed that features compute, optical and packet switching domains. Leveraging a custom SDN/NFV platform the authors experimentally demonstrate the provisioning of virtual backhaul and mobile core services, by means of instantiating a virtual EPC on a compute domain and setting up MPLS and optical connections on demand through the packet and optical backhaul network. We extend the work in [26] by demonstrating how the presented 5GOS can orchestrate end-to-end virtual Wi-Fi and LTE services over four different network and compute domains.

The ONF has proposed the Open Disaggregated Transport Network (ODTN) for data center interconnect. ODTN exposes the visibility and control of a multi-vendor optical domain through the Transport API (TAPI) [15]. The 5GOS presented in this paper is designed to be able to incorporate different technology domains, hence an ONF ODTN domain could be integrated within the hierarchical control plane architecture introduced in Section III.

Within the RAN domain, several orchestration platforms have recently been proposed, such as FlexRAN [16] or 5GEmpower [17], which manage open source virtual RAN implementations like OpenAirInterface [21]. The 5GOS can accommodate these platforms in two ways. First, the platform components can be deployed through an underlying MANO domain managed by the 5GOS. Second, once up and running, FlexRAN or 5GEmpower can be integrated with the 5GOS as a separate management domain that supports RAN slicing in a native way. The latter model is the equivalent to the one we use in this paper to deploy the Wi-Fi service.

Finally, the Wide Area Network (WAN) component of the 5GOS is based on the multi-technology hierarchical control plane proposed by the 5G-XHaul project in [9] and [13]. The work in this paper integrates this hierarchical WAN control plane with MANO compute domains in order to be able to provision end-to-end services integrating network and compute resources, while providing a detailed experimental evaluation of service provisioning times.

III. 5GOS Architecture

A. Overall Architecture

The generic architecture of the 5GOS was first proposed in [7] and is depicted in Figure 1. The goal of the 5GOS is to orchestrate *network services* across different *domains*, where a network service is understood as a concatenation of virtual or physical network functions. In the context of the 5GOS, a domain is understood as a self-contained set of compute and network resources including an NFV infrastructure, to provision VNFs over compute resources, one or more domain SDN controllers to control the network resources, and a domain orchestrator that allows to deploy network services that make use of network and compute resources within the boundaries of the domain. The goal of the 5GOS is to provision end-to-end services across domains, hence its central component is the *Multi-Domain Orchestrator* (MDO) that composes end-to-end services across domains interacting with each of the domain-level orchestrators. A service management platform, including a repository and related service management tools, interfaces with the MDO one one side and with the operator business technology stack on the other side. The generic 5GOS architecture supports multiple instantiations featuring different actors in the telecom ecosystem. For example a Mobile Network Operator (MNO) could compose resources from different infrastructure operators, offer network services to its tenants, i.e. Mobile Virtual Network Operators (MVNOs), which would then offer connectivity services to end-users.

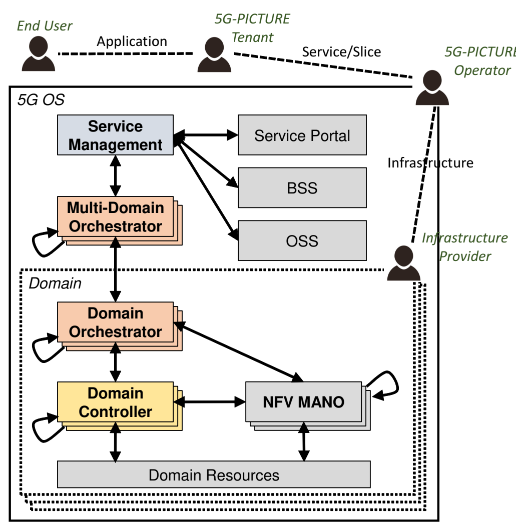


Fig. 1. 5GOS generic architecture

Whereas Figure 1 describes a generic architecture, Figure 2 presents a 5GOS instantiation in the context of 5G mobile network infrastructures, to support the provisioning of end-to-end virtual Radio Access Network (RAN) services. At the top of Figure 2 we can see the MDO with three different types of interfaces, which connect to five different technology domains:

- **MDO - RAN** interface: This interface connects the MDO to a *RAN Controller*, which is a control plane entity supporting the provisioning of virtualized Wi-Fi or mobile connectivity functions over Wi-Fi Access Points (APs), and eNB/gNB base stations or small cells supporting this functionality. In the case of Wi-Fi, virtual SSIDs can be used to provision a dedicated connectivity service.

