H2020 5G-TRANSFORMER Project
Grant No. 761536

Final design and implementation report on the MTP (report)

Abstract

This deliverable provides the final version of the Mobile Transport and Computing Platform (5GT-MTP) design addressing the following aspects: the final architecture of the 5GT-MTP; updates on 5GT-MTP interfaces towards the service orchestrator (5GT-SO); the final workflows between the 5GT-SO and the 5GT-MTP as well as workflows among the various components of the 5GT-MTP.

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Disclaimer

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List of Acronyms

Acronym	Description
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5GPPP	5G Infrastructure Public Private Partnership
5GT-MTP	Mobile Transport and Computing Platform
5GT-SO	Service Orchestrator
5GT-VS	Vertical Slicer
AMF	Access and Mobility Function
API	Application Programming Interface
AS	Application Server
CN	Core Network
CU	Centralized Unit
CPRI	Common Public Radio Interface
CPU	Central Processing Unit
DB	Database
DC	Data Centre
DU	Distributed Unit
DNS	Domain Name System
E2E	End to End
eNodeB, eNB	Evolved Node B
EPC	Evolved Packet Core
ETSI	European Telecommunication Standardization Institute
gNB	Next Generation Node B
IM	Infrastructure Manager
IoT	Internet of Things
KPI	Key Performance Indicator
LL	Logical Link
LPA	Local PA
LTE	Long Term Evolution
MEC	Multi-access Edge Computing
MEO	Multi-access Edge Orchestrator
MEP	Multi-access Edge Platform
MEPM	MEC Platform Manager
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MNO	Mobile Network Operator
MVNO	Mobile Virtual Network Operator
NBI	Northbound Interface
NF	Network Function
NFV	Network Function Virtualization
NFVI	Network functions virtualization infrastructure
NFV-NS	NFV Network Service
NFV-NSO	Network Service Orchestrator
NFVO	NFV Orchestrator
NFVO-RO	Resource Orchestrator
NG-RAN	Next Generation RAN
NRT	Non Real Time
NSD	Network Service Descriptor

NSI	Network Slice Instance
NSSI	Network Slice Subnet Instances
OLE	On site Live Event Experience
OSNR	Optical Signal to Noise Ratio
OSS	Operating Support System
PA	Placement Algorithm
PDU	Protocol Data Unit
PM	Performance Monitoring
PNF	Physical Network Function
PNFM	PNF Manager
PoP	Point of Presence
QoS	Quality of Service
RAM	Random Access Memory
RAN	Radio Access Network
ResOrch	Resource Orchestration
REST	Representational State Transfer
RNIS	Radio Network Information Service
RRM	Radio Resource Management
RT	Real Time
RU	Radio Unit
SIB	System Information Blocks
SBI	Southbound Interface
SDN	Software Defined Networking
SLA	Service Level Agreement
SLPOC	Single Logical Point of Contact
SMS	Short Messaging Service
S-NSSAI	Single Network Slice Selection Assistance Information
TA	Tracking Area
TAI	Tracking Area Identifier
TD	Technology Domain
TN	Transport Network
UPF	User Plane Function
vCPU	Virtual CPU
VIM	Virtual Infrastructure Manager
LL	Logical Link
LLD	Logical Link Descriptor
VM	Virtual Machine
VNF	Virtual Network Function
WIM	Wide area network Infrastructure Manager

Executive Summary and Key Contributions

This deliverable reports the final release (R2) of the Mobile Transport and Computing Platform (5GT-MTP), highlighting updates on the 5GT-MTP architecture with respect to the initial architecture presented in D2.1 [1].

The novelties introduced has the aim to improve the 5GT-MTP architecture presented in the first release providing new features and functionalities that takes into account the feedback received by the Proof of Concept (PoC) to simultaneously support the needs of different vertical industries (such as, eHealth, automotive, entertainment, eIndustry and MNVO).

In more details, the main updates reported in this deliverable are related to:

- **5GT-MTP features**: new features have been added to support Radio and MEC infrastructures, resource Monitoring and Local Placement Algorithm.
- **5GT-MTP functional components**: two new modules have been introduced, the *Local PA,* and the *Monitoring Driver* to provide resource optimization and manage the communication with the Prometheus monitoring platform adopted in the project, respectively. Moreover, the already existing modules have been extended to support the new features introduced in R2. In particular, the *Abstraction Engine,* the R*esOrch* and the *DB* have been extended to take into account also Radio and MEC resource domains; the *Dispatcher* has been extended to support also the *Monitoring Driver* and *Local PA* module.
- **5GT-MTP interfaces:** interfaces have been updated to allows the instantiation of MEC and Radio Application and to handle the communication with the monitoring platform and the PA algorithms;
- **Workflows**: changes have been done to the workflows to take into account the interaction with Radio and MEC domains.

For an easy reading of the deliverable, the document has been divided into two parts. The first part, presented in the main body of the document, reports the summary of the updates on the initial design of the 5GT-MTP platform. The second part, instead, reports a full self-contained description of the 5GT platform.

Details on software implementation are reported in D2.4 [4].

1 Introduction

The aim of 5G-TRANSFORMER is to deliver a complete scalable 5GT-MTP design and implementation to handle infrastructure manager's resources while supporting integrated MEC and radio services, new abstraction models (with also mobility support) and dynamic local placement of virtual functions.

The 5GT-MTP is responsible for the orchestration of resources and the instantiation of VNFs over the infrastructure under its control, as well as of managing the underlying physical mobile transport network, computing and storage infrastructure. In a nutshell, it manages all the infrastructures as a Single Logic Point of Contact (SLPOC), providing a common abstraction view of the managed resources to the 5GT-SO.

While, in the first phase, the project focused on transport (WIM) and data-center (VIM) resource controllers, in the second phase the abstraction and the resource management have been extended by supporting also both RAN and MEC resource infrastructures.

The objective of this deliverable is to provide the final version of the 5GT-MTP design highlighting the updates introduced in Release 2 (R2) with respect to the previous release described in D2.1 [1]. The main updates are related to: i) features, ii) functional components, iii) 5GT-MTP interfaces and iv) supported workflows (among the different building blocks and 5GT architecture elements.

In order to keep the main body of the document as short as possible, the deliverable is divided into two parts:

- The main body: it focuses only on a summary of the updates towards the 5GT-MTP final architecture introduced in the second release.
- Annex I: it reports and details a self-contained description of the 5GT-MTP.

In more details, the deliverable reports the updates towards the 5GT-MTP final architecture in Section 2, describing the extension to the 5GT-MTP architecture in terms of new features, functional components and related interfaces This section also shows updates on 5GT-MTP workflows, and reports a short description of the updates on the software implementation. The main body of the deliverable is concluded in Section 3.

The complete description of the updates on the 5GT-MTP platform is reported in the Annex I. For a better reading of the deliverable, the Annex maintains the same structure of the main body.

2 Updates of Mobile Transport Platform architecture

2.1 5GT-MTP architecture overview

The 5GT-MTP architecture is aligned with the initial architecture presented in D2.1 [1]. However, additional functional components and related interfaces to provide new or enhanced features have been added to cover the targeted use cases requirements (e.g., MEC and Radio support) [5] or to take into account feedback from the PoC.

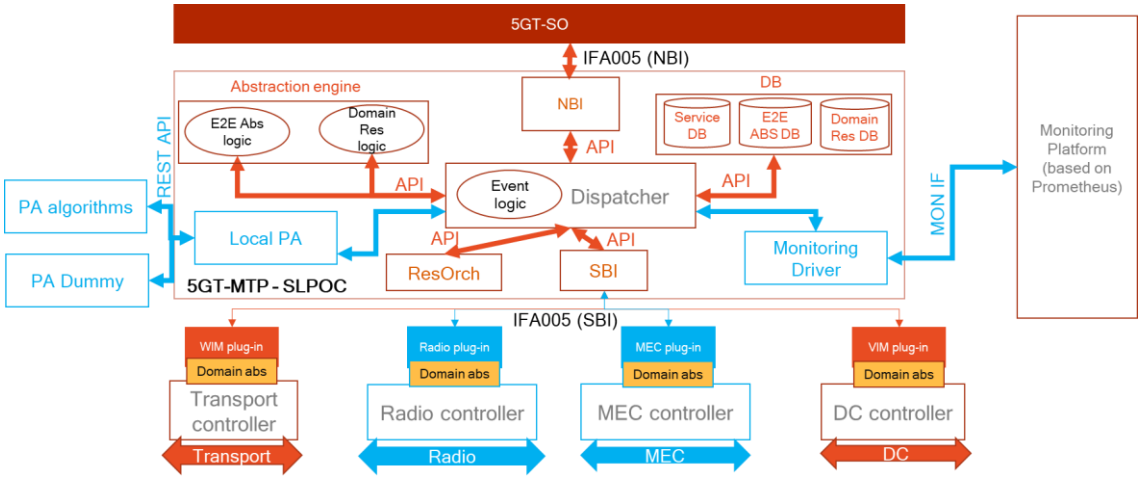

FIGURE 1: UPDATES ON 5GT-MTP ARCHITECTURE

Figure 1 shows the final 5GT-MTP architecture highlighting in blue the major updates with respect to the Release 1 (R1) ([1], [2]).

Moreover, minor changes have been also applied to other components, e.g., the Abstraction engine, as reported in Section 2.2.

As shown in the Figure 1, the architecture still maintains the structure proposed in R1 acting as a single point of contact for the 5GT-SO. It provides the suitable abstract view of the physical resources and orchestrate resources selecting and configuring transport, Radio, MEC and DC resources compliant with the request from the 5GT-SO.

A description of the novel functional blocks is reported in Section 2.3 and in more detail in Section 5.4.

2.2 5GT-MTP features

The second release (R2) of the 5GT-MTP platform introduces new features with respect to the initial architecture specification, reported in D2.1 [1], and the first release (R1) of the prototype, delivered in D2.2 [2].

In particular, the following features have been introduced:

- *Radio and MEC support:* this feature will extend the proposed abstraction method in order to support both Radio and MEC domains/technologies.
- *Network Slicing:* this feature has been introduced to provide the required slicing support in a scenario where heterogeneous technologies co-exist within the transport network
- *Resource Monitoring:* this feature has been introduced to provide the monitoring functionality of the infrastructure resources controlled by the 5GT-MTP.

- *Local Placement Algorithm (PA):* this feature provides resource optimization inside an infrastructure manager domain.

More details of the mentioned features are provided in Annex I, i.e., Section 5.3.

2.3 5GT-MTP functional components

To support the new features covered in R2, new functional components have been introduced and some extensions have been added to the existing ones (i.e., those supported in R1).

A brief description of the functional components updates is reported below, for a complete description, instead, please, refer to Annex I (i.e., Section 5.4):

- The ***Abstraction Engine*** has been extended to include both Radio and MEC resource domains. The scope of the module is to provide an abstraction layer to the upper software component of the general 5GT architecture (i.e. Service Orchestration or 5GT-SO). The module considers a myriad of available resources from transport (WIM), data-centers (VIM), RAN and MEC and provides a common abstract view in terms of service parameters (e.g., bandwith, latency) that can be guaranteed with the available resources.
- The ***Dispatcher*** is an Event bus that provides communication between the 5GT-MTP modules using a publish-subscribe pattern. It allows all MTP modules to post events that are handled by specific handlers. It has been extended to include new events integrating the monitoring driver and the local Placement Algorithm in the internal MTP workflow.
- *The* ***ResOrch*** module orchestrates the 5GT-MTP procedures among the controlled domains (i.e., VIM, WIM). In R2 it has been extended to allows also the orchestration of Radio and MEC domains. ***DB*** is a front-end that connects to an external SQL server and handles all the queries (i.e., to insert entries, update data and retrieve parameters) towards the database to store and retrieve abstraction, aggregation and service information. It has been extended to store and retrieve data about RAN and MEC managed resources.
- ***Local PA*** is a new module that provides the selection and optimization of resources thanks to dedicated and specialized resource Placement Algorithm (PA) algorithm. It handles the communication with an external PA module by means of a new REST API. The aim of local PA module is two-fold. First, the local PA module contacts an external PA module in order to get decision about the specific VIM where to put a VNF in a multi-VIM domain. Second, the local PA module may contact an external PA module to compute the interNfviPop connectivity for a logical link between a pair of NFVI-PoP GWs with specific network constraints.
- ***Monitoring Driver*** is a new functionality that manages the communication with the monitoring platform of the 5G-T architecture (based on Prometheus) [11]. It uses the monitoring interface exposed by the Monitoring Platform to register itself to the platform, create performance monitoring jobs and get alert notifications. Moreover, it handles notifications about the status of infrastructure resources (i.e., compute, storage, networking, radio, and MEC resources) by posting specific events to the dispatcher.

2.4 5GT-MTP interfaces

In R2, the MTP interfaces have been updated to support the new features and functional components introduced.

The following updates have been introduced:

- *MTP NBI* to include the instantiation of MEC App and Radio functions (e.g., vEPC) to trigger monitoring jobs, allocate/terminate intra-NFVI-PoP connectivity within the DC and explicitly start/stop the allocated VNF resources;
- *MTP SBI* to trigger on demand the allocation/termination of intra-NFVI-PoP connectivity within the DC and start/stop allocated VNFs;
- *MEC SBI* is part of the MTP SBI and is used to enable the communication with the MEC domain;
- *MTP Monitoring Interface* to handle the communication with the monitoring platform;
- *MTP Placement Algorithm (PA) interface* to handle the communication with the placement algorithms.

A detailed description of the 5GT-MTP interfaces is reported in the Section 5.5 of the Annex I.

2.5 Updates towards 5GT-MTP workflow

To optimize the orchestration of infrastructure resources, in R2, the workflows presented in D2.1 [1] are updated to include also the Radio and MEC domains. The updated workflows, including MEC domain are described in Annex I of this deliverable in Section 5.6. Note that, since discussion on Radio is ongoing, the handling of Radio resources will be described in D1.4.

2.6 Updates towards the 5GT-MTP software implementation

All the updates reported above have been deployed and implemented in R2. The complete software implementation can be downloaded from GitHub [3]. A detailed description of the reference software is reported in D2.4 [4].

3 Conclusions

In this deliverable we have described the updates towards the final 5GT-MTP architecture implementation, highlighting the novel features and functionalities being adopted and considered.

We presented an updated version of D2.1 [1] that integrates and extensively discusses these modifications within the overall architecture specification. This encompasses the main updates related to extended features and functional components, 5GT-MTP interfaces and workflows.

The changes/extensions introduced in the R2 aim to support also Radio and MEC infrastructures to improve the features already supported in R1 that focused only on transport and DC resources. Moreover, R2 provides resource Monitoring and Local Placement Algorithm to optimise the resource usage.

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5 Annex I: 5GT-MTP Design and Implementation

5.1 Requirements on the 5GT-MTP

Technical requirements on the overall 5G-T system have been defined in D1.1 [6]. These requirements focus on properties related to vertical services and relevant use cases. General requirements related to the overall system are described in [7]. Additional general requirements on the 5G-TRANSFORMER system, emerged during the development of the project, are described in D1.3 [8]. In this section, we define the related functional requirements specific to the 5GT-MTP updating the ones reported in D2.1 [1] with new requirements, defined during the project, for the distinct phases referred before.

In this deliverable we follow – with slight adaptations – the notation for requirements used already in [5][1]. For each requirement, the following fields should be provided:

ID	Requirement	F/NF
ReqX.XX	e.g. The vehicle shall be connected to a 5G router	F/NF

The meanings of the above fields are as follows:

- **ID:** is the identifier of the requirement (written in the form ReqX.XX).
- **Requirement:** a complete sentence explaining the requirement.
- **F/NF:** if the requirement is either Functional (F) or Non-Functional (NF).

NOTE: The requirement field is written according to the approach followed by IETF documents using the keywords “must”, “must not”, “required”, “shall”, “shall not”, “should”, “should not”, “recommended”, “may” and “optional”. In this document those terms (keywords) are to be interpreted as described in [8].

1. **MUST** This word, or the terms “**REQUIRED**” or “**SHALL**”, mean that the definition is an absolute requirement of the specification.
2. **MUST NOT** This phrase, or the phrase “**SHALL NOT**”, mean that the definition is an absolute prohibition of the specification.
3. **SHOULD** This word, or the adjective “**RECOMMENDED**”, mean that there may exist valid reasons in particular circumstances to ignore a particular item, but the full implications must be understood and carefully weighted before choosing a different course.
4. **SHOULD NOT** This phrase, or the phrase “**NOT RECOMMENDED**” mean that there may exist valid reasons in particular circumstances when the particular behavior is acceptable or even useful, but the full implications should be understood and the case carefully weighed before implementing any behavior described with this label.
5. **MAY** This word, or the adjective “**OPTIONAL**”, mean that an item is truly optional. One vendor may choose to include the item because a particular marketplace requires it or because the vendor feels that it enhances the product while another vendor may omit the same item. An implementation which does not include a particular option **MUST** be prepared to interoperate with another implementation which does include the option, though perhaps with reduced functionality. In the same vein, an implementation which does include a particular option **MUST** be

prepared to interoperate with another implementation which does not include the option (except, of course, for the feature the option provides).

The 5GT-MTP is involved in the service lifecycle at different stages. Thus, different requirements can be considered according to each stage, namely (1) Discovery, (2) Fulfilment, (3) Assurance, and (4) Decommissioning.

5.1.1 Discovery

During the discovery phase, the 5GT-MTP exposes the underlying infrastructure, following the appropriate abstraction levels, to the 5GT-SO. The following requirements are identified:

TABLE 1: REQUIREMENTS ON THE DISCOVERY PHASE

ID	Requirement	F/NF
ReqMTP.Di.01	The 5GT-MTP shall store a catalog of NFVI-PoPs available within the 5GT-MTP's administrative domain, and related resources (i.e., computing, storage, networking) in addition to the available PNFs/VNFs.	F
ReqMTP.Di.02	The 5GT-MTP must provide the means to expose available resources with the appropriate abstraction levels to 5GT-SO.	F
ReqMTP.Di.04	The 5GT-MTP shall keep up-to-date the catalog of related NFVI components	F
ReqMTP.Di.06	The 5GT-MTP shall expose the current state of the available PNFs.	F
ReqMTP.Di.07	The 5GT-MTP shall certify the credentials of entities accessing its NFVI catalog.	F
ReqMTP.Di.08	The 5GT-MTP shall allow creating several instances of the same VNF	F
ReqMTP.Di.09	The 5GT-MTP shall store a catalog containing the service connection points along with some metadata, such as the location, etc.	F
ReqMTP.Di.11	The 5GT-MTP must provide the 5GT-SO with the means to send detailed resource allocation requests	F
ReqMTP.Di.12	The 5GT-MTP must provide the 5GT-SO with the means to configure VNF instances	F
ReqMTP.Di.13	The 5G-MTP system should integrate diverse technological environments such as RAN and MEC.	F

5.1.2 Fulfilment

During the service fulfilment phase, the 5GT-SO orchestrates (namely, creates and instantiates) network services requested by 5GT-VS, using the infrastructure abstraction provided by the 5GT-MTP. From the 5GT-MTP perspective this involves: appropriate configuration of the VNFs and PNFs, and allocation of resources in available NFVI-PoPs and their potential and required network (e.g., WAN) interconnectivity.