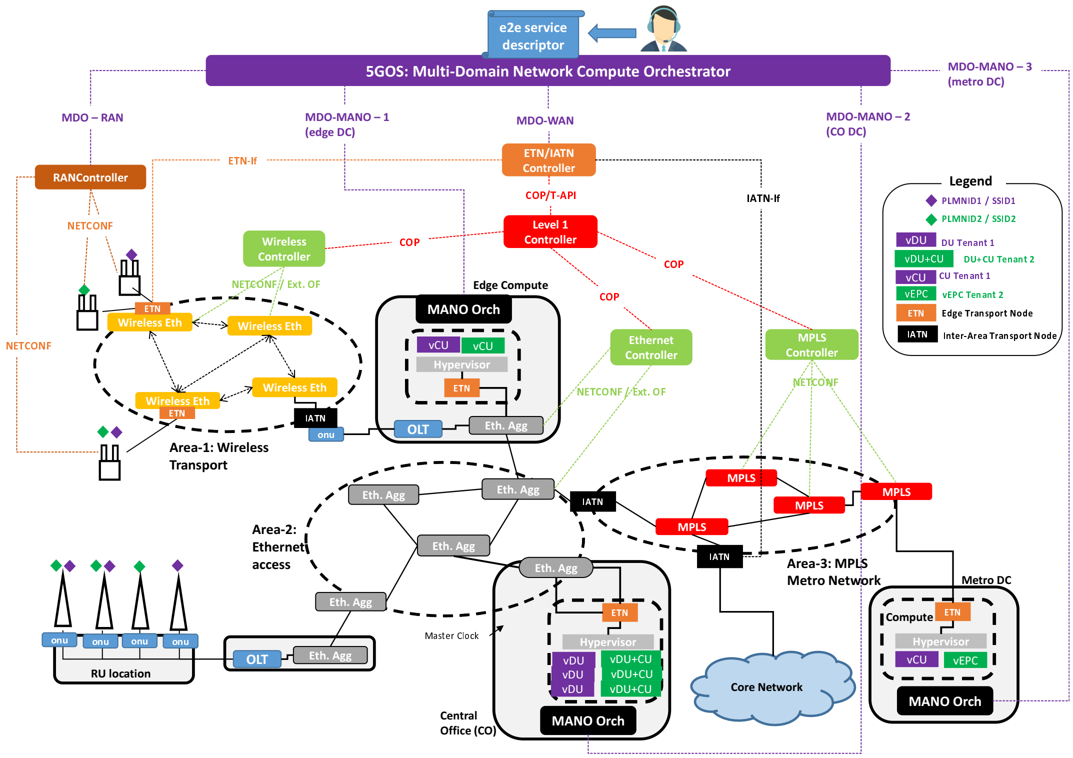


Fig. 2. 5GOS instantiation to orchestrate e2e virtual RAN services

In the case of a 3GPP network the Multi-Operator Core Network (MOCN) technique can be used for the same purpose. The interested reader is referred to [12] for a detailed description of this component.

- **MDO - WAN** interface: This interface connects the MDO to a hierarchical SDN control plane that allows to provision connectivity services across multiple SDN controlled domains, e.g. *Area-1*, *Area-2* and *Area-3* in Figure 2. In Section III-B we provide a detailed description of this hierarchical control plane.
- **MDO - MANO** interface: This interface connects the MDO to a self-contained compute domain. It is assumed that compute domains represent an NFV infrastructure, but no explicit assumption is made on the orchestrator technology being used therein, i.e. one compute domain could use OSM as orchestrator and another one ONAP [18]. In Figure 2 we can see three different MDO-MANO interfaces, which respectively interface with an edge Data Center (DC), a Central Office DC, and a metro DC.

By means of the previous interfaces the MDO is capable of provisioning end-to-end virtual RAN services that are composed of virtual access and core network functions instantiated across the distributed compute facilities and connected through the Wide Area Network (WAN). Multiple RAN network services can be instantiated using this architecture. For example we can see in Figure 2 two different tenants with their respective VNFs colored green and purple. The first tenant deploys a cellular network service where several virtual Distributed Units (DU) are placed in the Central Office and a single virtual Centralized Unit (CU) is placed in the metro DC. Instead, the second tenant deploys a cellular network service where various virtual integrated DU+CU functions are deployed in the Central Office, and a single virtual core (vEPC) is deployed in the metro DC. The previous description applies to the macro-cell functions. The tenants' network services also include a connectivity service over Small Cells or Wi-Fi APs, where in this case virtual SSIDs or MOCN identifiers are configured in the physical network devices (Small Cells or APs) through the MDO-RAN interface. In addition a virtual CU function is deployed at the edge DC controlling the Small Cells for a given tenant.

The goal of the 5GOS is to automate the provisioning of the aforementioned network services, including both the deployment of the required functions in each compute domain, as well as the required multi-domain connectivity between compute domains. We describe in the next section how the multi-domain connectivity across the WAN is achieved.

B. MDO-WAN: Hierarchical SDN Control Plane

In order to interconnect distributed compute facilitates the 5GOS leverages the hierarchical SDN control plane for transport networks proposed by the 5G-XHaul project in [9].

This hierarchical SDN architecture features three different entities in the data-plane. The *Transport Nodes* (TNs) that are pure forwarding devices grouped in technology-specific areas, e.g. wireless backhaul, Ethernet or MPLS. Forwarding within said areas is controlled by a *Level-0 controller*, i.e. the green boxes in Figure 2. Different technology areas are interconnected through the *InterArea Transport Nodes* (IATN), depicted in black in Figure 2. Finally, RAN or compute domains interface with the transport network areas through *Edge Transport Nodes* (ETNs), depicted in orange in Figure 2. A *Label Switched Path* (LSP) forwarding model is assumed, where the L0 controllers program the LSPs in each domain and IATN nodes bind LSPs between domains. ETNs receive the traffic coming from the RAN or compute domains tagged with an end-to-end service identifier, e.g. an inner VLAN or VXLAN tag, and bind the received frames to the LSP of the immediately connected technology area that interconnects to the ETN hosting the target remote VNF. A layer 2 encapsulation based on Provider Backbone Bridging (PBB) is used in the ETN to encapsulate incoming packets. The LSP identifier is included in the outer PBB header, e.g. using an outer VLAN tag as LSP identifier.

In the control plane the MDO issues an end-to-end connectivity request through the MDO-WAN interface to the *ETN/IATN Controller* function requesting to interconnect two distributed compute or RAN domains. The ETN/IATN Controller resolves the ETN addresses involved in the communication and requests an end-to-end connection to the *L1 controller*. The L1 Controller determines the areas involved in the end-to-end communication and subsequently issues partial connectivity requests to each of the involved L0 Controllers. Once all the per-domain LSPs are setup the ETN/IATN Controller programs the necessary bindings in the ETN and IATN functions. The Control Orchestration Protocol (COP) [14] is used to interface the aforementioned control plane entities.

A detailed description and evaluation of this hierarchical control plane architecture can be found in [13].

C. Dynamic Slicing Engine for Transit Providers

The architecture described in Figure 2 assumes that the operator deploying the 5GOS has a control interface to all the domains involved in the end-to-end service provisioning, e.g. the COP interface between the L1 Controller and all the L0 Controllers. However, in practice transport connectivity services are often leased from a transport provider that only offers data-plane endpoints under a given SLA, and does not provide a control plane interface to manage tenant flows across the transit domain. Hence, as part of the 5GOS architecture we propose a *Dynamic Slicing Engine* (DSE) technology that allows transit providers to dynamically instantiate connectivity slices offering an openflow control plane interface to their tenants. Different slices can be prioritized using openflow priorities and rate limiters. The DSE technology is integrated with the 5GOS MDO-WAN hierarchical control plane through the COP interface between the L0 and the L1 controller.

The DSE is based on the concept of Topology Mapping, which involves describing slices, network elements or services as a topology graph of resource providers. Thus, resource maps are created between overlay topologies that request resources and one or more underlay topologies that provide resources, subject to constraints. The DSE utilises two fundamental concepts: *tactics* and *strategies*. Tactics are modular units that represent resource availability and consumption. Tactics can be composed and layered to define connectivity slices and create end-to-end network models by performing topology mapping. Strategies are powerful decision engines that resolve ambiguities in how the network is configured, e.g. answering questions such as “What path should this traffic take?” or “What VLAN should I use?”. In Section V we benchmark the time required by the DSE to instantiate a connectivity slice.

D. Scalability and Troubleshooting

The scalability of the 5GOS is constrained by the design of the hierarchical transport network, where individual transport connections are used between each pair of domains connected within a given service, and thus the number of connections can grow with the square of the number of domains in a given service. However, the connectivity provisioning times reported in section V guarantee that practical services can be deployed in a matter of minutes. Another potential scalability bottleneck is the use of VLAN tags in each domain to signal transport connections, which could be addressed using double tagging.

Finally, bringing under a common umbrella the management of heterogeneous technology domains, as proposed by 5GOS, greatly simplifies end-to-end service troubleshooting as impairments in different domains can be correlated.

IV. 5GOS IMPLEMENTATION

A. Multi-domain Testbed design

In order to enable the functional and performance validation of the 5GOS architecture we deploy an experimental multi-domain testbed joining the laboratory facilities of the four institutions supporting the authors of this paper. This integrated multi-domain testbed is depicted in Figure 3, and is composed of four distinct domains that we describe next.