The following requirements are identified:

TABLE 2: REQUIREMENTS ON THE FULFILMENT PHASE

ID	Requirement	F/NF
ReqMTP.Fu.01	Depending on the modality of the contracted service, the 5GT-MTP may be required to offer proper configuration and management interfaces to instantiated VNFs or requested PNFs.	F
ReqMTP.Fu.02	The 5GT-MTP shall allow VNF scaling (up/down/in/out)	F
ReqMTP.Fu.03	The 5GT-MTP shall allow resource scaling (up/down/in/out)	F
ReqMTP.Fu.06	The 5GT-MTP shall certify the credentials of entities accessing its NFVI.	F
ReqMTP.Fu.07	The 5G-MTP system should permit the extension of connectivity among different NFVI-PoPs from multiple providers at both intra- and inter-domain levels.	F

5.1.3 Assurance

The 5GT-MTP is responsible for guaranteeing the performance agreements requested by the 5GT-SO via orchestrating the pool of needed VNFs as well as allocated resources within NFVI-PoPs and PNFs. Additionally, sufficient monitoring information is needed to keep track of ensuring the demanded 5GT-SO requirements on the demanded network services. The following requirements are identified:

TABLE 3: REQUIREMENTS ON THE ASSURANCE PHASE

ID	Requirement	F/NF
ReqMTP.As.01	The 5GT-MTP must provide the 5GT-SO tools to monitor the QoS attained to the instantiated VNFs, allocated PNFs (and VLs) and their related resources.	F
ReqMTP.As.02	The 5GT-MTP shall certify the credentials of entities accessing its NFVI monitoring information.	F
ReqMTP.As.04	The 5GT-MTP should be provide fault-tolerant functionalities and report failure events upstream to the 5GT-SO as long as the 5GT-MTP is not able to recover / restore the event failures impacting the service continuity.	F
ReqMTP.As.05	The 5G-MTP system must provide means for optimizing the deployment of network services in terms of resources, performance indicators.	F

5.1.4 Decommissioning

Once a service is decommissioned, the 5GT-MTP shall release the used resources and terminate the allocated VNFs as a response to the 5GT-SO termination operation. The following requirements are identified:

TABLE 4: REQUIREMENTS ON THE DECOMMISSIONING PHASE

ID	Requirement	F/NF
ReqMTP.De.01	The 5GT-MTP must be able to identify the allocated resources for a VNF upon a VNF termination procedure	F
ReqMTP.De.02	The 5GT-MTP must be able to identify the monitoring mechanisms to be de-activated as a result of a VNF termination or resource deallocation	F
ReqMTP.De.03	The 5GT-MTP must be able to notify the 5GT-SO about either VNFs or resources terminated	F
ReqMTP.De.04	The 5GT-MTP must restore the state of available PNFs when its allocation is terminated	F

5.2 5GT-MTP final architecture

Figure 2 depicts the architecture of the 5GT-MTP with all the different components. From the top-down view, the 5GT-MTP is based on the Single Logical Point of Contact (SLPOC) architecture as defined in IFA028 [10], but implements additional features like abstraction, monitoring and radio and MEC control. The 5GT-MTP SLPOC module exposes abstracted resource view to the 5GT-SO ([11]) via the NBI. Moreover, it is connected to different plugins: the transport WIM plugins, the VIM plugin, Radio plugin and the MEC plugin. These plugins expose different (abstracted) resources view to the 5GT-MTP via the defined SBI. More details on WIM, VIM and Radio plugin are reported in D2.2 [2]. MEC plugin instead is described in Section 5.5.3

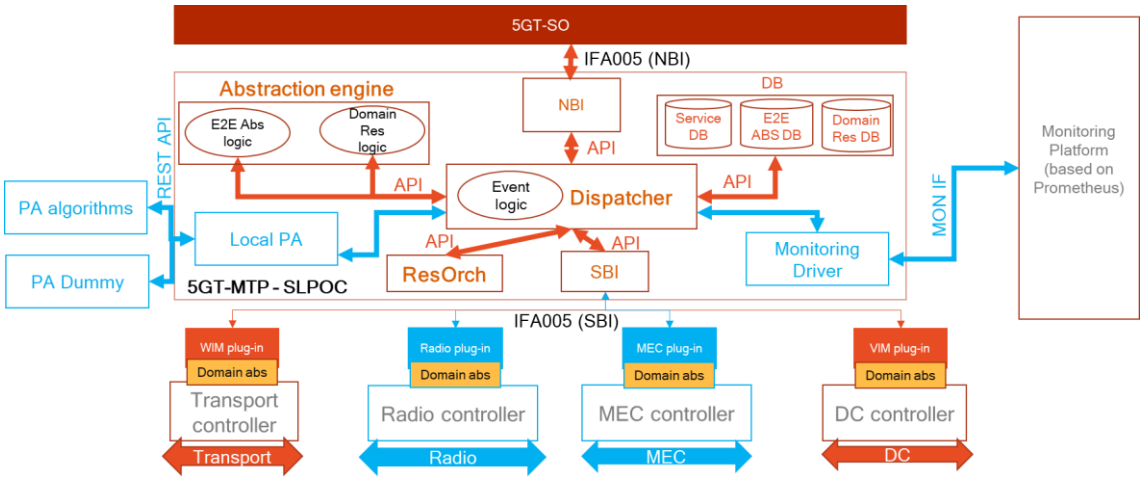


FIGURE 2: 5GT-MTP FINAL ARCHITECTURE

5GT-MTP architecture consists in the following components and building blocks:

- **Abstraction Engine**: This module implements all algorithms and procedures related to the abstraction. The "Domain Resource Logic" performs the aggregation of the domain resources, while the "E2E Abstraction Logic" performs the computation of the abstracted view. In the service allocation process, such modules are also responsible to select the transport domain resources to allocate for accommodating the required service.

- **Database (DB)**: It is a common module that stores all the information and details regarding the domain resource, the abstraction view and the services that are allocated.
- **Resource Orchestrator (ResOrch**: It orchestrates the 5GT-MTP operations between the VIM/Radio and Transport WIM/MEC domains.
- **North-Bound Interface (NBI)**: It handles the IFA005 communication and proprietary 5GT API for specific inter-NFVI-PoP connectivity purposes (based on IFA005 principles and contents) with the 5GT-SO.
- **South-Bound Interface (SBI)**: It handles the IFA005 communication with the plugins.
- **Dispatcher**: It manages the inter-process communication between the 5GT-MTP components (i.e., NBI, SBI, DB, RO, Abstraction Engine). The communications use specific interfaces that each component exposes to the dispatcher.
- **Local placement algorithm (Local PA)**: It takes decisions about where to put a VNF in multi-VIM domains and select the transport resources for inter-NFVI-PoP connectivity via an external PA module. The communication between the local and external PA modules is done through a defined and proprietary 5GT REST API.
- **Monitoring driver**: It is a module that communicates with the Monitoring Platform [11]. It creates the performance monitoring (PM) jobs on the Monitoring Platform and handles alert notifications from the Monitoring Platform.

5.3 5GT-MTP features

5.3.1 Abstraction and information model

Resource abstraction is a key element for the interworking between the 5GT-MTP and the 5GT-SO. For this reason, the proposed abstraction models will meet the following needs:

- keep the independency between the technology deployed in transport and radio, and the information model to describe its resources so that the same information model may be maintained even if the technology changes;
- guarantee a clear separation of tasks and responsibility, to facilitate, for instance, fault locations;
- decouple the radio and transport solutions that can evolve to different releases independently;
- associate radio and transport to different providers that can be combined to each other in N:M relationship, where N and M are positive integers.

In the follows, we present the abstraction models for the different infrastructure resources. In particular Section 5.3.1.1 presents the abstraction for transport and compute resources; finally, how to support mobility and MEC application is reported in Section 5.3.1.3 and Section 5.3.1.4, respectively.

5.3.1.1 Domain abstraction

The 5GT-MTP is responsible for providing the 5GT-SO with the information about the available resources (including Radio, NFVI-PoP, transport and MEC), so that the 5GT-SO can make decisions on service orchestration. Because of the varying level of trust among organizations and the complexity associated to resource management, the 5GT-

MTP, in general, does not provide all its infrastructure details. Rather, it presents to the 5GT-SO the information with a certain level of abstraction.

Specifically, the resources managed by an 5GT-MTP can be divided into two groups: computing resources and network resources (for Radio resources, please, refer to Section 5.3.1.3). Computing resources are the physical machines (e.g., servers or compute hosts) that can accommodate VNFs and are typically characterized by CPU, memory, and storage resource capabilities. Computing resources are grouped depending on the location in the NFVI-PoPs. The physical machines of an NFVI-PoP are managed by the VIM. Network resources are represented by the network forwarding units and the physical links interconnecting them. WIMs control the network resources connecting different and remote NFVI-PoPs.

An infrastructure can thus be represented as a composition of network and computing (including storage) resources controlled by WIMs and VIMs, respectively. Since the nature of these resources is intrinsically different, the abstraction mechanisms for these two types of resources are also different.

Three abstraction models have been defined:

1. 5GT-MTP exposes all physical resources (i.e., Radio, transport, storage and computing) to the 5GT-SO.
2. 5GT-MTP exposes all the available cloud resources.
3. 5GT-MTP exposes aggregated cloud resources availability.

As said, the first model exposes all the physical resources (radio, transport, storage, and computing) as shown in Figure 3.

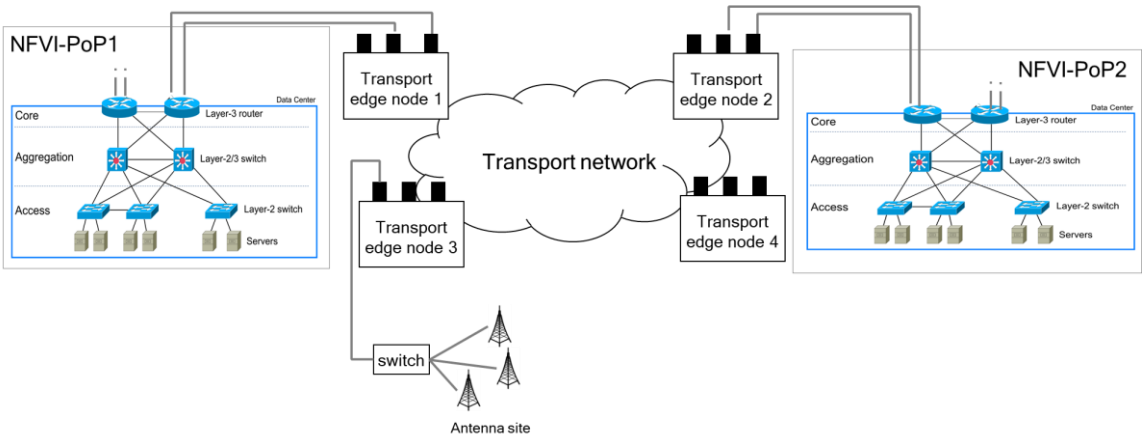


FIGURE 3: PHYSICAL INFRASTRUCTURE - ABSTRACTION MODEL 1

In the abstraction model 2, the 5GT-MTP reports all details about computing resources while the network resources are abstracted as a set of logical links connecting the NFVI-PoPs (Figure 4).

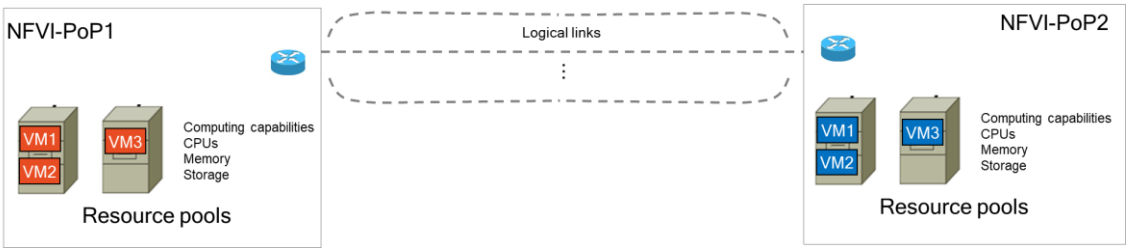


FIGURE 4: ABSTRACTION MODEL 2

Finally, in the third abstraction model (Figure 5) also the computing resources are abstracted. The 5GT-MTP reports the computing capabilities, CPUs, memory, storage, with an NFVI-PoP granularity instead of by physical-machine granularity as in model 2. Regarding the network resources, only the connections between NFVI-PoPs are reported, i.e., logical links with a given bandwidth and latency.

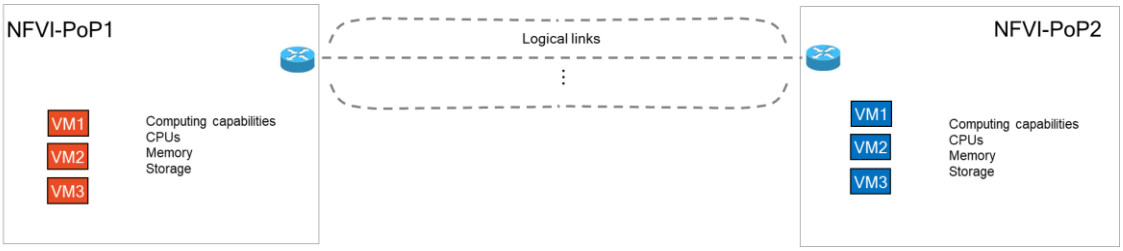


FIGURE 5: ABSTRACTION MODEL 3

For models 2 and 3, for the network abstraction, two options are possible:

a. for MNO/MVNO service only transport resources are abstracted (using logical links) instead the mobile resources are exposed. Radio and mobile function implemented on generic processing (e.g., vEPC) will be exposed as DC resources.

b. for other verticals both transport and mobile resources are abstracted in logical links.

5G-T has adopted and implemented the above described abstraction model 3.

5.3.1.2 Information models for compute, storage, and network resources

This subsection reports the information models to describe abstracted network, compute, memory, and storage resources. Table 5 shows the information model of a logical link with specific reference to the abstraction model 2. An abstracted topology is seen as a list of logical links. An identifier is associated to the logical link, then the identifiers of the source and destination NFVI PoPs are reported, as well as identifiers and IP addresses of the source and destination routers. Then, information about the bandwidth of the logical link is included as well as the intrinsic delay (e.g., related to the propagation network delay). The path connecting the two routers is hidden.

TABLE 5: INFORMATION MODEL OF THE LOGICAL LINK

Parameter	Description
logicalLinkId	Identifier of the logical link
abstrSrcNfviPopId	Identifier of the NFVIPop source
abstrDestNfviPopId	Identifier of the NFVIPop destination
srcRouterId	Identifier of the source router
dstRouterId	Identifier of the destination router
srcRouterIp	IP address of the source router
dstRouterIp	IP address of the destination router
totalBandwidth	Total bandwidth carried by the logical link

reservedBandwidth	Reserved bandwidth in the logical link
availableBandwidth	Available bandwidth in the logical link
allocatedBandwidth	Allocated bandwidth in the logical link
linkDelayValue	Delay introduced by the logical link

Table 6, Table 7, and Table 8 show the information model of compute, memory, and storage resources, respectively, associated to an abstracted resource zone. All of the three resources are reported with information of total, reserved, available, and allocated capacities. The abstracted zone is a portion of an NFVI PoP managed by a specific VIM, which also knows the geographical info and the network connectivity endpoint (or gateway) of the NVI PoP.

TABLE 6: INFORMATION MODEL OF THE COMPUTE RESOURCE

Parameter	Description
totalCapacity	Total CPU capacity in the abstracted resource zone
reservedCapacity	Reserved CPU capacity in the abstracted resource zone
availableCapacity	Available CPU capacity in the abstracted resource zone
allocatedCapacity	Allocated CPU capacity in the abstracted resource zone
abstrResourceZoneId	Identifier of the abstracted resource zone

TABLE 7: INFORMATION MODEL OF THE MEMORY RESOURCE

Parameter	Description
totalCapacity	Total memory capacity in the abstracted resource zone
reservedCapacity	Reserved memory capacity in the abstracted resource zone
availableCapacity	Available memory capacity in the abstracted resource zone
allocatedCapacity	Allocated memory capacity in the abstracted resource zone
abstrResourceZoneId	Identifier of the abstracted resource zone

TABLE 8: INFORMATION MODEL OF THE STORAGE RESOURCE

Parameter	Description
totalCapacity	Total memory storage in the abstracted resource zone
reservedCapacity	Reserved storage capacity in the abstracted resource zone
availableCapacity	Available storage capacity in the abstracted resource zone
allocatedCapacity	Allocated storage capacity in the abstracted resource zone
abstrResourceZoneId	Identifier of the abstracted resource zone

5.3.1.3 Mobility support

To support the mobility of the users, the virtual resources exposed to the 5GT-SO can be aggregated based on the coverage area concept to guarantee for a specific type of vertical service.

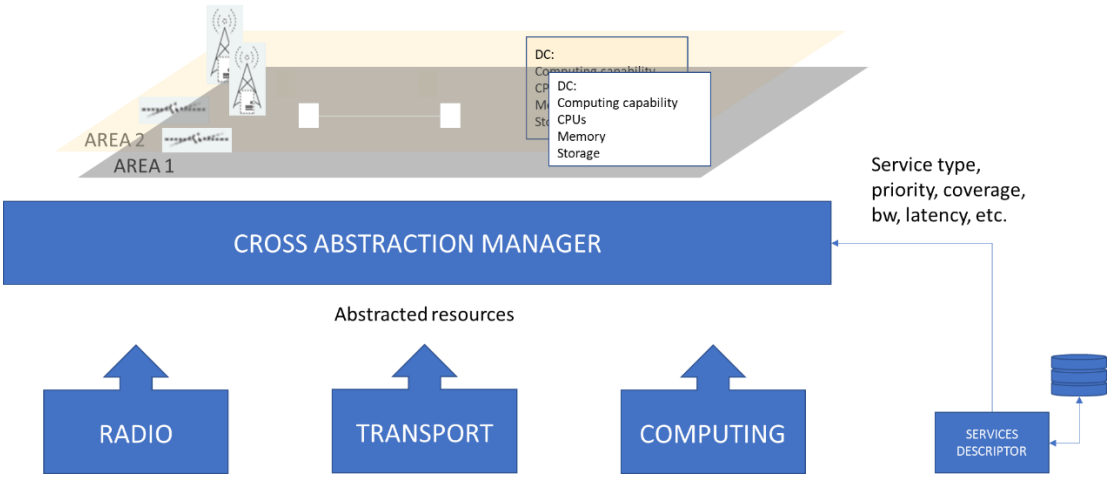


FIGURE 6: CROSS-ABSTRACTION FOR MOBILITY SUPPORT

A new level of abstraction (called cross-abstraction) has been introduced (Figure 6).

The cross-abstraction manager is a method implemented in the 5GT-MTP abstraction engine module that integrates radio abstracted resources with the abstracted resources received form transport and computing layers. How transport and computing resources are abstracted is described in the Section 5.3.1. Radio resources, instead, are abstracted in terms of radio coverage area. In more details, this module organizes the resources provided by the radio domains based on the geographical areas where the vertical services need coverage. To each geographical area is associated a radio coverage that is a subset of radio resources (e.g., enodeB, EPC) that are controlled by a specific domain. How these resources are mapped to the coverage area depends on the policy of the infrastructure provider of the domain. Thus, each domain is represented as a "radio PoP" containing a list of supported coverage area.

In Table 9, an abstraction – processed by 5GT-MTP to be delivered to 5GT-SO – is detailed. The 5GT-MTP has the complete view of cells, DUs, CUs, and and optionally of EPCs including User Plane Function (UPF[1]), as shown in Figure 7. Note that, EPC/UPF can be included or not in the RAN abstraction, based on the vertical service requirements (e.g., MVNO vs. other user services). In the following we assume that the EPC is included in the RAN abstraction. Thus, 5GT-MTP also has the view of the connectivity to the EPCs and such connectivity is in charge of the radio controller. The abstracted coverage area sent to the 5GT-SO is the union of the several cells drawing the perimeter of the area. To keep the freedom of any shape for the area, the perimeter is described by a set of ordered geographical points, as illustrated in Figure 7 (P_1-P_N) and reflected in Table 9 (line 2). By connecting these ordered geographical points, the perimeter is identified.

[1] UPF is the External PDU Session point of interconnect to Data Network and it includes, among other functions, the support of packet routing & forwarding, packet inspection, QoS handling; UPF has part of the P-GW functionality from EPC in 4G.

Finally, the view at 5GT-SO is the perimeter as shown in Figure 8, including information of the UPFs gateways. The information model in Table 9 also includes bandwidth values, which depend on the signal-to-interference-noise-ratio that is a function of several parameters such as the distance between user equipment and antennas and fading. Examples of propagation models can be found in the ITU Radiocommunication Sector document ITU-R M.2412-0 for several scenarios such as rural, urban, and indoor environments. Then, the signal-to-interference-plus-noise ratio imposes a proper modulation and code for transmission, which finally determines the bandwidth. B-max is defined as the maximum among the maximum bandwidth values involving all the cells. B-min is the minimum bandwidth at the perimeter.

TABLE 9: ABSTRACTION OF THE RADIO COVERAGE AREA

Parameter	Description
Id	Identifier of the area
geographicalAreaInfo	It provides information about the covered area expressed as a list ordered points identifying a perimeter. Such points are identified with geographical coordinates (latitude and longitude)
B-min	Minimum bandwidth (Mb/s) that can be allocated to a service, e.g. along the perimeter
B-max	Maximum bandwidth (Mb/s) that can be allocated to a service in the area, e.g. in proximity of an antenna
Gateways	List of IP addresses associated to UPFs gateways

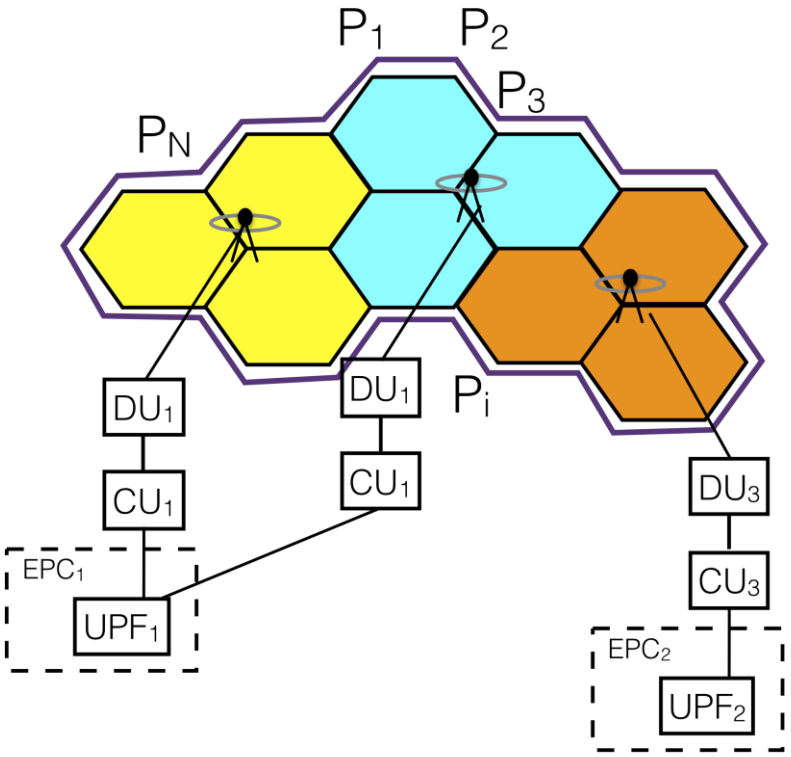


FIGURE 7: 5GT-MTP VIEW

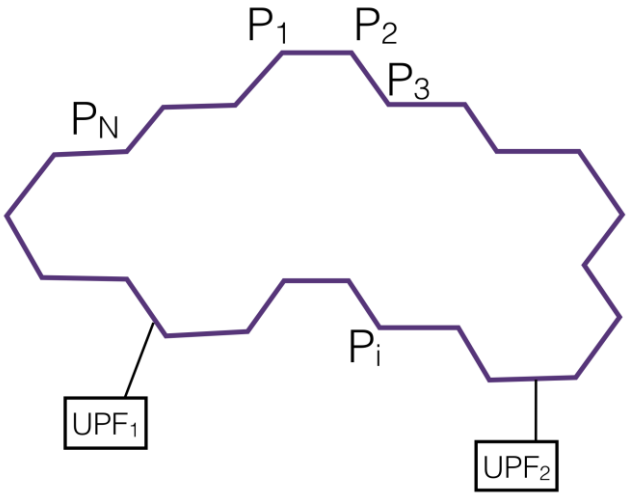


FIGURE 8: 5GT-SO VIEW OF THE COVERAGE AREA

5.3.1.4 MEC support

The 5GT-MTP plugin is designed around the hypothesis of a regional abstraction, as shown in Figure 9. In particular, it assumes that the mobile network is organized in tracking areas, each including a number of cells/eNodeBs, which are in turn organized in regions. Each region corresponds to a single telco (edge) NFVI-PoP and a single MEC Platform (MEP). This abstraction is generic and captures deployments with arbitrary granularities. For example, it does not preclude the case for edge NFVIs operating micro-data-centers collocated with eNodeBs or where there is a single edge NFVI per tracking area.

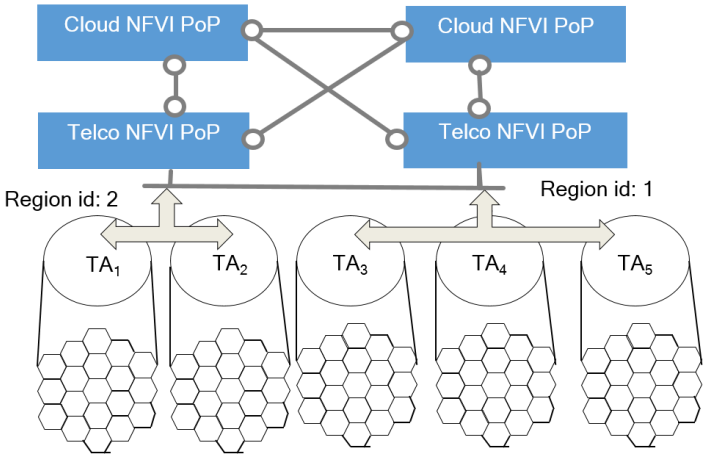


FIGURE 9: MEC REGIONAL ABSTRACTION

The MEC MTP plugin maintains a mapping between MEPs and regions in its internal database. In particular, for each region, it stores information about the API endpoint of its corresponding MEP, which it retrieves when it receives a MEC service request from the 5GT-MTP to apply the necessary traffic management or other rules.

Edge NFVIs, however, are treated by the 5GT-MTP as regular ones when it comes to managing application images, to instantiating applications, and handling their lifecycle management. In this respect, MEC application instantiation takes places as in the case for regular VNFs, with the exception that the 5GT-MTP will need to communicate with the MEC plugin after the instance has been created by the VIM plugin, in order to pass on to it MEC-specific information. The MEC plugin then acts as a MEC Platform Manager (MEPM), interacting with the MEP to configure it over the Mm5 [34]reference point of the ETSI MEC architecture.

In particular, the information sent to the MEC plugin includes traffic rules and DNS rules, which the latter uses to configure the MEC platform appropriately so that specific traffic is offloaded to MEC application instances. These rules are encoded in the MEC application descriptor (AppD) in its appTrafficRule and appDNSRule fields, and are complemented with information received by the VIM plugin (e.g., the IP address of the MEC application instance). One other differentiator is the fact that typically edge NFVIs feature lower latency and offer specific services provided by the MEC platform, such as the RNIS. This information is exposed by the 5GT-MTP to the 5GT-SO in order for the latter to optimally decide on instance placement. Specific latency constraints and service requirements, as these are encoded in the appLatency, appServiceProduced, and appServiceRequired fields of an AppD, are used by the 5GT-SO to satisfy placement constraints, and by the 5GT-MTP to (i) appropriately configure the MEP via the MEC plugin for specific application instances, and (ii) to ensure that latency constraints are not violated. Further details on the interface exposed by the MEC plugin to the 5GT-MTP can be found in Section 5.5.3.

The information model used is the same one used to allocate compute resources (reported in the Table 6) plus a set of parameters exposing information related to the MEC region that are used for the placement of MEC applications. It includes a unique identifier of the region, the area covered by the region and the guaranteed delay that the region can assure to a service that is allocated in this region.

The information model that is used to expose MEC region is represented in Table 10.

TABLE 10: ABSTRACTION MODEL OF THE MEC SPECIFIC PARAMETERS

Parameter	Description
Id	Identifier of the MEC region
geographicalAreaInfo	It provides information about the region covered area expressed as a list ordered points identifying a perimeter. Such points are identified with geographical coordinates (latitude and longitude)
D min	Minimum delay that can be guaranteed for the service allocated in the region

The main deployment scenario supported by our current MEC implementation is that of a shared MEP per region, where a single MEP instance handles the applications and traffic of all MEC tenants. It should be noted that this MEP instance can operate in a native or virtualized way (i.e., running itself as a VNF in the edge VIM).

5.3.2 Slicing in the RAN

The concept of network slicing applies as well to the RAN, providing logical radio access networks with customized characteristics and capabilities tailored for specific vertical services. The 5GT-MTP consists of the actual infrastructure (physical or virtual) over which the vertical slices are created. Moreover, the 5GT-MTP is the single point of contact for the service orchestrator as well as it abstracts all available physical and logical resources of a slice comprising of radio, transport network and compute resources. The 5GT-MTP radio controller provides the abstraction of the radio access network (RAN).

This section presents some aspects of RAN slicing such as the RAN slice concept itself, realization, practical deployment options and challenges as a basis for the discussion on the cooperation between the radio controller and the mobile network itself. Moreover, further constraints and limitations imposed by standardized RAN architecture with regards to RAN slicing are explained.

An end-to-end NSI is composed of network slice subnet instances (NSSI) of the RAN, core network (CN), Transport network (TN), and the vertical applications. In slice deployment, the complete NSI is defined at the 5GT-VS level by vertical service blueprint and the Network Slice Subnet Instances (NSSIs) may be shared by multiple network slice instances.

In a 5G mobile network, each NSI is uniquely identified by a Single Network Slice Selection Assistance Information (S-NSSAI). The S-NSSAI is used by end devices to indicate a specific slice to which the user wants to connect while accessing the 5G network. Depending on the SLA of the vertical in the subscription database, the operator provides the list of S-NSSAIs called Network Slice Selection Assistance Information (NSSAI) as a configuration parameter to the user. For a further summary of the network slicing concept see D1.3 [12] Section A3.1.7.

5.3.2.1 NG-RAN architecture

To support the wide range of variety of services and applications envisioned in 5G, the NG-RAN is being designed as a modular as well as programmable network platform to be built based on NFV and SDN. In 5G radio design, the RAN functionality is expected

to be implemented rather flexibly as a set of physical and cloud optimized virtualized network functions. These functions may be decomposed and placed in a Distributed Unit (DU) and Centralized Unit (CU) placed at different locations of the network where the actual deployment can be adapted according to the service demand. Such architecture promises to provide the required flexibility, responsiveness and adaptability to meet demands in various business models and Mobile (Virtual) Network Operators M(V)NO environments. Figure 10 illustrates the flexible NG-RAN architecture and the functional split as the Radio, Distributed and Central RAN units (RU, DU and CU respectively). Using the NFV framework, this architecture allows a further functional split within the central RAN functions where the user plane and control plane are placed as CU-CP and CU-UP in separate central RAN unit, which communicates via a standardized E1 interface. In principle, several functional split options and placement of the RAN network functions in DU or CU are possible such as high layer split at the PDCP to lower layer split (i.e. MAC/PHY and lower PHY split) [13]. However, due to the stringent requirements on real-time (RT) processing, NFs related to the RT processes such as PHY, MAC and RLC are preferably be placed within the DU while the non-RT (NRT) process may flexibly be handled by VNFs hosted in the CU, as depicted in Figure 10.

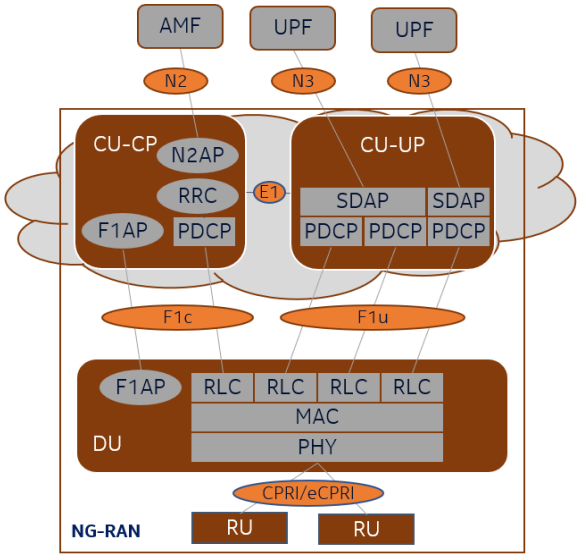


FIGURE 10: NG-RAN ARCHITECTURE AND FUNCTIONAL SPLIT

Such architecture, therefore, promises to deliver a diverse RAN functional behavior and a numerous degree of flexibilities on the implementation as well as placement of the different RAN (V)NFs tailored to the specific services for verticals and offers customized slices for M(V)NO suited to their business models and the needs of their vertical customers. The NRT NFs placed in the cloudified environment in the CU can be virtualized and be created optimized for different network characteristics of specific slices. The key degrees of flexibilities of the NG-RAN which enables supports for the creation and deployment of slice includes:

- creation of instances,
- placement of functions and transport links,
- radio resource management and transport resource management.

5.3.2.2 RAN Slicing Overview

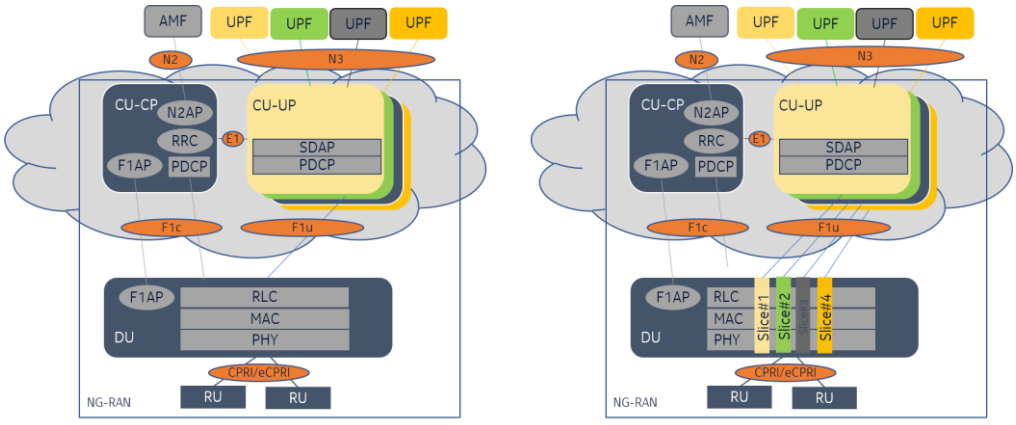
The Radio network part of the end to end network slice is composed of the radio network functions associated to this RAN-NSSI. It is responsible for applying the required network functionality and characterization of the operation of the different logical networks on the air interface. Depending on the business operation model, a vertical can have a customized list of requirements to be fulfilled by their network slice in their SLA. The SLA typically includes various kinds of requirements related to performance, service coverage, availability, security, reliability. In addition to the QoS demand of each service, the RAN slice is responsible for enforcing those slice specific SLAs. Unlike to the CN where slice dedicated instances can be flexibly created using VNFs based on the virtualized CN infrastructure, there is a limited flexibility and configuration options in the RAN slice because most of the RAN functions are implemented as a hardware appliances and RAN resources are expensive and scarce.

5.3.2.2.1 Slice Realization and deployment options in the RAN

A network slice is realized by instantiating associated NFs to deliver the desired e2e characteristics of the logical network. These NFs are realized on different types of the network infrastructure element such as dedicated hardware where these NFs are typically to be shared with less flexibility or on NFV infrastructure where slice customized VNFs can be flexibly implemented. NG-RAN slice components (RAN-NSSI) and slice specific NFs implementation can be comprised of both PNFs and VNFs. Moreover, depending on the deployment strategy and operational model of the M(V)NO, an e2e NSI can be realized based on RAN-NSSI composed of either slice dedicated or common/shared RAN-NFs.

For example, in the typical higher layer RAN split deployment option, the lower layers of RAN functions such as PHY and MAC are implemented in the DU-RAN as a PNF. Some functionalities of it can either be implemented as slice-specific with dedicated resource per slice or as a common DU-RAN NFs using a shared resource. However, the fact that the NFs are implemented as PNF with less flexibility and the limited resources available in the DU makes the realization of a slice-specific NFs with slice dedicated resource practically challenging. Moreover, such paradigm may also impose an additional constraint to the number of slices that can be supported by the RAN. On the other hand, following the operator's deployment strategy, the higher layer RAN functions can flexibly be realized as:

- Common/Shared NFs
  - CU-CP/UP common/shared for all slices with partitioned VNF
- Slice dedicated (V)NFs
  - CU-CP/UP VNF with dedicated internal resources: e.g. URLLC-slice



(a) NSI with shared VNFs

(b) e2e slice dedicated VNFS

FIGURE 11: NSI IMPLEMENTATION WITH DEDICATED AND SHARED (V)NFS

One of the characteristics of the e2e slice deployment is the degree of isolation that is desired to be achieved between slices. One NSI may be fully or partly, logically and/or physically, isolated from another NSI. In principle, an NSI instantiation may involve either a newly instantiated NSSI or reusing already created NSSIs across the RAN and CN. These (V)NFs of the NSSIs can be exclusively used by one slice or shared with another slice leading to a completely or partly isolated slice deployment, respectively. Slice isolation over the RAN slice subnet can be achieved to a different degree of flexibility on the DU and CU. Moreover, slice isolation on the DU where the RAN NFs are mainly implemented on a shared hardware can be realized via configuration derived from the SLA to guarantee the desired degree of slice isolation. Such operation can be highly facilitated and the number of slices to be simultaneously supported can be maximized via a highly dynamic and automated slice configuration/reconfiguration mechanism. However, such mechanism might not be practically optimized for some sensitive critical service supporting slices (e.g. URLLC). For such type of use cases, a dedicated and isolated slice can be deployed using a static configuration as well as with a dedicated spectrum or exclusively reserved radio resource on the air interface, Figure 11.

5.3.2.2.2 Network slice deployment and capacity dimensioning

Slices in a 5G mobile network cannot be deployed freely. Slices and their services are available only within a Registration Area (RA) where the RA consists of one or more Tracking Area (TA). A TA consists of cells of one or several gNBs. Each TA is identified by a TA identifier (TAI). As RA information is used only within the CN, defining the network slice coverage area is done using the TAIs. The size of a TA, small/large, may have implications mainly on the operation of non-stationary UEs as TA information is related to UE mobility. For example, UE-Idle mode, the location of a UE is known on tracking area granularity. Thus, the smaller tracking areas, the more often UEs have to perform tracking area updates. The association of the supported network slice(s) to the valid TAI and the information about the mapping of the TAI to the geographical area is provided to the UEs by the serving cell via broadcasted System Information Blocks (SIB). Depending on the slice type and the operator business models, some of the slice coverage may span from a nationwide to a very localized coverage such as in the private industrial environment. Figure 12 depicts, the slice coverage and TA mapping for mix of slice deployment situations.

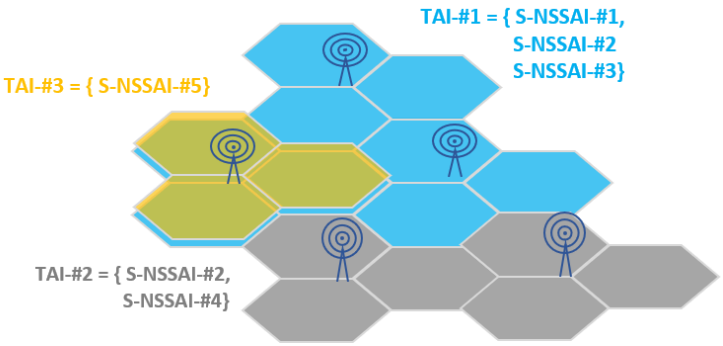


FIGURE 12: SLICE COVERAGE AND TRACKING AREA MAPPING

A gNB can support one or more layers of TAs each supports a list of valid slices. For example, in Figure 12, TAI-#3 could be an area where a slice for a specific localized industry zone is deployed with a dedicated resource and customized RAN configuration supporting only slice S-NSSAI-#5 laid over TAI-#1. Whereas TAI-#1 with 3 other slices listed, on the other hand spans a wider coverage region. The list of slices to be supported within a TA managed by higher layer management functions and orchestrators. A specific slice can be added/deleted by the operator or based on a vertical customer need to the TA list at any time. However, there can be some practical situations such as slice corresponding to certain S-NSSAI(s) might be temporarily/permanently unsupported in some cells due to several factors such as RAN incapability, unavailability of the shared or dedicated (virtual) resources, etc. Such issues make network slice deployment, service provisioning and ensuring availability of the service anywhere/time challenging.

5.3.2.2.3 Slicing in the context of RAN protocol layers

A 5G UE running diverse applications can simultaneously be connected to several slices for the respective services. The valid list of the slices a UE can access is indicated by the UE with NSSAI which consists of a list of one or more S-NSSAI that uniquely identifies a single slice in one PLMN. Upon registration process and completion of the connection setup, a PDU session is established for the specific service on a specific slice. Each 5G QoS flows, which refers to one or group of more IP flows with the same QoS treatment requirement, can be associated to a PDU session of the slice delivering the service. The 5G-RAN applies the radio resource management (RRM) policy and SLA of supported slices for the QoS differentiation across and within slice and ensure that the promised service quality is guaranteed. The 5G QoS framework, the UE subscribed slice list, the association of the IP flows within a slice and bearer mapping are briefly summarized and shown across the RAN protocol layers in Figure 13,[14].

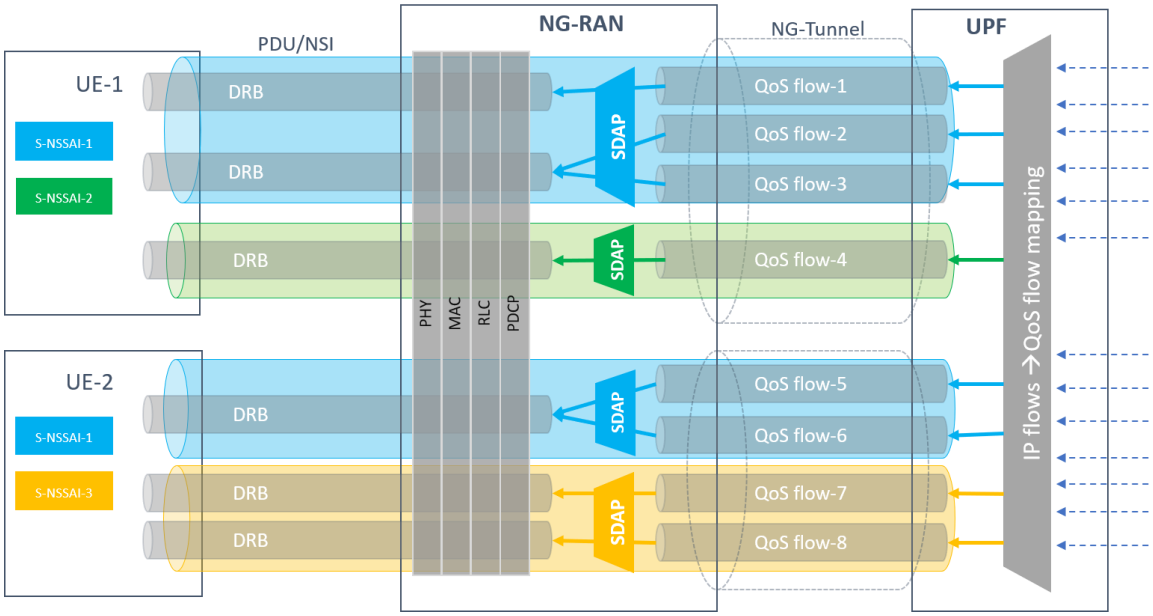


FIGURE 13: 5Q QOS FRAMEWORK AND QOS FLOW MAPPING WITHIN SLICE

In general, the 5G-RAN may serve a single UE with one or more NSIs simultaneously where each UE application/service is associated to its slice with the S-NSSAI. The S-NSSAI is associated to one or more NSI depending on the operator's deployment strategy or need. This means S-NSSAI to NSI mapping can optionally be one-to-one or one-to-many or many-to-one in the same or different TAs [15]. In the case of a fully shared NSI deployment, several S-NSSAIs are mapped to a single NSI whereas in one-to-many mapping, multiple NSIs are associated to a single S-NSSAI. Such one-to-many mapping NSI deployment option may be carried out for various reason such as redundancy to ensure service availability, ease of NSI-specific service upgrade or for seamless execution of slice administration/subscription change within a TA. However, the network at any one time serves the UE with only one of the NSIs associated to the S-NSSAI and each PDU sessions of a UE belongs to one and only one specific NSI per PLMN. The network may implement an automated mechanism for slice selection change and NSI mapping so that UEs can be dynamically steered to the right NSIs. The S-NSSAI and NSI mapping is illustrated with Figure 14 where NSIs consisting of the corresponding NFs of the RAN/CN-NSSIs and their interconnection is shown. This separation into different RAN-NSSIs corresponds to the provisioning of several end-to-end slices as described in D1.1, Section 1.2 [6]. The S-NSSAI to be used for a specific slice can be requested by the vertical when instantiating a vertical service or it can be decided by the 5G-TRANSFORMER system. This is similar to deciding on the IP address to address a service in a datacenter.