The *I2CAT* domain is located in Barcelona, Spain. It is depicted in the upper left corner of Figure 3 and features two technology domains. First, four wireless devices supporting virtual access and backhaul Wi-Fi services, implementing the SWAM software data-plane described in [8]. Second, a packet switching domain featuring openflow compliant devices. Several control plane functions are deployed as Virtual Machines (VMs) including a RAN Controller function supporting the provisioning of multi-tenant virtual Wi-Fi services and interfacing with the MDO through the MDO-RAN interface. A Level 0 controller provisioning LSPs across the openflow switching devices, and a Level 1 controller processing end-to-end path requests from the MDO. An ETN function interfacing the wireless access domain with the packet switching domain, and an IATN function interfacing the I2CAT domain with a transit provider are also deployed as VMs with software bridges.

The *UTH* domain is located in Volos, Greece. It is depicted in the lower left corner of Figure 3 and features a MANO domain supporting OpenStack based virtualization and OSM based orchestration. It also features a Software Defined Radio (SDR) acting as a cellular Remote Radio Head (RRH), and several openflow switching devices operating under a

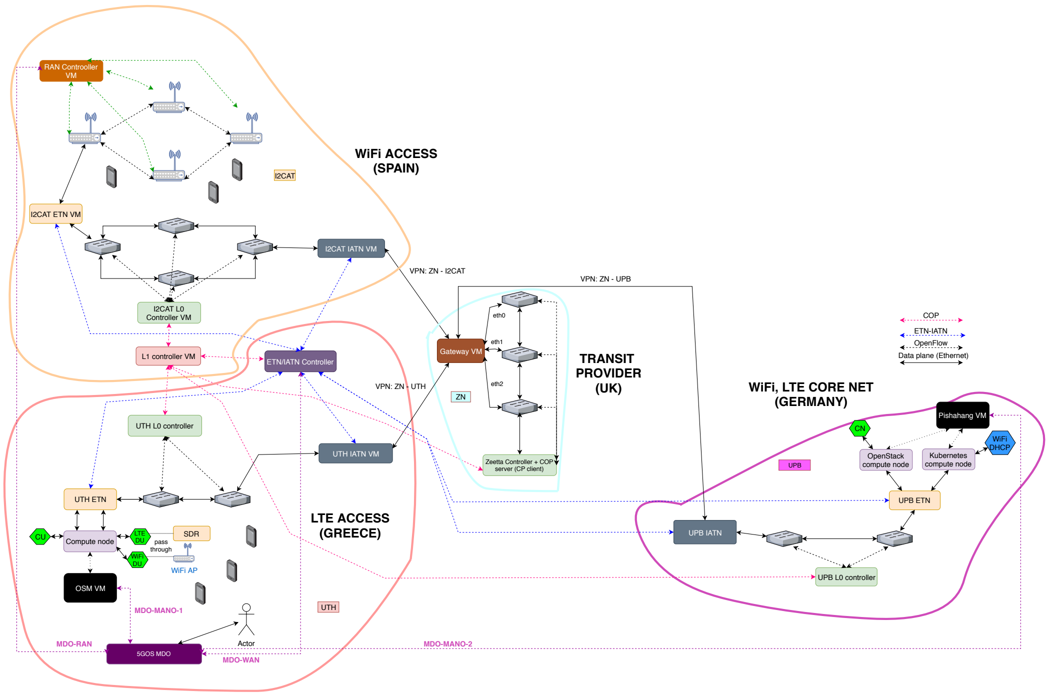


Fig. 3. Testbed set up to test multi-domain e2e RAN service provisioning

virtualised L0 controller. A virtual ETN function is used to interface the compute domain with the packet switching devices, and a virtual IATN function to interface with the transit provider. The UTH domain also hosts a VM implementing the ETN/IATN Controller supporting the MDO-WAN interface.

The *UPB* domain is located in Paddeborn, Germany. It is depicted on the right side of Figure 3 and features openflow compliant switching devices operating under a Level 0 controller. In addition, it features a compute domain supporting container based virtualization using Kubernetes and VM based virtualization using OpenStack. The Pishahang orchestrator [11] is used to jointly orchestrate containers and VMs.

The *ZN* domain is located in Bristol, UK. It is depicted in the middle of Figure 3 and features three EdgeCore 4610-54p devices and a Level 0 controller implementing the Dynamic Slicing Engine technology described in Section III-C. The ZN domain acts as transit provider interconnecting all the other domains through layer 2 VPN tunnels that connect to each of the per-domain IATN functions.

The MDO function is also virtualized and is hosted in the UTH domain. The MDO implements the following interfaces: i) an MDO-RAN interface against the RAN Controller function in the I2CAT domain, ii) an MDO-WAN interface against the ETN/IATN Controller function in the UTH domain, iii) an MDO-MANO-1 interface against the OSM orchestrator in the UTH domain, and iv) an MDO-MANO-2 interface against the Pishahang orchestrator in the UPB domain. All the implemented MDO interfaces are RESTful and the interested reader is referred to [19] for a detailed definition.