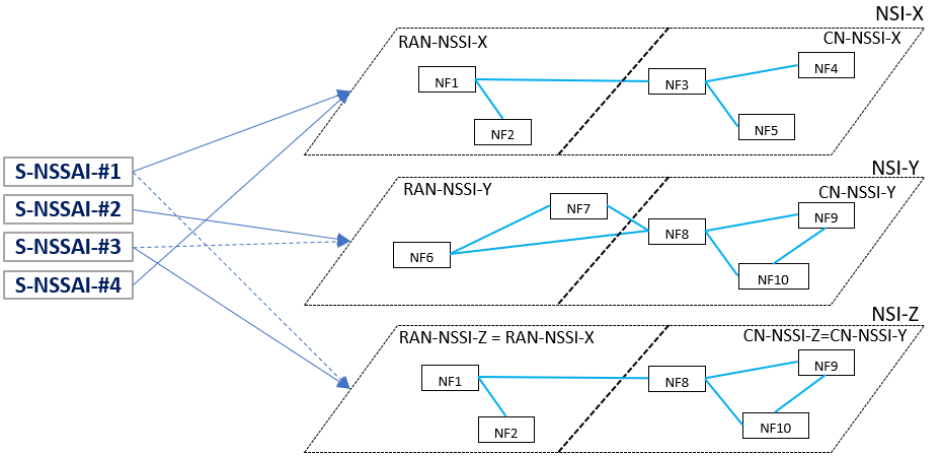


FIGURE 14: S-NSSAI TO NSI MAPPING

5.3.2.2.4 Slice Aware Radio Resource Management and Impact on Scheduler

The 5G-RAN is the key network element that enables provisioning of the various applications/services over the air interface network simultaneously to the different slices' end users. Depending on the slice deployment options employed such as degree of slice isolation, resource sharing model, SLA and QoS demand of slice services, the RAN implementation should be able to address these requirements laid by the M(V)NO and service/slice tenant in an optimized and efficient manner. In this regard, the scheduler is responsible for ensuring the fulfilment of the QoS and enforcing the SLA as it is the one who takes care of the radio resource assignment each UE. In this regard, the radio resource management and scheduler functions are crucial and play key role in ensuring the delivery of the desired system performance. Besides to the strict service QoS requirements, tenants might be interested to choose and pay for different options of resources usage or share scheme on the air interface and how it is granted to their slice and how slice-specific shares are handled such as exclusive or dynamic sharing manner, how much of the slice services are prioritized to be considered in the SLA. In general, the M(V)NO may have several possible resource sharing schemes as part of their business model

- Shared resource: where no slice specific shares are granted, and no slice priority is enforced such that a slice is served on first come first served basis.
- Dedicated resource: portion of system resource is dedicated and granted to a slice. Unless conditioned policy is applied, no other slice can use this dedicated slice's share even if it is unused [16].
- Exclusive allocation or dedicated spectrum: the total resource pool of spectrum is exclusively reserved for a specific slice.

These criteria, if included, within the SLA shall be supported for the slice deployment and be addressed by the RAN. Hence, this requires defining a slice aware RRM policy and designing a scheduler that is responsible to fulfil the promised QoS as well as slice specific-SLAs. However, a mix of different radio resource sharing models employed for specific-slices might not be efficiently supported simultaneously with one scheduler. On one hand, different slices may have different frame structure design on the air interface and implement various scheduling time such as standard-Transmission Time Interval (TTI), short-TTI, mini-slot which may require a dedicated scheduler function design. However, an architecture that supports a slice-specific scheduler makes implementation

more complex and challenging as the real time processing as well as computing hardware resources on the RAN are scarce and have limited flexibility and scalability.

5.3.2.3 Practical Aspects of RAN Slicing

With RAN-slicing, the NG-RAN shall be able to flexibly offer different functional behaviors, support various KPIs and enable to construct flexible SLAs to meet the demands of specific tenants and slice-specific services. Some of the capabilities include flexible creation and placement of RAN function instances optimized for a specific slice. The practical implementation of the gNB's PNF and VNFs as well as the degree of the achievable flexibility are limiting factors. The practical limitation on the slice deployment and slice-based 5G service provisioning for an M(V)NO lies mainly on the RAN subnet of the end to end slice. This is due to the fact that delivering a different and diverse slices' services simultaneously on a single physical infrastructure in the most efficient way while ensuring the promised SLAs for every single business slice is challenging. Furthermore, the level of isolation that can be practically achieved on the radio air-interface is limited thereby constraining the ability to independently configure, optimize the RAN parameters separately per tenant/slice. As the network elements in the RAN are cost optimized mass-volume products, the efficient usage of the provided resources is crucial.

5.3.2.3.1 gNB capacity requirements regarding Slicing

The RAN capacity dimensioning aspect in terms of slice support is highly dependent on the employed slice deployment paradigm such as whether the slice is either statically/semi-statically configured or dynamically deployed. In the static slice deployment paradigm, each slice-NSI configuration is created and maintained based on a strict agreement between the vertical/tenant and the M(V)NO and may be due to a stringent service requirement and/or business model of the tenant. However, such approach could lead to a limited number of slice support per gNB due to the slice dedicated resource reservation while resulting in a huge CAPEX and OPEX as well. On the other hand, a great deal of system automation can enable to apply a more efficient and dynamic slice deployment where slice specific requirements can be created on a self-service portal with a list of requirements (which can be handled by the vertical slicer) and the slice may be created and managed in self-organized manner for the specific situation, location and time scale. In such dynamic slice deployment, an operator must use own automation to fulfil the listed service requirement without exclusively dedicating resources per slice while maintaining the desired operational isolation. Such approach can effectively control slice life time more dynamically enabling multiplexing of several slices' deployment per RAN with in a localized TA as well.

The NG-RAN capacity and the number of slices that can be supported, in general, depends on the type and capacity demand of the slices within that TA as well as the end to end capacity of the RAN infrastructure such as computation and transport. Moreover, the scheme of RAN slice subnet instantiation either via a dedicated or shared network function is another factor that essentially determines the gNB capacity dimensioning. For example, the number of slices that can be supported on a single gNb could be related to the granularity of splitting up resources, for instance a 10Gbps transport interface can be split in a rather fine granular manner and could be used by 1000 NSIs with non-GBR traffic, on average providing 10Mbps per NSIs. On the other hand, let's assume 8 UEs can be scheduled per TTI and there are several URLLC NSIs. Then at most 8 NSIs can be supported, allowing one UE per TTI to be scheduled per NSI. Different resources at a

gNb support different granularities in splitting them and share them among different slices. This granularity depends also on the requirements of availability of a resource for a slice. The more stringent the requirements, the more static the split would be. Both the granularity of the split as well as the requirements limit among how many NSIs a resource can be split. Correspondingly, this limits the amount of NSIs a gNb or RAN can support. The limits may be different per slice type. E.g. there could be a limit for URLLC NSIs and a different one or no limit at all for eMBB NSIs.

In general, the common RAN capacity and gNB resources which are potentially to be shared across slices are limiting factors and some of them are:

- Air interface capacity
  - Amount of UEs scheduled per TTI. If a gNb supports multiple carrier frequencies, then this number may be larger.
  - Separation of PRACH among slices
- Management capacity
  - Number of slices that can be managed on a gNb
  - Number of slices that can be monitored on a gNb.
- Control plane capacity
  - Amount of different AMF (sets) to which a gNb can connect
  - C-plane procedures per second
  - Counters
- Transport capacity
  - Number of distinguishable VPNs, limited by e.g. usable VLANs, VRFs, BTS IP addresses, etc.
  - TRS counters and generally amount of to be managed TRS interfaces.
  - Capacities can be different on N3, F1, Xn interfaces.
- Platform capacities
  - Buffer space
  - memory
  - internal communication

5.3.2.3.2 Slicing and Air-Interface

With the RAN-slicing, the air interface should support coexistence of different types of slices associated to specific services and/or tenants. In line with this, the NR flexible air interface design has introduced different spectrum options, scalable ODFM with multi-numerology structures and duplex techniques where various configuration options are specified to deliver a service-specific optimized air interface behavior, such as a dedicated spectrum, mini-slot, short-TTI. Thus, gNB is expected to support several slices potentially with a mixed numerology and shared/dedicated spectrum options. For example, an URLLC slice type deployment might require an end to end slice instance configuration to be operated on a dedicated spectrum or an exclusive time frequency resource grid. Such a deployment option can guarantee slice SLA and offers an easier slice management due to complete RAN-slice subnet resource isolation, it is, however, costly and not optimized for such scarce and expensive spectral resource usage. Figure 15 illustrates the possible different configuration options for the radio resources over the air interface for a mixed numerology of multiple slices.

FIGURE 15: MULTIPLEXED SLICE AND MIXED NUMEROLOGY SUPPORT

In Figure 15 (a), the complete spectral resources are shared by all slices and the burst arrival of a mini slot/short-TTI slice such as URLLC services can be always prioritized over the other slices such as eMBB and be scheduled right away. Such scheme is done in a more dynamic manner and ensures maximized utilization of radio resource while supporting the slice-specific numerology and scheduling time. Where as in Figure 15(b), the slice specific resource can be exclusively reserved and the respective frame structure, numerology configuration types are applied. In this case, each slice is exclusively reserving its own pool of radio resources guaranteeing resource availability all the time but may be unused in the absence of slice traffic. Moreover, slice specific radio resource reservation may require a dedicated RRM entity and logical scheduler implementation.

5.3.2.3.3 Options for slice aware Radio Resource Scheduling

The requirement to support multiple slices over a single NG-RAN is demanding a technical solution on how to apply the best radio resource management (RRM) and policy to fulfil the SLA for each slice while delivering enhanced system efficiency. NG-RAN radio resource management can be better achieved through RRM slice conditioned policies and an optimized slice-aware radio scheduler design. In order to optimally manage the over-all system resource and radio resource usage within a slice and across slices, the RRM may host a common resource management entity where all the rules and translations of SLAs of different tenants can be carried out. Such slice specific translation and supervisions can be done at higher layers of the RAN protocol which can be placed on the virtualized central RAN units. The scheduler architecture and implemented algorithm should be aware of a slice and the rules for assigning, reserving and partitioning of the radio resources of the system as well as the share per slice. Hence, a more flexible and adaptive resource management and scheduler design is crucial to provision slice customized RAN-feature while delivering an optimized operational efficiency.

The architecture and implementation of the slice aware radio resource scheduler design can be determined by several factors:

- The first factor is the radio resource assignment policy such as resource reservation and agreed share of slices. Such factors determine, how much resources are promised and how are those provisioned with either exclusive share per slice or a flexible slice share letting a more adaptive resource usage within an inter-slice share.
- The second factor is the desired algorithm implementation to apply the different metrics and prioritization rules with respect to different slice and their traffic. This can be attributed to the slice service type, the requested nature of the e2e slice deployment and the isolation level desired over the RAN slice subnet. For example, different and customized scheduler algorithms can be implemented for different slices. Such implementation option may seem to better guarantee

service/slice specific metrics however, it is practically challenging from the system processing limitation.

- The third factor can be driven by the architecture where different scheduler can be implemented and placed with in the CU or DU depending on the service/slice type and related requirements on latency: e.g. for eMBB and URLLC type slices.

Independent of how it is implemented, the scheduler should be able to support a more adaptive and flexible radio resource assignment fulfilling requested SLA and satisfying the tenant business model while efficiently utilizing the radio and system resource. Moreover, high level of coordination needs to be supported to coordinate several scheduling instances across different slices, monitoring slice policies to adaptively react by monitoring the slice traffic behavior as well.

5.3.2.3.4 Impact of Slicing on Transport

Slicing is impacting a lot as well on the transport networks connecting the virtual or physical RAN network functions. E2e transport is accomplished using multiple layers and several segments.

Transport in a mobile network consists of two main layers. The e2e transport layer that connects the end-user applications running on the UEs to application servers (APs), clients and peers represents an own IP network of itself that runs on top of the network elements of the mobile network, which are interconnected within another IP network on a second layer, which is independent from the first e2e layer.

The e2e IP flows of the first layer are virtually tunnelled through the mobile transport network forming the second layer.

Segments of the lower layer transport may comprise the low latency fronthaul (like “eCPRI” over Ethernet or “CPRI” over Fiber), the high latency fronthaul (for interfaces like “F1” or “W1” used in 3GPP compliant cloudified deployments with central unit (CU) and distributed unit (DU)), mobile backhaul (for interfaces like “NG2”, “NG3”, “S1” and “X2”), the IP core network and the datacenter transport networks.

The three first segments are falling traditionally into the RAN transport domain, while the latter two are traditionally considered as Radio Core transport domain. In 5G networks however, this split will blur. “Edge Datacenters” for instance will be located much closer to the applications running on the UEs to allow a short latency for the communication. The same will hold true for “Mobile Edge Computing” (MEC), where servers are collocated to BTS sites, allowing fastest response times via local breakouts or similar.

5.3.2.3.4.1 Aspects of slicing on e2e transport layer

Slices form independent networks. In most simple case a UE may connect to just one slice (e.g. an IoT device to the IoT slice). Slices are forming as well independent addressing domains. This means that another device, connected to another slice, may use the same IP address value as the first device that, however, is placed in another slice.

3GPP specifies that one UE will be able to connect to up to eight slices. A UE needs in this case to be able to provide at least eight independent IP interfaces that can connect to up to eight independently managed IP addressing domains. Each of the eight interfaces will be served via its own set of QoS flows and bearers in the air interface.

This has implications as well to the operating systems used for the UEs. The UEs and their operating systems need to support isolation for the slices, the applications running within those and the IP connection to the outside world, if needed. Today's operating systems need thus to be extended.

Support for SW Containers, Virtual Machines or isolation done by other methods must be introduced in Android, IOS or other mobile OS to fully use the benefits of the slicing concept in a single device.

5.3.2.3.4.2 Aspects of slicing in RAN transport networks

Transport is organized as a set of layers. The most prominent Transport Stack is the OSI seven-layer stack. The most used one is the Ethernet/IP stack. However, in RAN transport networks also other stacks (e.g. optics/WDM, OTN) are implemented.

- Low latency Fronthaul Network Segment

Low latency fronthaul networks connect the baseband units of an DU doing the radio signal processing with the radio units (RU) emitting the actual radio waves. Traditional radio units have the building blocks for sending and receiving the radio signals but have only rudimentary network functions.

The widely used CPRI is a TDM based interface, not used outside radio networks. Combined with the stringent latency requirements there is barely equipment available for networking on CPRI layer. Most often CPRI links are built as point-to-point connections using dedicated fibres or as WDM network with dedicated wavelengths per CPRI connection.

CPRI links carry antenna signals that comprise a time-domain series of combined IQ-data of all UEs of a particular cell. The minimum granularity that can be allocated to one slice is thus "cell" as well. While for some vertical services, like public safety networks, this may be sufficient, for the bulk of the other projected vertical services the low latency CPRI Fronthaul network does not allow isolation of individual slices.

With the advent of Ethernet based eCPRI the general situation improves in terms of packet-based networking. Ethernet Switches are widely available and widely deployed. However, the situation does not change regarding the support of slicing. With the currently standardized PHY splits, comprising a series of frequency-domain IQ symbols, it is still not possible to generate independent flows to a dedicated UE in a cell or to particular slice terminations within one UE. Again, the smallest granularity that can be allocated to a slice is "cell". - High Latency Fronthaul Network Segment and Mobile Backhaul Segment

The high latency Fronthaul Network segment (sometimes called "midhaul network"), spans between the DU and the CU of an gNB or eNB. Both, CU and DU may host virtualized functions of the BTS, connected via standardized interfaces, like F1 in case of NR or the coming W1 in case of LTE.

The traditional Mobile Backhaul Segment connects the backhaul interfaces of the gNB-CU, like N2, N3, Xn and X2 with the core functions or adjacent gNBs and eNBs. Backhaul interfaces of LTE eNBs comprise S1 and X2.

5G CU and DU as described above are slice aware and can setup e.g. the F1 interface in a way that allows the isolation of slices within the transport segment. The management granularity in the high latency Fronthaul network is on bearer level. One bearer, with in

case of NR all contained QoS flows, belongs to one slice. Thus, a mapping is possible and slice isolation can be done.

While bearers are a supported concept in eNB backhaul interfaces S1 and X2, they do not exist in the N2 and N3 backhaul interfaces of an NR gNB. They are replaced by the above mentioned QoS flows. As QoS flows are finer granular than bearers and can be as well mapped to slices.

Isolation among the slices may happen on several layers of the transport stack. At the physical interface of the DU or the CU, VLANs may be used for Ethernet based networks. However, as most mobile transport networks are IP based, virtual IP interfaces belonging to one slice can be implemented by a virtual routing function (VRF). This isolates the IP address spaces among each other and allows independent allocation of IP addresses within each space.

For the actual transport network between CU and DU and between CU and core quite often provider-based VPNs are applied. Many solutions for L2 and L3 networks exist, more traditional ones including MPLS, or new emerging ones, like Openflow-controlled[17].

- **Datacenter Transport**

The transport network connecting different servers within a DC differs significantly from the transport networks as described for low latency fronthaul, high latency fronthaul and mobile backhaul networks.

DCs are designed to cope with an enormous number of tenants and applications that are deployed in a uniform, consistent computing environment. Deployment speeds of software are measured rather in seconds than days. This requires a high degree of automation. In fact, many of the concepts of software defined networking that now are proposed for the mobile transport have been originally developed for DCs.

Common building elements of DCs are servers, racks and pods. Several servers are mounted in a rack and some racks form a pod. Special pods exist for connecting the DCs with the outside world via edge routers.

One commonly used topology for DC networks today is the so-called multi-tier Clos network. A Clos network provides not only good connectivity of the servers towards the outside world (north-south traffic), but as well for the traffic flowing between the servers within the DC (east-west traffic). The first tier of switches, which are connected directly to the servers are called top-of-rack (ToR) switches after their usual location, i.e. the top of the server rack. The switches in the next tier are called leave switches. They connect the ToR switches within a pod. Finally, the pods are connected via the next tier of switches called spines switches.

Multitenancy and traffic isolation are inbuild features of DC. Thus, those networks are well prepared for the isolation of traffic belonging to different slices. One way to do this is using Virtual eXtensible Local Area Networks (VXLANs) and IP-in-IP tunnels together with a routing protocol (BGP, OSPF or IS-IS) in the Clos Network.

5.3.3 Monitoring

The 5GT-MTP monitoring service is in charge of collecting monitoring parameters related to the managed physical infrastructure in support of assurance of the requested QoS and the optimization of the infrastructure usage in general. In particular, the monitoring at the

5GT-MTP level addresses the metrics related to the utilization and the performance of the physical and the virtual infrastructure, in terms of computing and network resources. However, it does not focus on the consumption of virtual resources associated to specific virtual functions or network services, since such parameters are handled at the 5GT-SO monitoring level.

The 5GT-MTP monitoring service relies on a monitoring platform that follows the same architecture of the 5G-TRANSFORMER monitoring platform defined in D4.3 [11]. In this case, the monitoring data is extracted from the infrastructure through different kinds of monitoring agents, depending on the type of target measurements. In particular, for monitoring data related to physical resources, the agents operate on the network or in the physical servers, while for monitoring the virtual resources the agents work at the VIM or WIM level. For what concerns the monitoring of networking resources, the agents can be embedded in the SDN controller acting as WIM. This approach is particularly suitable to collect data about the traffic exchanged on specific links, or statistics about the packets received, transmitted or dropped in particular ports. Moreover, additional agents may be deployed in dedicated monitoring elements that interact with network probes or active monitoring tools (e.g. embedding traffic generators or traffic shapers). This approach may be adopted to perform measurements related to statistical metrics of bandwidth or delay in a given network segment. Regarding computing resources, the agents embedded in the servers are able to collect data related to power consumption, load of traffic on the server's network interfaces, CPU, memory or disk utilization. Operating at the VIM level (e.g. through an agent collecting data from OpenStack), it is possible to collect further data associated to single virtual resources, like the resource utilization for specific Virtual Machines.