B. Target e2e RAN services

The multi-domain testbed described in the previous section is used to validate the functionality of the 5GOS, and to benchmark the time required to provision on-demand end-to-end RAN network services. Notice that this KPI is aligned with the overarching KPIs laid out by the 5GPPP [20], in particular with the goal of *reducing service provisioning time from 90 hours to 90 minutes*. In order to perform this validation we define two test network services, which we describe next.

First, we consider a *virtual LTE service* that consists of a virtual eNB dynamically instantiated in the UTH domain along with an Evolved Packet Core (EPC) deployed in the UPB domain. The eNB and the EPC are connected through the UTH, ZN and UPB transport domains through the establishment of a dynamic end-to-end connection. Two VNFs are involved in this network service, namely an OpenAirInterface (OAI) [21] eNB image packaged in a VM and deployed in the UTH MANO domain, and an OAI vEPC component packaged as a VM and deployed in the UPB MANO domain. The MDO provisions the virtual LTE service by triggering the eNB deployment through the MDO-MANO-1 interface, the vEPC through the MDO-MANO-2 interface, and the end-to-end connectivity through the MDO-WAN interface.

Second, we consider a *virtual Wi-Fi service* that consists of a SWAM service deployed over the wireless nodes in the I2CAT domain, and a core network component packaged as a container including a DHCP server and a web server deployed at the UPB domain. The SWAM service at the I2CAT domain consists of two virtual access points radiating an SSID in two different wireless nodes and a wireless backhaul path

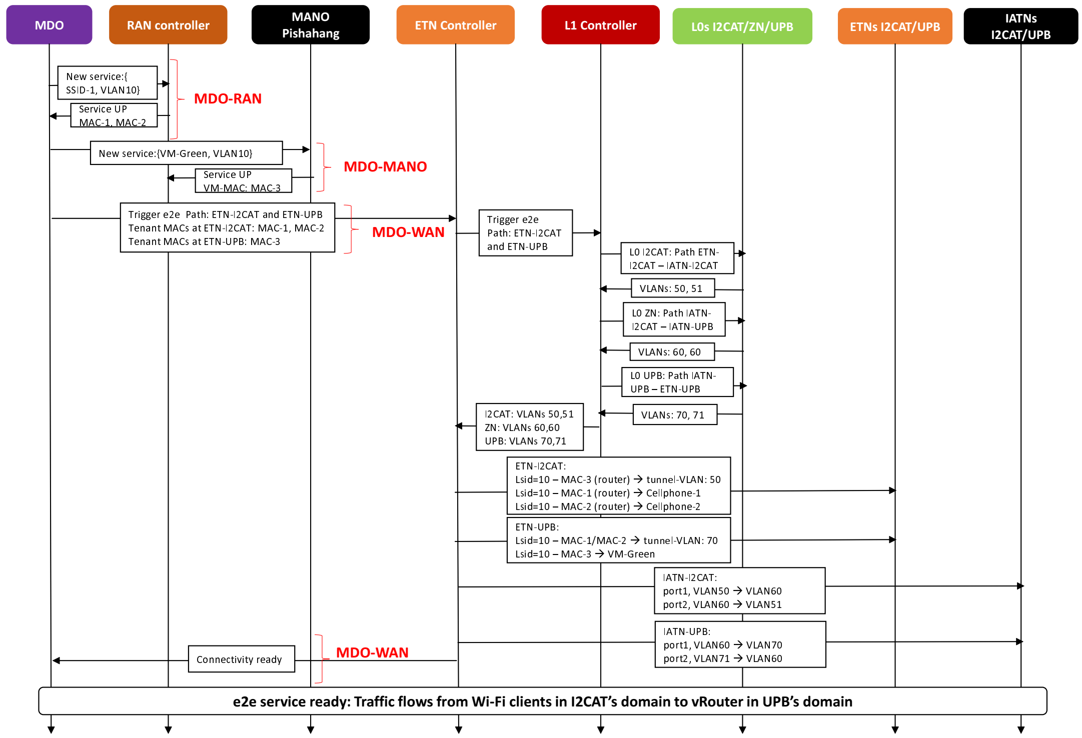


Fig. 4. Signalling involved in the provisioning of the e2e virtual Wi-Fi service

connecting them; the interested reader is referred to [8] for details on this technology. The MDO provisions the virtual Wi-Fi service triggering the SWAM service through the MDO-RAN interface, the core network container through the MDO-MANO-2 interface, and the end-to-end connectivity through the transport network areas of the I2CAT, ZN and UPB domains using the MDO-WAN interface.

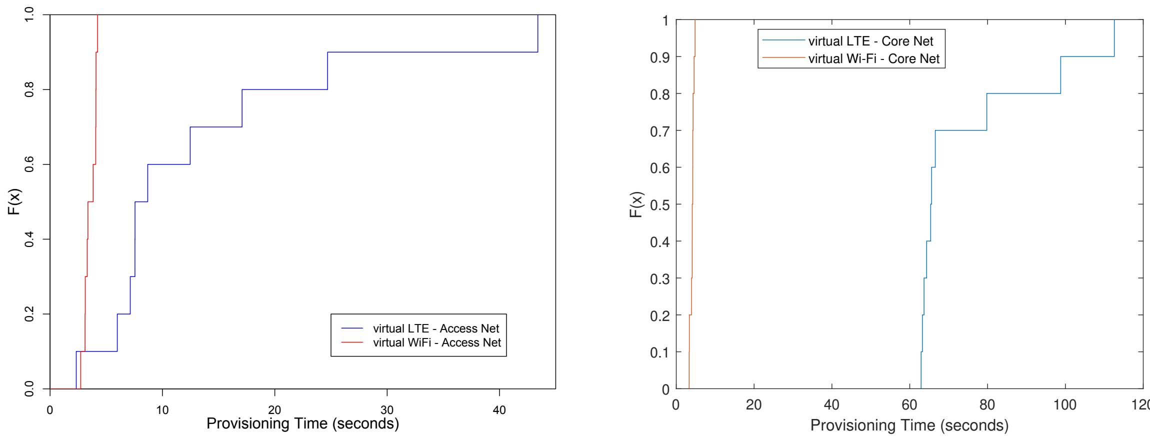
Figure 4 depicts the signalling flow from the MDO to the various control plane components required to instantiate the virtual Wi-Fi service, where we see the following steps:

- The MDO triggers the deployment of the SWAM service through the MDO-RAN interface especifying the target SSID radiated by the virtual APs and an end-to-end service VLAN. The service VLAN is used to identify the packets belonging to this service in the ETN function deployed in the I2CAT domain. The RAN Controller confirms the creation of the service and returns the MAC addresses of the client devices that are allowed to connect to the virtual APs. These MAC addresses will be required to program the ETN data-paths.
- The MDO triggers the deployment of the core network component through the MDO-MANO-2 interface, indicating the same end-to-end service VLAN. The Pishahang orchestrator confirms the creation of the service and returns the MAC address of the deployed container.
- The MDO triggers the provisioning of the end-to-end connectivity through the MDO-WAN interface. For this purpose it indicates to the ETN/IATN Controller the ETN end-points involved in the connection, i.e. ETN I2CAT and ETN UPB, and the MAC addresses of the end-user devices connecting in each domain.
- The ETN/IATN Controller triggers a creation of an end-to-end connection by issuing a path request to the L1 Controller indicating the I2CAT and UPB ETN functions.
- The L1 Controller identifies the domains that need to be traversed to implement the end-to-end connection, i.e. I2CAT, ZN and UPB, and issues partial path requests to the respective L0 controllers of each domain. The L0 controllers respond with the identifiers (VLAN IDs) of the LSPs provisioned in each domain to serve the different segments of the end-to-end connection.
- Armed with the LSP identifiers of each transport domain and with the MAC addresses of the connecting end-points the ETN/IATN Controller programs the bindings in the ETN functions of the I2CAT and UPB domains, and in the IATN functions of each domain. At this point the ETN/IATN controller confirms that the end-to-end connection is configured.

A similar signalling flow is required in the set up of the virtual LTE service. In this case though the MDO interacts with the UTH MANO domain to set up the OAI eNB, instead of interacting with the RAN Controller in the I2CAT domain.

V. Performance Evaluation

Using the multi-domain testbed introduced in the previous section, we present now an experimental evaluation of the time required to provision the virtual LTE and the virtual Wi-Fi services. To collect the results reported in this section



(a) virtual Access Network provisioning times

(b) virtual Core Network provisioning times

Fig. 5. Benchmarking the MDO-RAN and MDO-MANO interfaces

we triggered from the MDO the set up of the different services at least ten consecutive times and report here the measured Cumulative Distributed Functions (CDF) in each of the involved interfaces, i.e. MDO-RAN, MDO-WAN and MDO-MANO.

A. Benchmarking the MDO-RAN and MDO-MANO interfaces

Figure 5 reports the CDF of the provisioning times measured in the MDO-RAN and MDO-MANO interfaces for the virtual LTE and virtual Wi-F services.

Figure 5(a) depicts the time required to provision the access network. In the case of the virtual LTE service the access network is provisioned by instantiating an OAI eNB VM connected to an SDR in the UTH domain, through the MDO-MANO-1 interface where the MDO interfaces with the OSM orchestrator. In the case of the virtual Wi-Fi network the access network is instantiated by setting up a SWAM service where the MDO interfaces with the RAN Controller function in the I2CAT domain. We can see in the figure how the access network setup for the Wi-Fi service is below 5 seconds, whereas the virtual LTE service can take up to 40 seconds to deploy the virtual eNB. The reason for this difference is that the RAN Controller uses OpenDayLight [23] southbound plugins such as NETCONF, OVSDB and OpenFlow to instantiate a virtual AP in the wireless nodes using the *hostapd* tool [22], and to setup a wireless backhaul path. In the case of the virtual LTE service though a VM with the eNB OAI image needs to boot, which is already available in the target compute node, exhibiting a larger delay and variability.