The original monitoring data collected through the different agents is stored in the monitoring platform and made available for queries and reports. Alert notifications are also supported through a subscription-based approach (see D4.3 [11] for further details about alerts generation in 5G-TRANSFORMER monitoring platform). The monitoring data collected at the 5GT-MTP monitoring platform is mostly consumed by the 5GT-MTP itself, e.g., to detect failures at the infrastructure level or to feed its internal resource allocation algorithms. A subset of these monitoring parameters may also be exposed to the 5GT-SO monitoring platform, e.g. through the mediation of additional agents deployed on the 5GT-SO side. However, it should be noted that the 5GT-MTP, acting as a "management entity" of the physical infrastructure, is allowed to retrieve monitoring data related to both physical and virtual resources. On the other hand, the level of information exposed to the 5GT-SO is limited to virtual resources only (e.g. the consumption of CPU for a given VM or the traffic load in a virtual network).

The workflow to activate monitoring for a given set of physical or virtual resources at the 5GT-MTP level follows the same procedures defined for the configuration of monitoring jobs and monitoring alerts at the 5GT-SO level (see D4.3 [11] for further details). In summary, this workflow requires the initial creation of performance monitoring jobs to collect elementary measurements through "exporters" (i.e. the monitoring agents) retrieving data from servers, network monitoring tools, VIMs and/or WIMs. Then one or more dashboards can be created to visualize graphs with performance metrics via web browser. This reporting can be accessed by the infrastructure provider or by the consumers of the 5GT-MTP interfaces. Finally, subscriptions can be created based on arbitrary thresholds on the collected data, allowing the 5GT-MTP to monitor the infrastructure and react whenever a failure or a performance degradation is detected.

5.3.4 Optimization algorithms

The optimization algorithm/s at the 5GT-MTP aim at providing a more granular and/or expanding the output of the executed 5GT-SO PA regarding the heterogeneous resources to be selected and allocated for a specific network service. It is worth outlining the heterogeneity aspect that those algorithms and mechanisms must encompass with respect to the resources entailing: cloud, transport and RAN. Bearing this in mind, it becomes notably complex devising a single algorithm which is able to optimize the allocation of the resources on top of the resource heterogeneity. For this reason, a plausible solution relies on segmenting the optimization on technological / resource basis. In other words, a specific algorithm is devised to optimize the selection and allocation of the resources regarding the intrinsic features of those resources. Thus, in the following it is addressed different algorithms specifically tailored to particular resources / network segments, namely, transport WAN, intra-NFVI-Pop cloud and RAN.

5.3.4.1 Placement algorithm (PA)

5.3.4.1.1 Logical Link Placement Algorithm (LL-PA)

The output of the 5GT-SO's PA algorithm is typically formed by a selected set of NFVI-PoPs where the corresponding VNFs will be instantiated as well as a set of Logical Links (LLs) that would enable the inter-NFVI-PoP connectivity satisfying the network service requirements. This output is then sent to the 5GT-MTP to be processed and used for conducting the operations and actions (e.g., cloud and network resource allocation) to come up with the deployment of a particular network service. In this set of operations and actions, due to the different abstraction mechanisms adopted in the 5GT architecture, it might be needed to trigger a new PA computation (but at the 5GT-MTP level), referred to as Logical Link PA (LL-PA) to accomplish a more accurate selection of the resources. Herein, we focus on the description of the 5GT-MTP LL-PA where the objective is to optimize the inter-NFVI-PoP network resources, i.e. WAN domains and inter-WAN links.

The targeted optimization of 5GT-MTP's LL-PA aims at attaining the most efficient use of the network resources in terms of link bandwidth (e.g., balancing the use of the available bandwidth), network elements (i.e., switch) ports, etc, whilst satisfying the requirements associated to every LL. In this regard one of the main assumptions is that the pool of LLs at the 5GT-SO level for its PA may not be necessarily bound to a pre-defined and static inter-NFVI-PoP path. By doing so, some sort of flexibility is provided to the 5GT-MTP's LL-PA to compute and select those network resources that eventually allow accomplishing a more efficient use of the inter-NFVI-PoP resources.

Proposed LL-PA algorithm

The input information used by the proposed inter-NFVI-PoP 5GT-MTP LL-PA algorithm is:

- View of the network resources (i.e., nodes, links and related QoS attributes such as available bandwidth, delay/latency and cost/metric) of both WAN domains as well as inter-WAN links. Observe that the internal vision of each WAN domain is subject to the abstraction provided by the corresponding WIM plugin handling that domain.
- QoS constraints bound to a specific LL. Selected LLs for a network service made by the 5GT-SO's PA are assumed to be associated to a set of QoS parameters (which in turn must satisfy the network service requirements). Consequently, the QoS constraints that the 5GT-MTP's LL-PA needs to deal with are related to

those linked to the selected LLs rather than the imposed ones by the network service.

The output of the 5GT-MTP LL-PA algorithm for a specific LL forming the network service should specify a strict route connecting the two LL's endpoints that may traverse multiple WAN domain and inter-WAN links and satisfy the aforementioned QoS constraints.

The proposed algorithm is based on an implementation of a K Constrained Shortest Path Algorithm (K-CSPF) based on the well-known YEN algorithm [12]. The idea is to compute the shortest path that guarantees the QoS constraint in terms of minimum requested bandwidth and maximum tolerated latency. The shortest path can be computed in terms of either the number of hops or with respect to the associated cost/metric of every topology link within WAN domains and inter-WAN links. The output of the PA algorithm is to provide up to K feasible shortest routes (in ascendant ordering with respect to the number of hops or the total path cost considering the link metrics). The term feasible is related to the fact that all the candidate routes should satisfy the bandwidth constraint. This means that the most congested path link (i.e., lowest available bandwidth) should be larger (or equal) than the demand bandwidth constraint.

From the set of (up to K) shortest paths, the adopted criteria selects the first route having an accumulated delay over the entire path lower (or equal) than the targeted latency/delay constraint.

If a feasible path cannot be found due to the lack of resources, etc., the expansion of the selected LL should be blocked. This in turn will result on blocking the requested network service.

For the sake of validating the previous 5GT-MTP LL-PA algorithm as well as the 5GT-MTP placement interface defined in Section 5.5.5, the following WAN scenario was considered where the devised LL-PA algorithm is triggered.

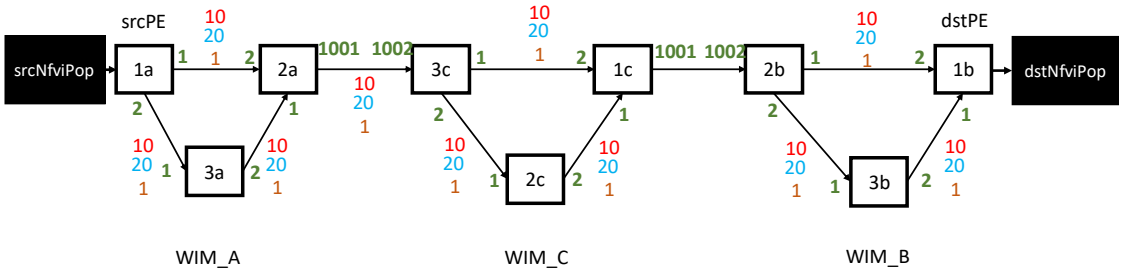


FIGURE 16: EXAMPLE OF MULTIPLE WANS (WIMS) TO VALIDATE THE PROPOSED 5GT-MTP LL-PA

As shown in Figure 16, three WAN domains (controlled by their own WIMs) and coordinated by a single 5GT-MTP entity are considered. Such WIMs are named as: WIM_A, WIM_C and WIM_B. Observe that WIM_A and WIM_B provide the external transport connectivity to both srcNfviPop and dstNfviPop. transport links can be sorted by either intra- or inter-WAN links. Regardless of the WAN link type, all links are characterized by a set of attributes which required to execute the LL-PA mechanism:

- Node endpoints being connected by the link, e.g. Node 1a and Node 2a are connected by a unidirectional link.
- Local and remote link identifiers (green-colored values).
- The link cost (orange-colored value).

- The available bandwidth (blue-colored values).
- The associated link delay (red-colored value).

The above intra- and inter-WAN link information constitutes indeed the WAN topology passed to the LL-PA (via the API described in Section 5.5.5). As input information to the LL-PA is also delivered the two Provider Edge (PE) nodes associated to the LL required to be expanded by the algorithm. In the example shown in Figure 16, the targeted LL to be expanded connects both srcNfviPop and dstNfviPop. In the request LL-PA computation is also indicated the amount of available bandwidth to be allocated through the computed WAN path supporting the LL as well as the maximum end-to-end latency that the output WAN path must not exceed. Using the defined REST API, the request sent by the 5GT-MTP to the LL-PA with the above information and parameters is reflected in the following figure. In the figure, it is shown the response of the LL-PA mechanism which carries the successful computed WAN being formatted as detailed in Section 7.5.5. For the considered example the computed path is though the route formed by the nodes: 1a → 2a → 3c → 1c → 2b → 1b. The exchanged request/response messages along with the computed path takes around 25 ms.

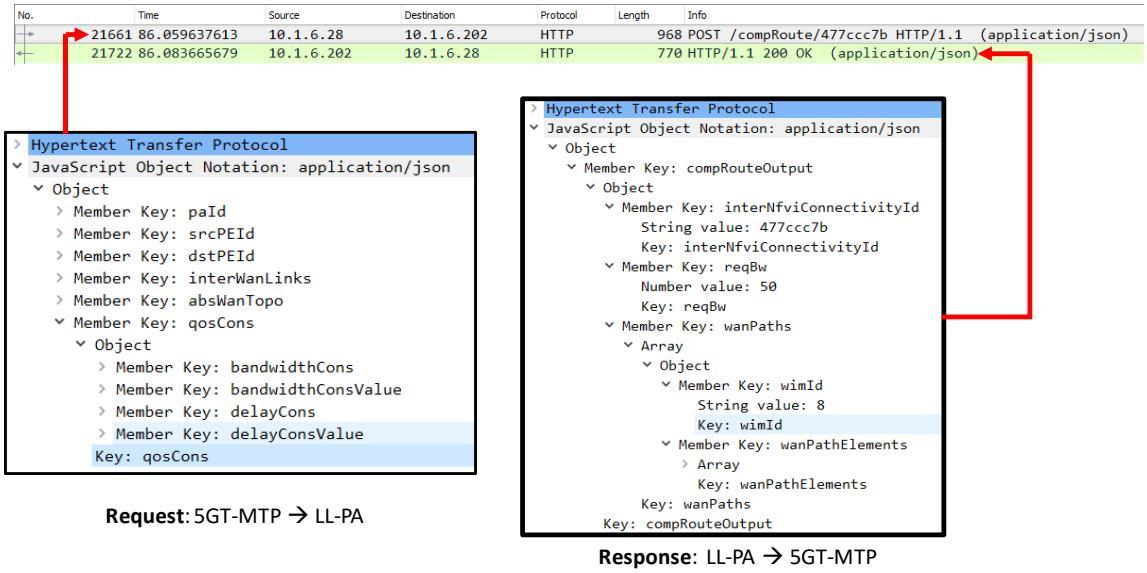


FIGURE 17: REST LL-PA API EXECUTING THE LL-PA

5.3.4.1.2 VNF Placement algorithm (VNF-PA)

In this Section we present an algorithm for VNF placement within a NFVI-PoP, which minimizes the power consumption of the NFVI-PoPs, managed by the 5G-TRANSFORMER platform. Our optimization is of utmost importance, since it helps meeting two project KPIs, i.e., energy efficiency and, indirectly, OPEX reduction. In the following, it is assumed that the 5GT-MTP receives the associations among VNF/NFVI-PoP from the 5GT-SO. By doing so, the proposed VNF-PA algorithm is able to choose on which specific machine (e.g., server) of the NFVI-PoP the VNF has to be actually allocated and run. Therefore, our objective is to obtain a VNF PA algorithm that minimizes energy consumption at each NFVI-PoP.

Next, we first formalize our problem as a multi-resource Generalized Assignment Problem, then we present our heuristic algorithm and our simulation results.

5.3.4.1.2.1 A Generalized Assignment problem for MTP VNF placement

Let us consider an NFVI-PoP composed by servers with heterogeneous characteristics. We assume that each server $s \in S$ in an NFVI-PoP has a power cost for being initialized equal to β_s. Furthermore, as in [18], we assume that each server s, when active, consumes additional power proportionally to its CPU utilization. Let us further consider that each VNF is described by a set of features F, which have to be considered at placement instantiation. Such features reflect the requirements of the VM that on-boards the VNF (note that a VM on-boards at most one VNF in 5G-TRANSFORMER). Examples of VNF features/resources are: CPU, RAM, storage, etc. Only if a server has enough room for each VNF feature, it can be eligible as a candidate for the VNF placement.

To simplify our problem formulation, we normalize each VNF feature requirement by the corresponding capacity at each server. By doing so, we can easily consider when a server is ON. When normalized, the sum of the VNF requirements of each feature $f \in F$ assigned to s sums at most to one and we can express capacity constraints as $\sum_{v \in V} \gamma_{vs}^{f} x_{vs} \leq x_s$, where x_s and x_{vs} are binary variables expressing, respectively, the fact that server s is ON and that VNF v has been placed in server s, while γ_{vs}^{f} is the requirement of VNF v for feature f at server s. Modeling power consumption of server s becomes easy as well, since it can be written as $\alpha_s \sum_{v \in V} \gamma_{vs}^{1} x_{vs} + \beta_s x_s$, where α_s is the power consumption proportional to CPU utilization and γ_{vs}^{1} is the CPU requirement of VNF v at server s. Nevertheless, considering the fact that servers are different from each other, the aforementioned normalization has the disadvantage of creating server-dependent VNF requirements.

All in all, for a set of VNF requests V, the exact formulation of our optimization problem is as follows:

$$
\begin{aligned}
\underset{x_s, x_{vs}}{\text{minimize}} \quad & \sum_{s \in \mathcal{S}} \left[\beta_s x_s + \alpha_s \sum_{v \in \mathcal{V}} \gamma_{vs}^{1} x_{vs} \right] & \\
\text{subject to} \quad & \sum_{v \in \mathcal{V}} \gamma_{vs}^{f} x_{vs} \leq x_s, & \forall s \in \mathcal{S}, f \in \mathcal{F} \\
& \sum_{s \in \mathcal{S}} x_{vs} = 1 & \forall v \in \mathcal{V} \\
& \gamma_{vs}^{f} \in [0,1] & \forall s \in \mathcal{S}, f \in \mathcal{F} \\
& x_s, x_{vs} \in \{0,1\} & \forall s \in \mathcal{S}, f \in \mathcal{F}
\end{aligned}
$$

FIGURE 18: OPTIMIZATION PROBLEM FOR VNF PLACEMENT WITHIN A SINGLE NFVI-POP SERVER

Our optimization is very similar to the so-called multi-resource Generalized Assignment Problem (mGAP) [19]. Nevertheless, there is a substantial difference. In mGAP, the cost of assigning an item to a bucket is fixed. In our optimization, instead, the power cost of assigning a VNF to a server depends on the fact that the server was previously initialized or not. Interestingly, any heuristic for the mGAP problem that assigns VNFs to servers in a sequential order may also be applied to our optimization. In such heuristics, when a new VNF placement is performed, the power cost of assigning such a VNF to a server

contains, if needed, the initialization power cost. Table 11 summarizes the variables used in this section.

TABLE 11: NOTATIONS

Variable	Description
$\mathcal{V}$	Set of VNFs requests
$\mathcal{S}$	Set of Servers
$\mathcal{F}$	Set of Features for each request
β_s	power cost for initializing $s \in S$
α_s	proportional power cost for CPU utilization at $s \in S$
γ_{vs}^{f}	requirement of $v \in V$ for feature f at server s
x_s	binary variable, ON/OFF server s
x_{vs}	binary variable, VNF v assigned to server s

5.3.4.1.2.2 The MTP VNF placement algorithm

The mGAP is an optimization problem which has been widely studied, and several heuristics have been presented. Therefore, we exploit the state-of-the-art solutions, tailoring them to our specific problem. As mentioned above, the 5GT-MTP receives from the 5GT-SO the VNF/NFVI-Pop associations. To exploit off-line heuristics, which perform better than the on-line ones, we assume that the 5GT-MTP does not executes instantly the decisions of the 5GT-SO. Rather the 5GT-MTP stores them for a time window T. Upon the time window T expires, the 5GT-MTP places all the VNFs collected and migrates all the VNFs of non-critical services altogether, exploiting an off-line heuristic [19]. Herein, we present the pseudo-code of such a heuristic (see below Figure 19) and its application to our optimization problem.

Algorithm 1 Gavish et al. algorithm

procedure VNF PLACEMENT
  $V_F = \mathcal{V}$
  Compute S_v, the set of servers with enough capacity to receive VNF $v, \forall v$
loop:
  if $V_F = \emptyset$ **then return** Pairs VNF/Server
  else
    if $\exists s$ such that $S_v = \emptyset$ **then return** Unfeasible
    else
      $\forall v \in V_F$, define s_1^v such that $\phi_1 = \alpha_s \gamma^1_{vs_1^v} + (1 - x_s)\beta_s$ is minimum in S_v
      $\forall v \in V_F$, define s_2^v such that $\phi_2 = \alpha_s \gamma^1_{vs_2^v} + (1 - x_s)\beta_s$ is minimum in $S_v \setminus \{s_1^v\}$
      $\forall v \in V_F$, $D_v = \phi_2 / \sum_{f \in \mathcal{F}} \gamma^f_{vs_2^v} - \phi_1 / \sum_{f \in \mathcal{F}} \gamma^f_{vs_1^v}$
      if $D_{v_1} = ... = D_{v_j} = ... = D_{v_*} = \max_{v \in V_F} D_v$ **then** Sort $v_1, ..., v_j$ so that

$$\sum_{f \in \mathcal{F}} \gamma^f_{v_1 s_1^{v_1}} > \sum_{f \in \mathcal{F}} \gamma^f_{v_j s_1^{v_j}}, \forall j$$

        Assign v_1 to $s_1^{v_1}$
      else Assign v_* to $s_1^{v_*}$, such that $D_{v_*} = \max_{v \in V_F} D_v$
      $V_F = V_F \setminus \{v_*\}$
      Update S_v, $\forall v \in V_F$

FIGURE 19: HEURISTICS FOR VNF PLACEMENT

In Algorithm 1, we assume that the set of VNFs that needs to be placed/migrated is represented by V. First, for each VNF $v \in V$, the set S_v of servers that can host v is obtained. At this stage, if a VNF v cannot be placed to any server, the algorithm returns unfeasible solution. Such event is possible since the SO, when assigning VNFs to NFVI-PoPs, has only aggregate knowledge on the NFVI-PoP capacity. For this reason, it is possible that no actual machine can host a VNF that the SO assigned to a specific NFVI-PoP. If instead all VNFs have at least a server to be assigned to, then the MTP computes VNF placements. For the 5GT-MTP, a VNF is critical if the energy efficiency difference between the first and the second best choice for v is the largest in V. Looping over V, the 5GT-MTP always assigns the most critical VNF to its best choice up to concluding VNF placement.

5.3.4.1.2.3 Simulation Results

We now seek to understand how close the performance of the heuristic algorithm described in Section 5.3.4.1.2.2 is to the optimum. To this end, we consider a reference scenario including:

- 10 non-homogeneous servers, whose capacity varies between 10 and 20 vCPUs;
- up to non-homogeneous VNFs, whose requirements vary between 0.1 and 2 vCPUs.

Our main metric of interest is the power consumption, computed considering the typical figure of 85 W per vCPU.

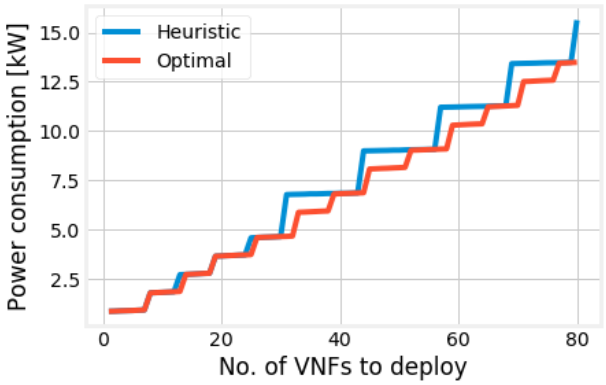


FIGURE 20: POWER CONSUMPTION YIELDED BY THE HEURISTIC ALGORITHM VS. THE OPTIMUM

As we can see from Figure 20, the power consumption yielded by our heuristic algorithm is very close to the optimum; indeed, it coincides with the optimum for many values of the number of VNFs to deploy.

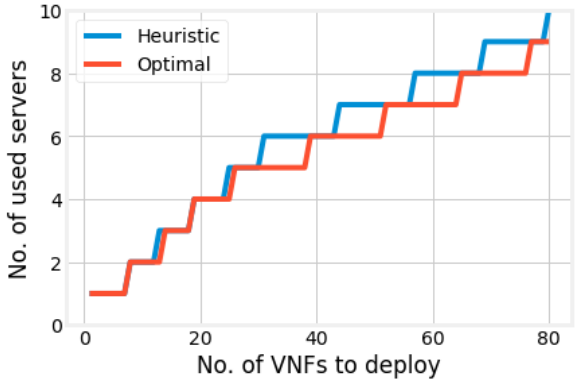


FIGURE 21: NUMBER OF SERVERS USED BY THE HEURISTIC ALGORITHM VS. THE OPTIMUM

Accordingly, Figure 21 shows that the heuristic algorithm occasionally activates one more server than the optimum. This, as shown in Figure 22, also results in a higher number of unused vCPUs.

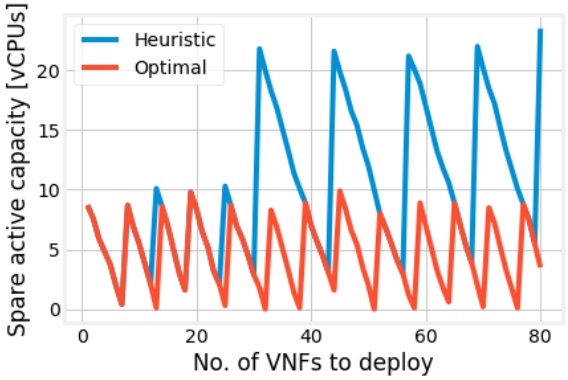


FIGURE 22: UNUSED VCPUS LEFT BY THE HEURISTIC ALGORITHM VS. THE OPTIMUM

5.3.4.2 RAN Split algorithms

The increasing mobile data traffic and the new demanding services ranging from augmented reality to Industry 4.0 applications challenge the performance of RAN and induce unprecedented expenditures to mobile operators.[2] It is apparent today that methods such as the densification of base stations (BS) and the over-provisioning of network links, albeit necessary, cannot address this problem in its entirety; and therefore new RAN solutions are required.

Distributed architectures (D-RAN) used in 3G/4G are cost-inefficient for dense networks due to their expensive radio units, and because they do not facilitate resource pooling. On the other hand, *centralized* RAN (C-RAN) architectures that have recently gained momentum, relocate most BS functions from low-cost Radio Units (RUs) to a central unit (CU). RUs perform physical-layer tasks and exchange I/Q radio samples with the CUs through the *fronthaul* network. This reduces costs and improves performance through the central control of tasks such as interference management. However, C-RAN's stringent latency and bandwidth requirements are hard to meet in most RAN deployments nowadays, while clean-slate fronthaul designs are very costly.

When such pure distributed (D-RAN) or fully centralized (C-RAN) solutions fall short, a hybrid RAN design where only some BS functions are centralized might be more suitable. Indeed, we see today a flurry of activities in this space by standardization bodies such as the IEEE 1914 WG and 3GPP RAN3. These efforts build upon the recent *softwarization* and *cloudification* of C-RAN through SDN/NFV (Software-Defined Networking/Network Function Virtualization) tools. This enables operators to determine the centralization level (*functional split*) of the so-called virtual RAN (vRAN) functions for each RU and in a way that accounts for the available network resources and user demand. This fine-grained network management approach is considered very important for the success of 5G systems. Nevertheless, *designing the vRAN architecture is a novel and particularly challenging problem*: each configuration has different bandwidth and latency requirements for data transfers across the function locations; involves different amounts of resources (computing power, link capacities); and induces different costs and performance benefits.

There are several levels of centralization, but the key splits are those in Figure 23. Split 1 does not have traffic overheads, enables the co-location of tasks of BSs, and enhances user mobility management. Whenever a CU is available, essentially there is no reason not to have split 1. Split 2 improves hardware utilization, enables multi-cell coordination for CoMP and eICIC, but has significant traffic overheads and an order of magnitude tighter delay bound (for data transfers among function locations). Finally, split 3 (C-RAN) consumes very high bandwidth (which is load-independent), has extremely low delay bounds, but maximizes spectrum efficiency and hardware usage. Finally, regarding the fronthaul, the expensive point-to-point links are expected to be replaced with packet-based shared links.

[2] For example, China Mobile reported for 2014 115.1% increase in mobile traffic, but 10.2% profit reduction (Proc. 1st IEEE 5G Summit'15).

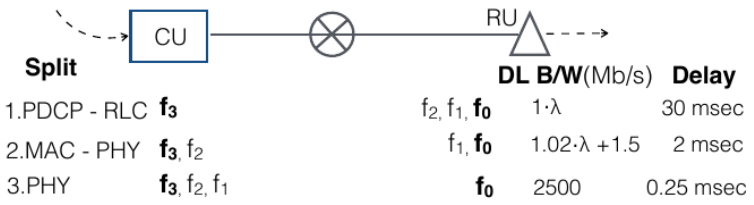


FIGURE 23: BANDWIDTH AND LATENCY REQUIREMENTS OF MAIN SPLITS; FUNCTION f_2 REQUIRES f_1, AND PLACEMENT OF f_3, f_0 IS FIXED; λ IS THE TRAFFIC

Despite the interest of industry and academia, we currently lack a methodology for designing vRANs. At the core of this intricate problem lies the decisions for selecting the function splits *and* the CUs-RUs routing paths which, clearly, should be jointly devised. Indeed, the optimal function placement for each depends on the capacity and latency of the RU-CU network path, which can only be known after the paths for the entire RAN are selected. On the other hand, finding the optimal path requires knowledge of the flow requirements in terms of volume and latency, which depend on the functional split of each BS. This coupling makes a traditionally challenging routing problem even harder due to the multiple split choices per BS.

The vRAN design problem is further compounded by the advent of (multi-access) edge computing (MEC), a business model where operators lease computing and network resources to vertical sectors, e.g., e-health industry. MEC services target ultra-low latency and high-bandwidth applications and therefore are mainly deployed close to users; and this, in turn, presumes a full-stack D-RAN implementation. Thus, there is an inherent tension between MEC and vRAN, which aims at the highest possible centralization of the RAN functions. Given the importance of MEC services (a new revenue source for operators) it is imperative to jointly design them with vRAN, in order to ease this tension and ensure that their performance will meet the expectations set in 5G.

5.3.4.2.1 FluidRAN

We propose FluidRAN, a rigorous analytical framework for the optimized design of virtual RAN (vRAN) networks. We model the BS operation as a chain of functions that successively process the traffic to/from the users. Some of these functions (e.g., PDCP in LTE systems) can be implemented in virtual machines (VMs) at the RUs or CUs; while others (e.g., turbo(de)coding in LTE systems) require specific hardware. The function implementation induces a computing cost that may vary across RUs and CUs, and similarly the selected paths affect the data transfer expenses. Our framework yields the vRAN configuration (splits and paths) that minimizes the aggregate operator expenditures.

Our contributions can be summarized as follows:

- *Optimization Framework*. We introduce an analytical framework for the vRAN design by considering the network and computing resources, and the splits' requirements. Our solution optimizes the placement of vRAN functions jointly with the data routing; and we leverage the Benders' decomposition method to enable its derivation for large systems.
- *Joint vRAN and MEC Design*. We analyze and model the inherent tension among vRAN and MEC. Our framework is extended to jointly decide the placement of MEC

services and vRAN functions, yielding a configuration that balances performance benefits and associated costs.

- *Performance Evaluation Using Real Networks*. We analyze 3 backhaul/RAN topologies of different operators, and use market data for costs and 3GPP specs. We show that there is not a one-size-fits-all vRAN configuration and that in practice packetized CPRI-based C-RAN is rarely a feasible solution; on the other hand, FluidRAN, provides significant cost benefits compared to D-RAN.

5.3.4.2.1.1 System Model

Fronthaul Network. We consider a RAN with a set $\mathcal{N}$ of N RUs and 1 CU.[3] These are connected through a packet-based network $G = (\mathcal{I}, \mathcal{E})$, where $\mathcal{I}$ is the superset of routers, CU (node 0) and the RUs; and $\mathcal{E}$ is the set of links connecting these elements. Each link $(i,j) \in \mathcal{E}$ has capacity c_{ij} (Mb/s) and introduces delay d_{ij} (secs). Let $p := \{(0,i_1),(i_1,i_2),\dots,(i_L,n): (i,j) \in \mathcal{E}\}$ denote a CU-RU n path; $\mathcal{P}_n$ is the set of all RU n paths and $\mathcal{P} = \cup_{n=1}^{N} \mathcal{P}_n$ the set of all CU-RUs paths. Each $p \in \mathcal{P}$ is described by the aggregate delay d_p of its constituent links. There is an average data transfer cost due to consumed energy, leasing costs, equipment utilization, etc. We denote γ_p the cost for path p (monetary units/byte) and define the *routing cost vector*:

$$\boldsymbol{\gamma} = (\gamma_1, \gamma_2, \dots, \gamma_{|\mathcal{P}|}).$$

RAN Functions. The RAN operation is modeled as a chain of 4 functions: f_0, f_1, f_2, and f_3 . Function f_0 corresponds to the basic radio tasks (analog processing, etc.) and it is placed at RUs. Assuming LTE, f_3 corresponds and is always placed at the CU (whenever there is one available). On the other hand, f_2 and f_1 are placed either at RUs or CU, and this decision is devised independently for each RU. The function placement sets the delay-bandwidth requirements between the CU and each RU, Figure 23. In vRAN f_2 and f_1 can be implemented in virtual machines (VMs). The cost for initiating and using a VM depends on the hardware. CUs are in central facilities and use high-end servers; hence this cost will be lower compared to RUs. We denote with α_n (monetary units) the average (offset) cost for instantiating a VM in RU n (due to cooling, leasing fees, etc.), with β_n (monetary units per cycle) the average cost for serving each request; and define the respective parameters α_0, β_0 for CU. The *computing cost vectors* are then:

$$\boldsymbol{\alpha} = (\alpha_0, \alpha_1, \alpha_2, \dots, \alpha_N), \quad \boldsymbol{\beta} = (\beta_0, \beta_1, \beta_2, \dots, \beta_N).$$

We denote with ρ_1 and ρ_2 the (nominal) processing loads (cycles per Mb/s) of f_1 and f_2, respectively. Moreover, each RU n and CU have processing capacity P_n and P_0 (cycles), shared by the VMs. When the load is below these bounds, a constant (and very small) processing delay is induced.

Demand. Each RU n serves the requests of users that are generated by an i.i.d. process$\{\Lambda_n(t)\}_{t=1}^{\infty}$, with $E[\Lambda_n(t)] = \lambda_n$ (Mb/s) and we denote the vector $\boldsymbol{\lambda} = (\lambda_n : n \in \mathcal{N})$. The requests at RU n create an aggregate flow emanating from the CU routed to RU n. Hence, the RAN operation can be modeled as a multi-commodity flow problem where the flows depend on the placement of RAN functions.

The objective of the operator is to select the vRAN configuration that will satisfy the users' demand while minimizing the aggregate expenditures. The latter, in such virtualized

[3] We consider 1 CU, as in practice the RUs are assigned to CUs before split decisions; and most often there is 1 CU location.

systems, are mainly due to computing and data routing costs. Several trade-offs arise here. On the one hand, placing the functions at RUs reduces the network's load and hence the routing costs. On the other hand, aggregating the RAN functions at the CU reduces computing costs (economics of scale) and offers centralized control that can improve the network's performance, e.g., through sophisticated interference management techniques. However, some splits have very tight delay constraints and create high fronthaul traffic, while the CU might not have enough computation power to accommodate all RAN functions. The operators' decisions need to be fine-grained, i.e., per RU, and consider all the above aspects. We formally state the RAN design problem as follows:

FluidRAN Design Problem (FRD): Given the anticipated demand $\boldsymbol{\lambda}$; a network $G = (\mathcal{I}, \mathcal{E})$ with links capacities and delays; computing and routing costs, $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$, determine:

- *service chaining*: where to place functions f_1, f_2 for each RU $n \in \mathcal{N}$ and the CU;
- *service provisioning*: how to route user traffic from the CU to the associated RU;

so as to serve the users request with the minimum cost.

The FluidRAN algorithm that solves this problem optimally is formally analysed in [21]. In short, we model the FRD problem as a mixed integer-linear program (MILP) and design an algorithm based on Benders decomposition. Benders decomposition is an approach that decomposed the main MILP program into two: a smaller integer program, which is easier to solve, and a linear program, solved iteratively. We skip these details here for the sake of conciseness and summarize instead the main results. From a high-level perspective, the steps taken by FluidRAN to solve our problem are the following:

1) Initialize a set of optimality cuts and a set of feasibility cuts.
2) Set Upper bound to a large number and a lower bound to minus the upper bound
3) Loop till convergence:
    a. Solve service chaining subproblem (master problem)
        i. This can be solved by branch-and-bound
        ii. Solution yields a new lower bound
    b. Solve dual problem of service provisioning subproblem (slave problem)
        i. If solution is bounded, extreme point yields optimality cut and solu
        ii. If solution is unbounded, extreme reay yields feasibility cut
        iii. Compute new upper bound
    c. Add new cuts to master problem

A formal description of this algorithm can be found in [21].

5.3.4.2.1.2 Results

In order to obtain realistic results, we use reference values for the system parameters from prior measurement-based studies, which are also complemented by our own lab measurements. Furthermore, we have conducted a thorough sensitivity analysis for the parameters, beyond their reference values.

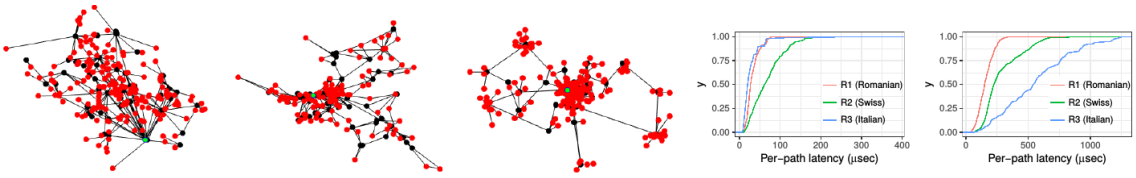
We parametrize our model conservatively, with 1 user/TTI, 20MHz BW (100 PRBs), 2x2 MIMO, CFI=1, 2 TBs of 75376 bits/subframe, and IP MTU 1500 B, that is, assuming a high-load scenario $\lambda = 150$Mb/s for each BS. We consider a single Intel Haswell i7-4770 3.40GHz CPU core as our unit of CPU capacity (*reference core*, RC). From our own measurements and those reported in [22], we estimate that, in relative terms, f_3 is responsible for 20% of the total consumption of a software-based LTE BS, f_2 consumes 15%, and f_1 up to 65%. From [23], we calculate the (absolute) computing needs of a software-based LTE BS. In our scenario a BS would require 750 μs of the reference CPU core to process each 1-ms subframe, which means a 75% CPU consumption; hence, we set $\rho_1 = 3.25$ and $\rho_2 = 0.75$ RCs per Gb/s, respectively. Finally, we set $P_0 = 100$ RCs and sufficient computing on each RU to run a full-stack BS, i.e., $P_n = 1 \text{ RC}, \forall n \in \mathcal{N}$.

In practice, estimating computing and routing costs is difficult as they depend on the employed hardware, leasing agreements, and so on. We note however that the function placement and routing decisions are essentially affected by the relative values of the computing cost parameters across RUs and CU (α_0, β_0 and α_n, β_n), as well as the ratios of computing over routing costs (γ). Hence, in the following we estimate and use such relative values for $\mathbf{a}$, $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$. According to [24], the equipment cost of a D-RAN BS is estimated to $50K whereas the respective cost of a C-RAN BS (i.e., RU with Split 3) is $25K. Based on this information, we assume that the function instantiation cost is approximately half when done in the CU, i.e., $\alpha_0 = \alpha_n/2$; and we set, unless otherwise stated, $\alpha_n = 1 \, \forall n \in \mathcal{N}$, i.e., homogeneous RUs, to ease the analysis. Regarding the processing costs, the main advantage of the CU compared to RUs comes from the pooling gains (cooling, CPU load balancing, etc.). Based on [25], we estimate the CU processing cost to $\beta_0 = 0.017\beta_n$ (linear regression in Figure 28a [25]). If we take as reference the processing cost at RU, then $\beta_0 = 0.017$ and $\beta_n = 1$.

We apply FluidRAN to three different topologies of real operators in Romania (R1), Switzerland (R2) and Italy (R3), shown in Figure 24. First, the *RAN configurations can be very heterogeneous*. The RANs have between 200 and 2000 RUs; R3 has only fiber links, R2 mainly wireless links and R1 fiber, copper and wireless links. The networks differ in the number of paths connecting each RU with the CU location. R1 has high path redundancy with a mean (median) value of 6.63 (7) paths, while R3 has often only 1 path (mean 1.6). Clearly, there cannot be a one-size-fits-all RAN split. Second, *these RANs do not have a typical (e.g., tree) structure*. Some RUs are placed as far as 20Km (R3) and 10Km (R2 and R1) while others are in 0.1Km distance from the CU. This renders heuristic or greedy routing policies inefficient.

Third, the RUs and CUs are *connected with diverse links* having capacity that ranges from 200Gb/s down to 2 Gb/s for R3 and 1.25Gb/s for the wireless links of R2. The capacity differences in conjunction with the different link lengths create variation in link and path delays. The figure also presents the eCDF of delays, calculated with a typical store-and-forward switching model that also includes transmission and propagation delays.[4] We observe that: (i) the delay might be up to 40 times higher in some links; (ii) a large number of RUs (different for each RAN) do not support C-RAN (split 3).

[4] We conservatively used $12000/c_{ij}$, 4μs/Km (cable) or 3μs/Km (wireless), and $5\mu secs$ for transmission, propagation, and processing delay, respectively.



(a) Romania topology (R1). (b) Swiss topology (R2). (c) Italy topology (R3). (d) Links Delay Distribution (e) Paths Delay Distribution

FIGURE 24 (A)-(C): THREE ACTUAL RANS IN EUROPE: RED DOTS INDICATE THE RUS' LOCATIONS; BLACK DOTS THE ROUTERS/SWITCHES; AND GREEN DOT THE CU.

Centralization Level and Split Selection: Figure 25 and Figure 26 depict the percentage of BS functions f_1 and f_2 placed at the CU (centralized) and the number of Benders iterations that our algorithm requires until convergence, respectively, for the three topologies under study. The results are plotted for an exhaustive set of combinations of CU computing capacity and BS load (λ). We observe that full centralization (C-RAN) is not possible in any of these systems. R2 has the smallest percentage of functions that can be placed at the CU, maximum of 58.6%. This is rather expected as it includes low-capacity wireless links. This under-provisioning is further evinced by the fact that no solution is feasible (not even D-RAN) when the RU load is larger than $\lambda = 100$ Mb/s. On the other hand, R1 achieves 93.7% centralization, even for high traffic (given sufficient CU computing capacity). In the lower plots, we have (artificially) boosted the links' capacity. We see now that both R1 and R3 can achieve full centralization (for high CU capacity), and R2 also centralizes 97.2% of the functions. This numerical test reveals that centralization in R1-R3 is mainly constrained by the links' capacity.