Figure 5(b) depicts the corresponding results for the core network component of the virtual LTE and the virtual Wi-Fi services, which are instantiated at the UPB domain through the Pishahang orchestrator. Again in this case the core network component of the virtual LTE service takes significantly longer, i.e. between one and two minutes, whereas the core component of the virtual Wi-Fi service takes less than five seconds. In this case the difference is due to the underlying virtualization technology. In the case of the virtual LTE service the core component is an OAI vEPC VM instantiated through OpenStack. In the case of the virtual Wi-Fi component the core component is a docker container instantiated through Kubernetes. It is well-known that containers are more lightweight than VMs and can be provisioned in less time [24].

These results illustrate the flexibility of the 5GOS architecture to orchestrate RAN services supported by very different access and core network virtualization technologies.

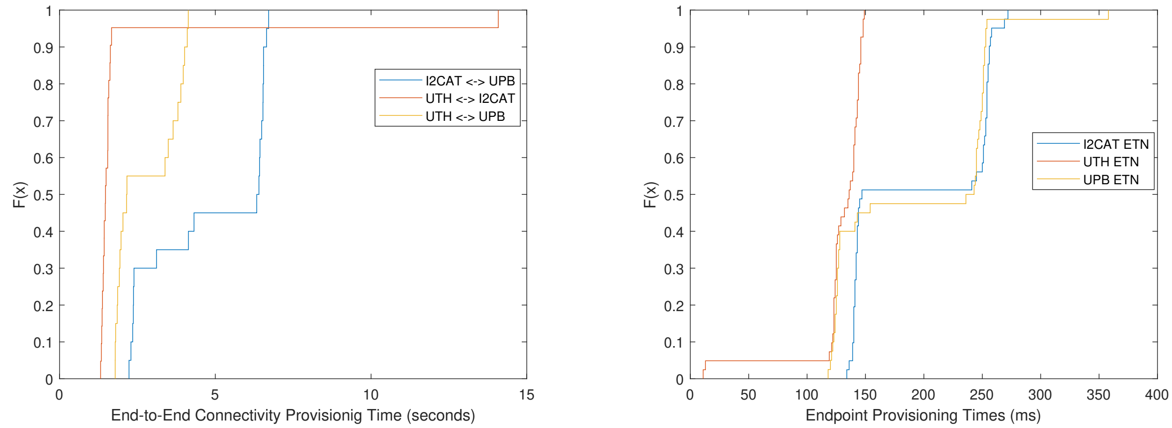
B. Benchmarking the MDO-WAN interface

Figure 6 depicts the end-to-end connectivity provisioning times through the MDO-WAN interface. Figure 6(a) depicts the provisioning times measured in the L1 controller, i.e. from the moment it receives a path request until the LSPs in all underlying domains are established. Figure 6(b) depicts the time required by the ETN/IATN Controller to program the bindings in the ETN and IATN functions.

We can clearly observe in Figure 6(a) that the dominant factor in the establishment of the end-to-end connectivity is the provisioning of the LSPs in the individual domains, as Figure 6 reports the connectivity provisioning times measured between each pair of domains in our testbed, which shows a large variability spanning between 2 and almost 15 seconds. Instead, programming the bindings in the ETN and IATN functions once the LSPs in each domain are established is much more predictable taking less than 500 ms (c.f. Fig. 6).

To understand the reasons for the large variability observed in the setup of the per-domain LSPs in the end-to-end connections we plot in Figure 7 the measured provisioning times in the L0 controllers of each domain, i.e. I2CAT, UTH, UPB and ZN. We can see in Figure 7(b) that the ZN domain dominates the overall delay and variability with measured times between 2 and 15 seconds, whereas the other domains experience provisioning times below 500 ms, as observed in Figure 7(a).