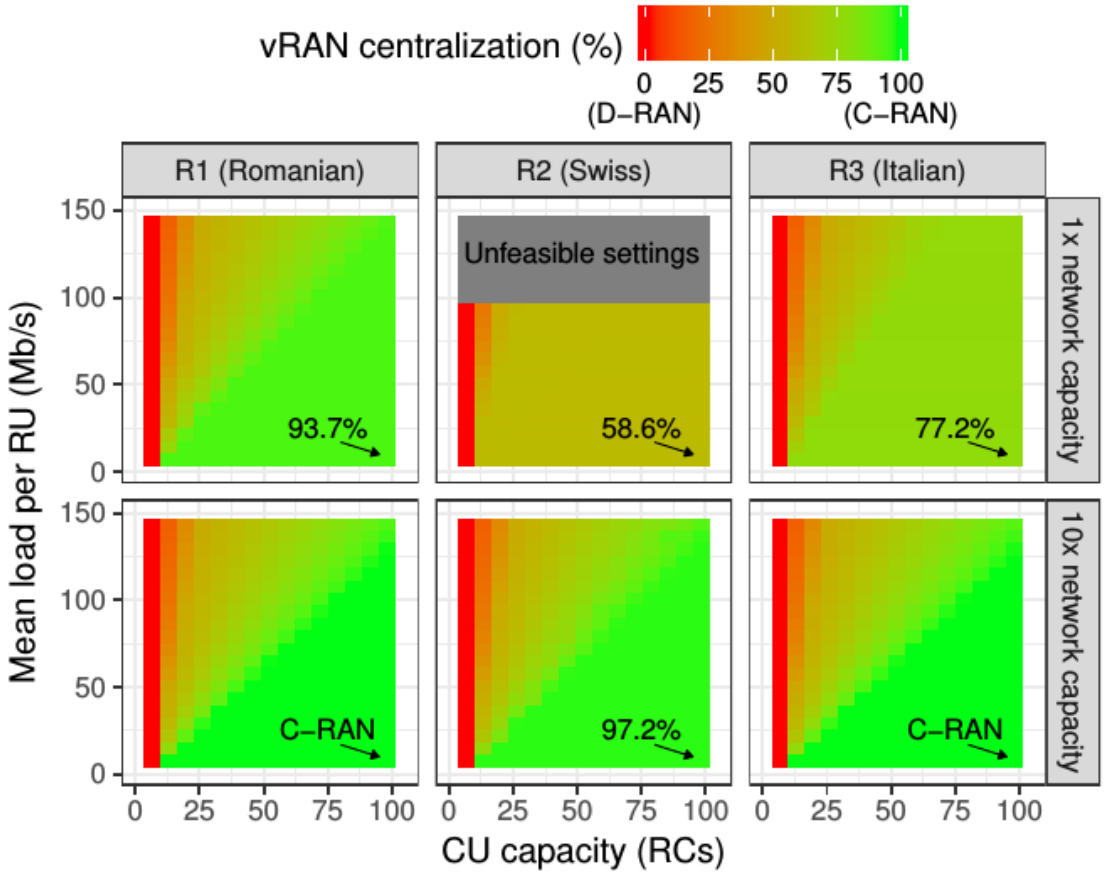


FIGURE 25: RATIO OF RAN CENTRALIZED FUNCTIONS IN SWISS, ROMANIAN AND ITALIAN TOPOLOGIES FOR DIFFERENT VALUES OF CU CAPACITY AND TRAFFIC LOAD

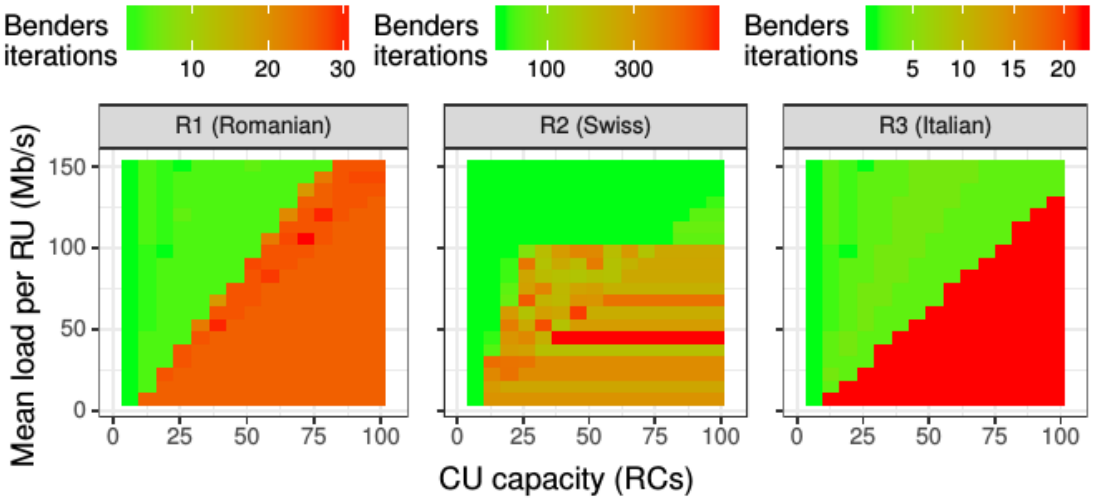


FIGURE 26: NUMBER OF BENDERS ITERATIONS IN SWISS, ROMANIAN AND ITALIAN

Impact of Parameters on vRAN Cost: We next perform a parameter sensitivity analysis using R3 (Italian topology). We first study the impact of routing cost on vRAN. Figure 27 shows both the percentage of centralized RAN functions and system costs, when $\alpha_n = \beta_n = 1 \, \forall n \in \mathcal{N}$ and $\alpha_0 = \beta_0 = 1$ which is the worst-case scenario where the CU has no computing efficiency advantage compared to RUs. The routing cost ranges from $\gamma = 0$

(no cost) to $\gamma = 2\ (\mathrm{Gb/s})^{-1}$ (twice the computation cost). Note that γ is defined with reference to computing costs in order to facilitate comparisons. We compare FluidRAN with D-RAN and C-RAN deployments. The latter two are special cases of FRD where the function placement variables are fixed, i.e., routing is still optimized. We stress that the latter is not implementable in these systems but the respective cost is shown for comparison purposes.

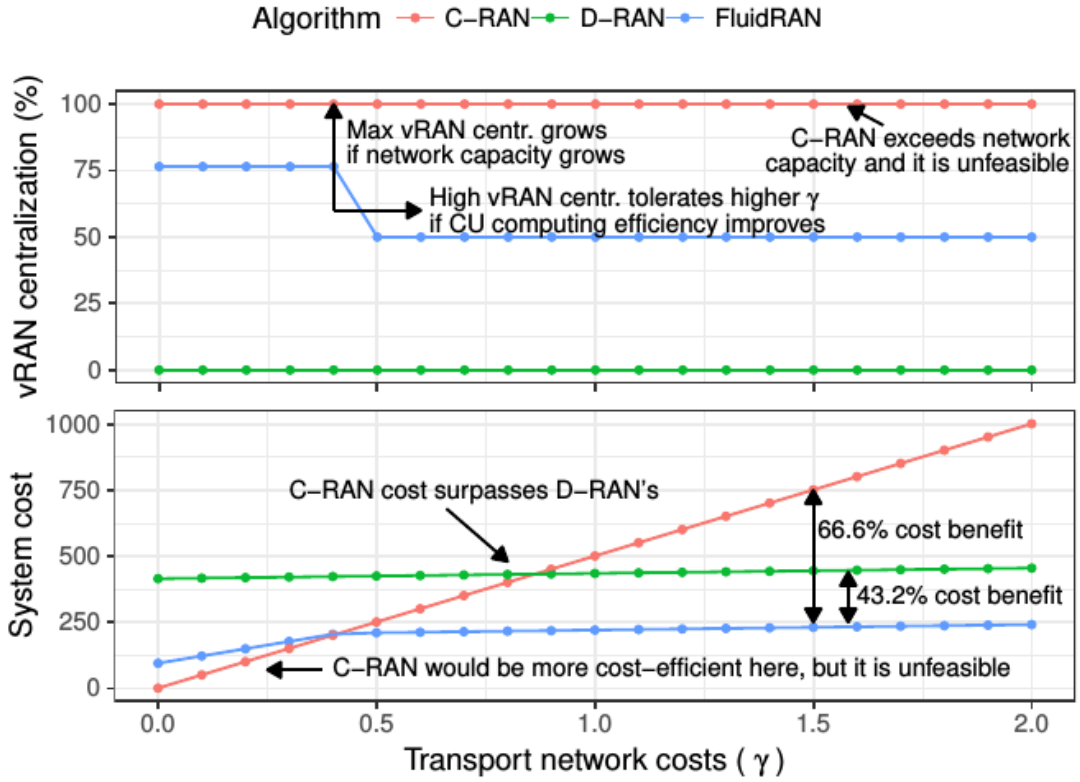


FIGURE 27: RAN CENTRALIZATION (TOP) AND SYSTEM COST (BOTTOM) FOR ITALIAN TOPOLOGY (R3) FOR $\alpha_n = \alpha_0 = 1$ AND VARIABLE TRANSPORT COSTS, FOR C-RAN, D-RAN AND FLUIDRAN ARCHITECTURES

Let us focus on the top plot of Figure 27. For low routing costs, i.e., $\gamma < 0.25$, FluidRAN finds in maximizing the amount of functions that are centralized (in this case 77.2%) the most cost-efficient solution. Clearly, even for $\alpha_n = \alpha_0$ and $\beta_n = \beta_0$, centralization is beneficial due to aggregation (less instantiations costs in CU). If we focus on the bottom plot we observe that, as we increase γ, there is a point where FluidRAN and C-RAN yield the same cost ($\gamma \sim 0.37$). If we further increase γ, the most cost-efficient configuration is to lower the amount of centralization to 50% (split 2 for all RUs). This reduces the amount of traffic in the network compensating in this way the high computational costs of RUs. Noticeable, the system cost of C-RAN overpasses traditional RAN when $\gamma > 1$. Finally, note that improving the computing efficiency at CU (i.e., decrease α_0/α_n) ensures high centralization even for large γ; and improving the links' capacity increases the maximum centralization.

Tension between vRAN and MEC: Finally, we analyze the impact of MEC on the cost and centralization of the 3 topologies. To this aim, we consider 4 services that differ on their computation needs: MEC 1 ($\rho_4 = 0$) and MEC 4 ($\rho_4 = 1$) are two extreme cases, MEC 2 ($\rho_4 = 0.0725$) and MEC 3 ($\rho_4 = 0.25$) mimic the computational needs of an

optimization application and a virtual reality application experimentally assessed in the literature. In order to highlight the impact of MEC on the vRAN operation, we plot the cost only for the latter (i.e., J_F instead of J_{FM}), and for the same reason we set $\gamma = 0$.

Figure 28 depicts the centralization and system cost of FluidRAN for different MEC loads $\lambda n^M = \lambda^M, \forall n$. Observe that as the MEC load λ^M increases, vRAN centralization is reduced in order to alleviate the saturated links. This effect is pronounced for computation-intensive MEC, since these services consume also the available CU computing capacity. Interestingly, computing-intensive MEC can increase multiple times (e.g., 2 times in R2 and 6 times in 6.5 times in R2) the system's expenditures. This increase is not only due to the new processing demand, which is obvious factor and hence not depicted in the figure, but also because vRAN must yield centralization gains when faced with heavy MEC services. Finally, note that for very high MEC loads all networks opt for D-RAN and have similar costs J_F (since they have similar number of RUs and $\gamma = 0$).

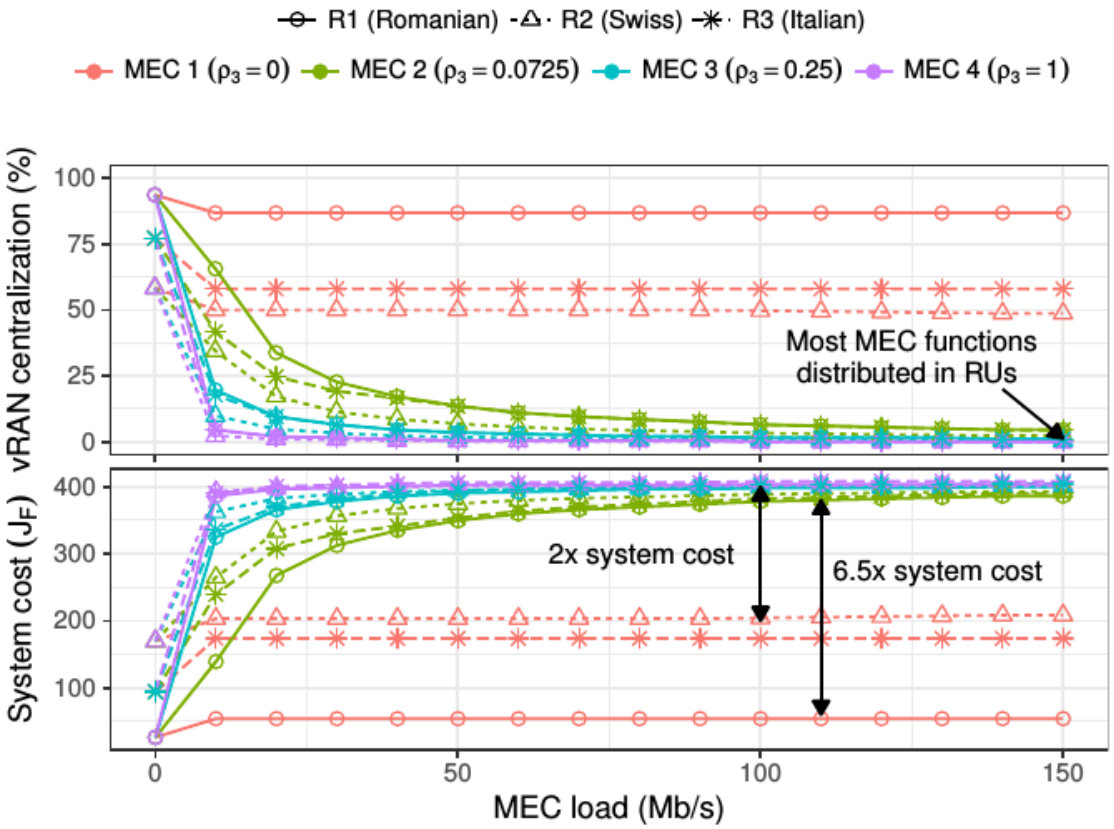


FIGURE 28: RAN CENTRALIZATION (TOP) AND COST (BOTTOM) FOR DIFFERENT MEC PROCESS CHARACTERISTICS AND LOADS. NON-MEC LOAD IS 10 MB/S FOR ALL RUS

5.3.4.3 DU-CU Interconnection recovery

In this section, we present a two-step scheme to recover DU-CU connectivity in Virtualized RAN fronthaul upon lightpath soft failure. The scheme is based on the combination of lightpath transmission adaptation and eNB functional split reconfiguration. The scheme complements the fast recovery of physical layer resilient schemes with the capability, through functional split reconfiguration, of recovering DU-CU connectivity even when optical network resources are scarce and lightpath rerouting

is not possible. This algorithm can be implemented in the 5G-MTP for guaranteeing RAN survivability.

5.3.4.3.1 Proposed Two-Step Recovery Algorithm

The proposed two-step recovery scheme architecture is depicted in Figure 29 and exploits the 5G-MTP functional blocks. The working lightpath (i.e., red solid line) connecting DU and CU is monitored by the *Monitoring Driver*. Such monitor reveals or even anticipate degradation in the quality of transmission of the working lightpath and it notifies the ResOrch. The ResOrch triggers the modification of the lightpath modulation format or the code redundancy increase (i.e., green dashed line). If the resulting lightpath rate is not capable of carrying the original functional split (i.e., DU1s1 and CU1s1), the ResOrch triggers the reconfiguration of the functional split to the one that can be supported by the lower lightpath data rate (i.e., DU1s2 and CU1s2). To speed up recovery operation, in this study, several DUs and CUs featuring different functional splits are already deployed and they are activated upon ResOrch request.

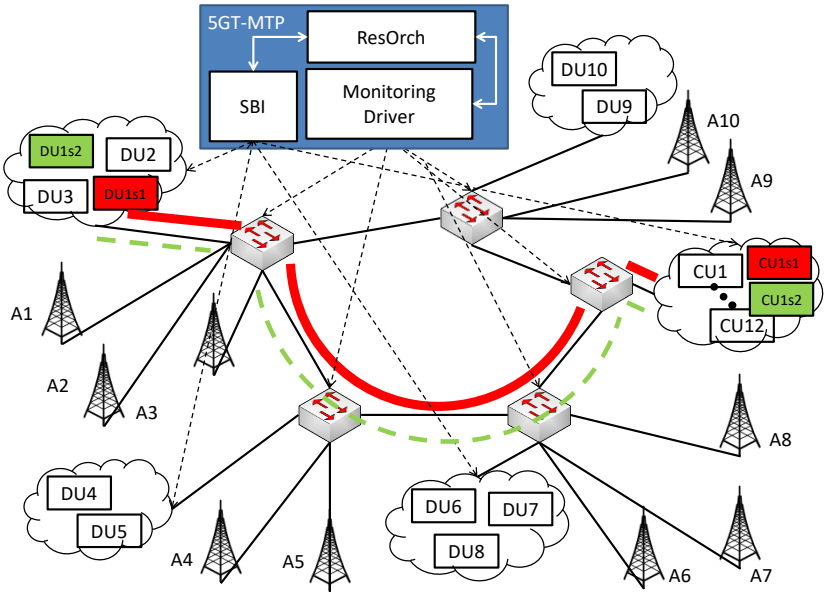


FIGURE 29: TWO-STEP RECOVERY SCHEME ARCHITECTURE

5.3.4.3.2 Performance Evaluation

The proposed two-step recovery scheme performance is evaluated through both simulations and a testbed experiment.

Simulations are conducted to evaluate the amount of traffic recovered by transmission adaptation (thus, without re-routing) in an optical metro network when link degradation occurs. A five-node ring topology with 10-km links is considered. Optical amplifiers are assumed as boosters. Poisson traffic is assumed (e.g., emulating small cell on-off), with exponentially distributed holding time with average $1/\mu = 5000$s. The offered traffic load is λ/μ, where $1/\lambda$ is the request mean inter-arrival time. Transponders support 200 Gb/s PM-16QAM and 100 Gb/s PM-QPSK. Lightpath BER is computed through optical signal to noise ratio (OSNR) and by assuming negligible the non-linear effects because of the limited distances of the topology. A BER lower than 10^{-3} is assumed as acceptable: 200 Gb/s PM-16QAM is considered acceptable with an OSNR

higher than 20.5 dB, while the model in [26] is adopted for 100 Gb/s PM-QPSK. Soft failures are randomly generated on a single link.

Figure 30a shows the recovered rate through transmission adaptation as a function of the offered traffic load, assuming that each soft failure introduces an OSNR penalty of 2dB. The overall rate impacted by soft failures increases with traffic load since more connections are active. The figure shows that 50% of the impacted traffic can be recovered with format adaptation. Indeed, with the considered link length and OSNR penalty of 2 dB, 100 Gb/s PM-QPSK is acceptable in any path. Figure 30b shows the recovered rate versus OSNR penalty with a load of 100 Erlang. The overall rate impacted by soft failures increases with OSNR penalty because the larger the penalty the higher the probability of exceeding the BER of 10^{-3}. When OSNR penalty is higher than 4 dB, the recovered traffic through format adaptation is not exactly 50% because for some connections also PM-QPSK presents unacceptable BER (typically the longest ones). Thus, in the considered scenario, after soft failure only half of the capacity originally offered by lightpaths is available for carrying DU-CU connections.

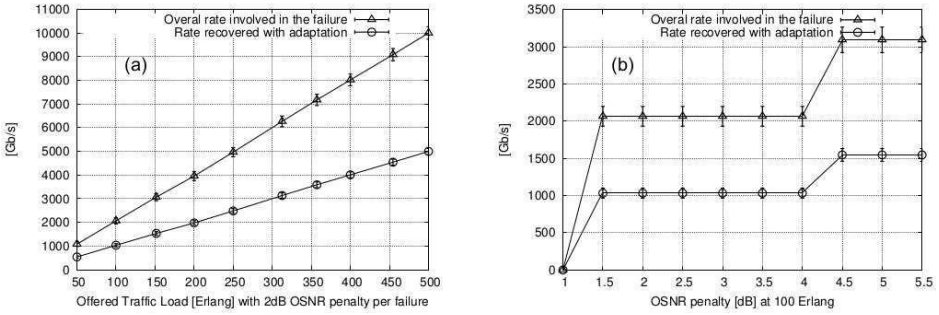


FIGURE 30: OVERALL RATE RECOVERED THROUGH FORMAT ADAPTATION AT: (A) VARYING THE OFFERED TRAFFIC LOAD WITH 2-DB-OSNR-PENALTY SOFT FAILURES; (B) THE OSNR PENALTY WITH 100 ERLANG OF TRAFFIC LOAD

Experiments are conducted to evaluate the performance of functional split reconfiguration that is triggered if the residual lightpath capacity is not sufficient to carry all the CU-DU connections. The considered experimental evaluation scenario is shown in Figure 31a. The Evolved Packet Core (EPC) is deployed in *Host Machine 1* by utilizing *Openair-cn* from OpenAirInterface (OAI) (*http://www.openairinterface.org/*). For the DUs and the CUs, two functional splits are considered: Option 8 and Option 7a in the 3GPP terminology (i.e., IF5 and IF4.5 in OAI terminology). Even in this case the OAI platform is utilized to implement DUs and CUs. As shown in Figure 31a, *Host Machine 2* contains a Docker with two containers (i.e., *container-CU1* and *container-CU2*) to deploy the two CUs. Similarly, the DU functions are hosted in *Host Machine 3* (i.e., *container-DU1* and *container-DU2*). *Host Machine 2* and *Host Machine 3* are directly connected by a 1 GbE link. The Ettus Universal Software Radio Peripheral (USRP) B210 acts as radio front-end and it is attached to *Host Machine 3*. The Huawei E3372 dongle, attached to *Host Machine 4*, is utilized as UE. Dongle and USRP are connected through coaxial cables with a 20 dB attenuation in the middle of the link. The 5G-MTP is emulated through a shell script running in *Host Machine 5*.

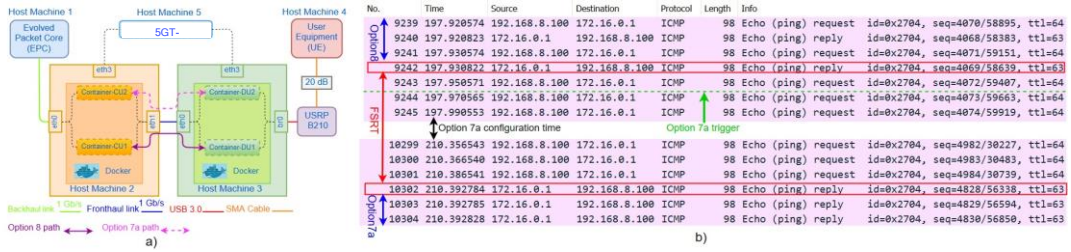


FIGURE 31: (A) SCENARIO CONSIDERED FOR THE EXPERIMENTAL EVALUATION; (B) CAPTURE (AT THE UE) OF ICMP MESSAGES EXCHANGED BETWEEN THE EPC AND THE UE

The considered performance evaluation parameter is the *eNB functional split reconfiguration time (FSRT)*, defined as the time elapsing between the last *ping* reply sent by the EPC to the UE before functional split reconfiguration and the detection of the first successive *ping* reply after functional split reconfiguration. The FSRT measurement is performed by continuously (i.e., every 1ms) sending ping messages from the UE to the EPC.