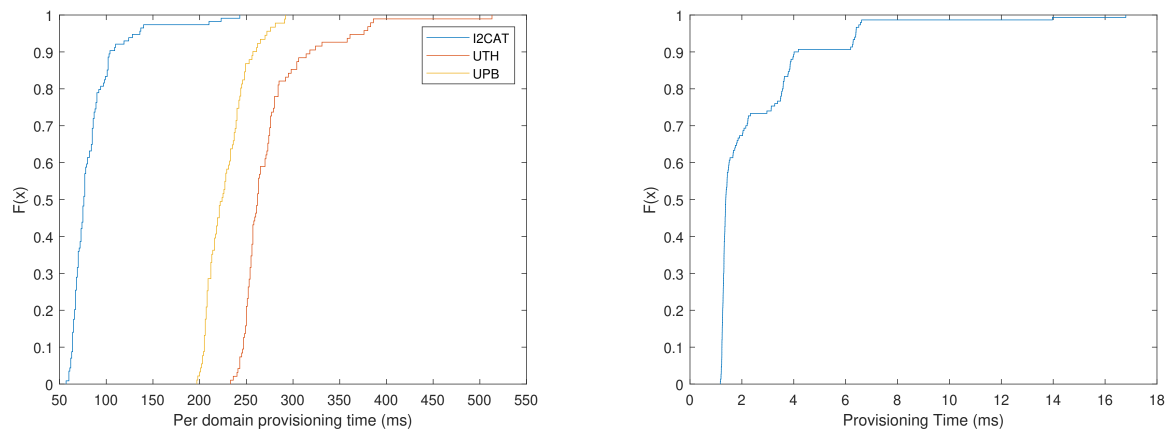
The larger delay observed in the ZN domain is due to the DSE technology described in Section III-C. Recall that the ZN



(a) Per-domain L1 provisioning times

(b) ETN and IATN programming times

Fig. 6. Benchmarking the MDO-WAN interface



(a) I2CAT, UTH and UPB domains

(b) ZN domain

Fig. 7. e2e connection provisioning time broken per domain

domain acts as transit provider in our testbed and is always traversed by an end-to-end connection. Upon a COP path request from the L1 Controller the DSE creates a full virtual network representation for the tenant, offering an openflow interface enabling the tenant to control the flows that traverse the transit provider. The large variance observed is affected by the design of the DSE, where any requests for connectivity triggered by the tenants is processed the COP adapter before being passed to the DSE, where they are reprocessed. Then, the COP adapter waits for the result, which is passed back to the tenant(s) once available. This process currently is synchronous with fixed polling intervals set to 10 seconds between the COP adapter and the DSE. In a practical implementation tenants and the transit provider could use some form of asynchronous event based interface to avoid using fixed length timers

C. Overall provisioning time

Figure 8 depicts the overall time to setup the virtual LTE and virtual Wi-Fi services, measured from the time the service creation is triggered at the MDO until the time packets can start flowing between the LTE or Wi-Fi clients connected at the UTH and I2CAT domains until the core network components instantiated in the UPB domain.

We can see in Figure 8 how the virtual Wi-Fi service can be set up in about 30 seconds, while the virtual LTE service may need up to 3 minutes. The reason for this difference lies in the underlying virtualization technologies used in the MDO-RAN and MDO-MANO interfaces for the two services, i.e. while the virtual Wi-Fi service uses lightweight virtualization by configuring Wi-Fi physical devices with NETCONF and using containers in the core network, the virtual LTE service uses VMs both in the access and in the core network.

Although the results we have presented are based on a limited testbed, where for example in the case of the virtual LTE service we only set up one eNB, the measured provisioning times clearly indicate that the deployment of larger networks could also be automated through the 5GOS leading to provisioning times much lower than those incurred in current mobile network deployments.

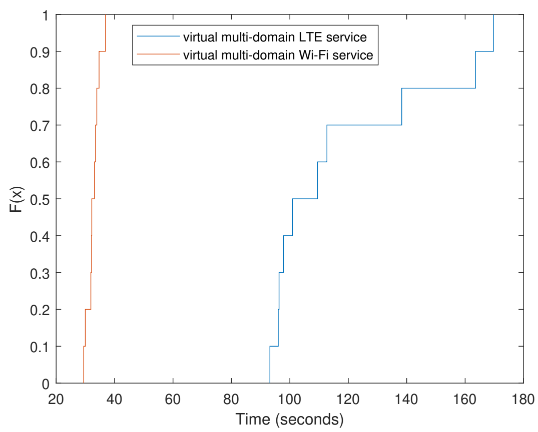


Fig. 8. Overall provisioning time for the virtual LTE and virtual Wi-Fi services

VI. Conclusions

To fulfill the 5G vision of providing customized virtual network deployments addressing different vertical needs poses significant challenges in terms of automated network deployment and operation. Leveraging NFV and SDN principles is key to accomplish this goal, but practical examples of holistic management frameworks that are able to orchestrate end-to-end RAN network services are still missing.

In this paper we present and validate the 5GOS, a lightweight management framework able to orchestrate virtual RAN services across distributed MANO, RAN and transport network domains, including transit providers. Using a multi-domain testbed we demonstrate the deployment of a virtual Wi-Fi and LTE service in less than three minutes. The generic design of the 5GOS makes it immediate to support new network services including for example a 5GNR access network.

While we believe that the 5GOS represents an important step towards the automation of the deployment of RAN network services, much work is missing on automating other network management tasks such as configuration and optimization, for which we plan to continue extending the 5GOS.

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