Figure 31b contains the wireshark capture at the UE (192.168.8.100) of the *ping* messages exchanged by UE and EPC (GTP interface address 172.16.0.1) during the eNB functional split reconfiguration from Option 8 to Option 7a. The timestamp of the wireshark is measured in *seconds*. As shown in the Figure 34b, once the functional split reconfiguration is undergoing, only ICMP request messages at the UE can be observed. The measured FSRT is about 12s. It includes a 2s sleep time to start first the DU and the CU and synchronize the fronthaul interface during Option 7a activation. The 5GT-MTP shell script contributes about 1s to enter into the containers and run the requested functional split option.

5.4 5GT-MTP functional components detailed overview

5.4.1 Abstraction Engine

The Abstraction Engine consists of two sub-modules: “E2E Abstraction Logic” and “Domain Resource Logic”.

5.4.1.1 E2E Abstraction Logic

This submodule implements the algorithms and procedures to compute the abstraction view exposed to 5GT-SO and detailed in Section 5.3.1. It takes the aggregated view of the domain resources (RADIO, Wim, MEC, VIM), from the DB, and provides as output the abstracted view and the relationship with the aggregated resources. Such information is then stored in the DB and exposes to 5GT-SO on request. This module is based on jGraphT [26] for graph operation (it is used for the logical link computation and abstract PoP computation).

5.4.1.2 Domain Resource Logic

This submodule uses the relationship between the abstract view exposed to SO and the aggregated view of domain resources (computed by the Domain Resource Logic) and select the domain resources to be allocated for a service request by SO. The module exploits the output of the optimization algorithm (described in Section 5.3.4) to optimize the resource usage by minimizing resource waste and energy consumption.

5.4.2 Dispatcher

This module is the core of the application that handles the entire communication between the 5GT-MTP modules. It is realized in a flexible way by using the event driven programming obtained using the EventBus defined in the GUAVA library (3rd party open source porting of android libraries in java) [27] and follows the “Event Driven Approach” (EDA): each 5GT-MTP module publishes a list of events that is able to handle at the bootstrap. Each event represents an operation performed by the module (it is implemented as a Java method). The dispatcher collects all published events and expose them to each module. In this way, when a module needs an operation executed by another module, it posts the related event. The post is captured by the dispatcher and sent to the modules handling the event. In more details, the list of events is collected in a separated java package (“events”). All events are classic “Plain Old Java Object” (POJO) grouped according the 5GT-MTP feature where such event can be invoked.

5.4.3 ResOrch

The module orchestrates the 5GT-MTP procedures among the controlled domains The orchestrated procedures are the allocation/termination of the logical link (i.e. link connecting DC gateway of two VIM that crosses one or more WIM) and the allocation/termination of MEC application (that requires coordination between VIM and MEC domain). The orchestration follows the sequence diagram described in IFA022 [29] (first creates the connectivity inside the WIM and then stitches it with the DC gateway of the VIM) and the workflow shown in Section 5.6.

5.4.4 DB

It is a common module used by the other components to retrieve abstraction, aggregation and service information; in addition, it contains the AppD description of the MEC app according to ETSI MEC 010-2 information model [31]. It is implemented as external SQL server (mySQL [32] is used for generation) and the java class is just a front-end that connects to the SQL server and handles all queries (e.g., insert entries, query to retrieve parameters). 3rd party open source JDBC driver [32][31] is used to manage SQL connections.

5.4.5 Local PA

It is a module that is invoked by the Resource Selection submodule to optimize the placement of VM and the usage of networking resources. The module is responsible to contact the optimization algorithm described in Section 5.3.4 5.3.4and provide the algorithm results to the other module. A REST API is used for the communication between this module and the optimization algorithm.

5.4.6 Monitoring driver

It is a module used to communicate with the 5GT Monitoring Platform (based on Prometheus). It uses the monitoring interface exposed by the Monitoring Platform to register itself to the platform, create performance monitoring jobs and get alert notifications.

This module is responsible to require monitoring activities related to infrastructure resources in terms of compute, storage networking, radio, and MEC and provides the output of the monitoring platform to the module requiring the monitoring job.

5.5 5GT-MTP interfaces

5GT basically adopts ETSI IFA005 [33] as well as specific IFA005-oriented API commands for the interfaces between 5GT-SO and 5GT-MTP and between 5GT-MTP and VIMs/WIMs. In a nutshell, IFA005 defines standard interfaces to enable a consumer block at the VIM north bound interface to retrieve information about resources capability (e.g., maximum CPU), to allocate and reserve a resource, and to be notified about a change of a resource.
For the monitoring, instead, the Prometheus monitoring platform has been adopted thus the interfaces use the REST API provided by this platform.
The considered interfaces involve the following operations: query, allocation, subscription, notification, termination and performance monitoring.

5.5.1 5GT-MTP NBI (5GT-SO SBI)

This interface is devised to provide the communication between both the 5GT-SO and the 5GT-MTP building elements providing macroscopically the following set of functionalities and/or operations:

i. Retrieving the abstracted information of the logical links (LLs) enabling the connectivity between pairs of remote NFVI-PoPs. Indeed, the LL is a virtual link abstracted from the underlying transport network infrastructure interconnecting a pair of NFVI-PoPs' Gws.
ii. Retrieving relevant information about each available NFVI-PoP not only about specific attributes defining the NFVI-PoPs (e.g., location, identifier, associated controller/VIMId, etc.) but also about the status of the cloud resources encompassing memory, CPU and storage.
iii. Create (and terminate) the inter-NFVI-PoP connectivity (i.e., selecting the resources such as bandwidth on the LLs) for a specific network service (which is unambiguously determined by the serviced parameter).
iv. Create (and terminate) the intra-NFVI-PoP connectivity at each selected NFVI-PoP, i.e., the connectivity between the VNFs to be instantiated and the selected NFVI-PoP's Gw (external network endpoint) to enable the interconnection to other remote NFVI-PoPs.
v. Create (and terminate) VNFs on a given NFVI-PoPs.

All the above functionalities are supported over a specific pool of REST API messages where the 5GT-MTP operates as the server and the 5GT-SO is the client. The content of the messages is encoded using JSON format. The aim of the API is to feed the Placement Algorithm (PA) executed at the 5GT-SO with the existing and updated cloud/network infrastructure (entailing both NFVI-PoPs and LLs) to select and trigger the allocation of the cloud and networking resources fulfilling the requirements of the incoming network services.

For the sake of completeness, Figure 32 depicts the view at the 5GT-SO of the resources being abstracted from the 5GT-MTP. As mentioned above, such a view is limited by specific details of the pool of existing NFVI-PoPs with their supported cloud resources (i.e., identifiers, type and status) as well as the set of inter-NFVI-PoP links (i.e., LLs). This information constitutes the input for executing the 5GT-SO PA algorithm.

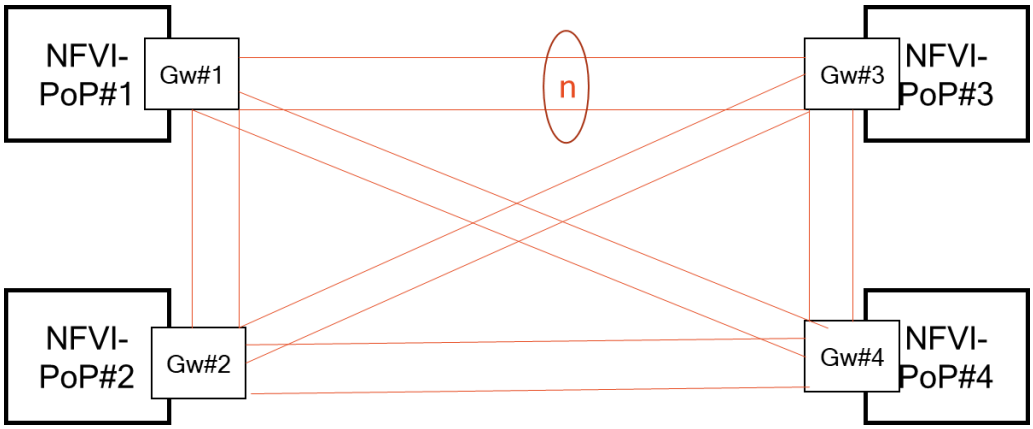


FIGURE 32: CLOUD/NETWORK VIEW AT THE 5GT-SO: NFVI-POPS AND LOGICAL LINKS (LLS)

In the following, specific details (i.e., contents) of the different API messages supporting those set of functionalities are provided.

5.5.1.1.1 Retrieval of NFVI-PoPs and inter-NFVI-PoP links information

This information is an on-demand basis collected by the 5GT-SO (e.g., whenever a 5GT-SO PA should be executed to have the most updated view of the whole infrastructure) via a GET method message where the required URI is set to */abstract-resources*. The request and response messages are named *ComputeNetworkResourceRequest* and *ComputenNetworkResourceResponse* (see Figure 33), respectively.

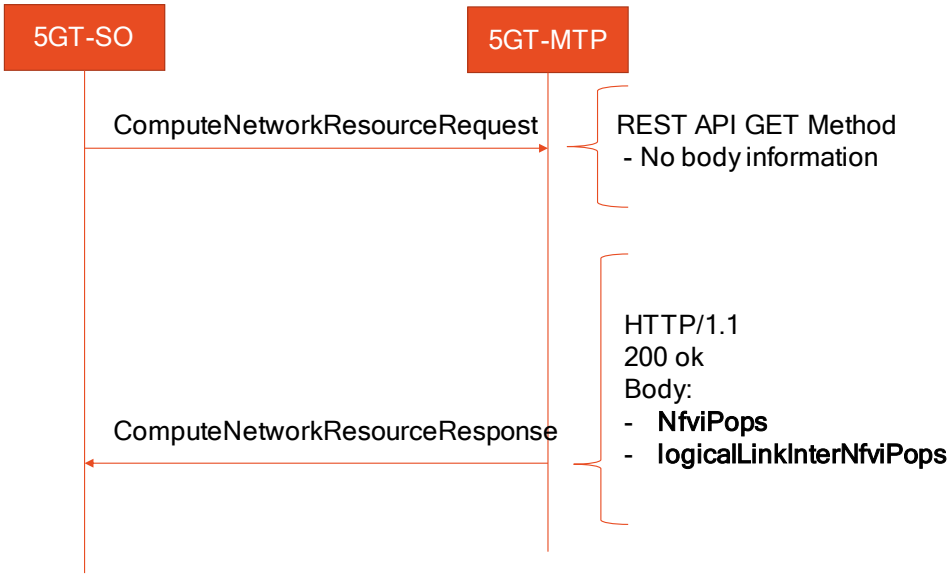


FIGURE 33: REQUEST/RESPONSE 5GT-MTP NBI FOR RETRIEVAL OF CLOUD AND NETWORK INFORMATION

The request message does not carry any content on the body, whilst a successful response (code 200) provides the details of the NFVI-PoPs and inter-NFVI-PoP links (i.e., LLs). In a nutshell, this information is presented and formatted in a hierarchical via two top-level JSON arrays, namely:

a. **NFVI-PoPs**: providing the set of available NFVI-PoPs.
b. **LogicalLinksInterNfviPops**: providing the set of (unidirectional and/or bidirectional) links connecting a particular pair of NFVI-PoPs.

NFVI-PoPs

As said before, this describes a top-level JSON encoding array where a component provides the parameters and attributes related to a given NFVI-PoP. Note that some of these attributes are already defined in [33]. Figure 34 shows a screenshot (via swagger REST API editor [33]) of the defined NFVI-PoP array carried in the body of the response message. The relevant attributes describing every NFVI-PoP element are:

- **Geographical Location**: information providing the location of the NFVI-PoP
- **VimId**: identifier of the VIM (NFVI-PoP controller)
- **networkConnectivityEndopoints**: set of NFVI-PoP's Gw (IPv4 address) which are the endpoints of the LLs enabling the inter-NFVI-PoP connectivity
- **nfviPopId**: identifier of the NFVI-PoP
- **resourceZoneAttributes**: set of attributes describing, in an aggregated manner, the specific cloud resources supported by the NFVI-PoP
    - **zoneId**: identifier for a specific resource zone segment of the NFVI-PoP
    - **zoneName**: name for a specific resource zone segment of the NFVI-PoP
    - **zoneState**: status of the specific resource zone segment of the NFVI-PoP
    - **zoneProperty**: properties and capabilities associated to the resource zone
    - **metadata**: allows adding other specific resource zone properties/details
    - **memoryResourceAttributes**: object specifying the status of the aggregated NFVI-PoP memory resource in terms of:
        - **availableCapacity**, **reservedCapacity**, **totalCapacity** and **allocatedCapacity**
    - **cpuResourceAttributes**: object specifying the status of the aggregated NFVI-PoP CPU resource in terms of:
        - **availableCapacity**, **reservedCapacity**, **totalCapacity** and **allocatedCapacity**
    - **storageResourceAttributes**: object specifying the status of the aggregated NFVI-PoP storage resource in terms of:
        - **availableCapacity**, **reservedCapacity**, **totalCapacity** and **allocatedCapacity**

```
{
  "NfviPops": [
    {
      "nfviPopAttributes": {
        "geographicalLocationInfo": "string",
        "vimId": "string",
        "networkConnectivityEndpoint": [
          {
            "netGwIpAddress": "string"
          }
        ],
        "nfviPopId": "string",
        "resourceZoneAttributes": [
          {
            "zoneId": "string",
            "zoneName": "string",
            "zoneState": "string",
            "zoneProperty": "string",
            "metadata": "string",
            "memoryResourceAttributes": {
              "availableCapacity": "string",
              "reservedCapacity": "string",
              "totalCapacity": "string",
```


FIGURE 34: 5GT-MTP NBI: GET METHOD WITH NFVI-POP ARRAY INFORMATION

LogicalLinksInterNfviPops

This provides a top-level JSON array where a single array component contains the parameters and attributes related to each available LL. To better illustrate the defined LL attributes, we rely on the Figure 35 to describe how every LL is identified and its corresponding addressing values. As shown, a LL connects two NFVI-PoPs in a unidirectional way. The data transmission direction (in the example from NFVI-PoP#1 towards NFVI-PoP#3), the LL is determined by a global *logicalLinkId*, and an unnumbered link identifier. The unnumbered link identifier is formed by the tuple: *srcGwIPAddress* and *dstGwIPAddress* which determines the IPv4 addresses of the NFVI-PoP Gw endpoints (according to the data transmission direction); and the *localLinkId* and *remoteLinkId* which are 32bit positive integers describing a specific link. By doing so, observe that multiple LLs between the same pair of *srcGwIPAddress* and *dstGwIPAddress* could be handled as long as *localLinkId* and *remoteLinkId* are different.

Last but not least, for doing a LL bidirectional, it is needed to add in the top-level array a component describing the identifiers and attributes in the reverser data transmission direction (in the example of Figure 35, from NFVI-PoP#3 towards NFVI-PoP#1). Note that for this LL, previous identifiers for *srcGwIPAddress* (Gw#1), *dstGwIPAddress*, (Gw#3), *localLinkId* (10000) and *remoteLinkId* (10000) are used by for defining the reverse direction, that is following the example the *srcGwIPAddress* is set to the Gw#3, *dstGwIPAddress*, is now Gw#1, and the same for *localLinkId* and *remoteLinkId.*

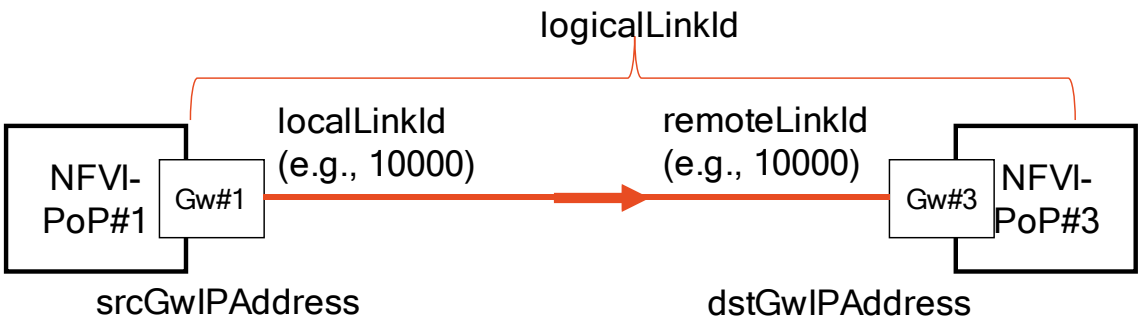


FIGURE 35: EXAMPLE OF THE IDENTIFIERS AND ADDRESSING OF A UNIDIRECTIONAL LL

Bearing in mind the above agreement for determining and specifying every created LL carried into the LogicalLinksInterNfviPops array, the following set of attributes per each LL is defined:

- **LogicalLinkId**: identifier used for determining a given LL
- **totalBandwidth**: total amount of bandwidth (in Mb/s) supported by the LL
- **availableBandwidth**: available bandwidth (in Mb/s) being not used on the LL
- **networkQoS**: object used to define a set of QoS parameters associated to the LL
  - **linkCost**: metric used for selecting the LL (e.g., associated to length of the LL)
  - **linkDelay**: delay (in ms) associated to the LL
- **srcGwIPAddress**: IPv4 of the ingress NFVI-PoP's Gw endpoint of the LL
- **dstGwIPAddress**: IPv4 of the egress NFVI-PoP's Gw endpoint of the LL
- **localLinkId**: positive 32-bit integer value associated to the identifier of LL at the source NFVI-PoP's Gw
- **remoteLinkId**: positive 32-bit integer value associated to the identifier of LL at the destination NFVI-PoP's Gw
- **networkLayer**: supported network layer capabilities of the NFVI-PoP Gws (e.g., L2, L3)
- **interNfviPopNetworkType**: describes the network connectivity type (e.g., L2-VPN, VXLAN, MPLS)
  interNfviPopNetworkTopology: describes the network connectivity topology (e.g., point-to-point, mesh, tree)

Figure 36 shows a screenshot (via swagger REST API editor [33]) of the defined *logicalLinkInterNfviPops* array carried in the body of the response message.

FIGURE 36: 5GT-MTP NBI: GET METHOD WITH LOGICALLINKINTERNFVIPOPARRAY INFORMATION

5.5.1.1.2 Allocating (and terminating) inter-Nfvi-Pops Connectivity

This operation commanded by the 5GT-SO and processed by the 5GT-MTP triggers the (de-)allocation of the network resources over a selected set of LLs used for deploying (/ releasing) a specific network service. The network resource allocation relies on the REST POST method with the URI set to */abstract-network-resources*, whereas the de-allocation of the network resources on previously selected LLs uses the REST DELETE method with the same URI.

Figure 37 shows the exchanged messages (i.e., *interNfviPopConnectivityRequest* and *interNfviPopConnectivityResponse*) between the 5GT-SO and 5GT-MTP to allocate the network resources (e.g., bandwidth) on a set of LLs being the output of the 5GT-SO PA mechanism. In the request message body, the following information is carried to proceed with the allocation in a set of LLs:

- **LogicalLinkPathList**: array containing a list of LLs where specific network resources (e.g., bandwidth) should be allocated. For each LL, it is determined a set of relevant identifiers and parameters:
  - **logicalLinkAttributes**: object specifying a fixed set of the selected LL's attributes
    - **logicalLinkId**: identifier used for determining a given LL
    - **srcGwIpAddress**: IPv4 of the ingress NFVI-PoP's Gw endpoint of the LL
    - **dstGwIPAddress**: IPv4 of the egress NFVI-PoP's Gw endpoint of the LL

        - **localLinkId**: positive 32-bit integer value associated to the identifier of LL at the source NFVI-PoP's Gw
        - **remoteLinkId**: positive 32-bit integer value associated to the identifier of LL at the destination NFVI-PoP's Gw
        -
    - **reqBandwidth**: requested amount of bandwidth (in Mb/s) to be allocated in a LL
    - **reqLatency**: requested maximum tolerated latency (in ms) to be guaranteed over an LL
    - **metadata**: used to specify relevant information about the addressing of the deployed VNFs at the NFVI-PoPs. This information will eventually allow configuring and programming the network elements (e.g., packet switches) forming the underlying inter-NFVI-PoP network infrastructure (also referred to as WAN).
- **networkLayer**: supported network layer capabilities of the NFVI-PoP Gws (e.g., L2, L3, …)
- **interNfviPopNetworkType**: describes the network connectivity type (e.g., L2-VPN, VXLAN, MPLS, etc.)
- **metaData**: used to specify the serviceId which is the identifier assigned by the 5GT-SO to unambiguously refer to a given network service. Observe that the same serviceId needs to be used regardless of the LLs being traversed by the network service. Moreover, other relevant information will be needed to be added such as the assigned IP addresses of the VMs (hosting the targeted VNFs) at each Nfvi-Pop. This information will allow the underlying WIM controllers coordinated by the 5GT-MTP to configure the required flow matching rules for transporting the data packets (e.g., sourced at a given VM and terminated at an another VM of different Nfvi-Pops). Additionally, metaData would be also used for carrying key information for supporting federation scenarios such as exchanging the used VLAN ids between separated domains.

The above set of attributes contained into the body of the *interNfviPopConnectivityRequest* message are shown in Figure 38 using the SWAGGER REST API editor [33].

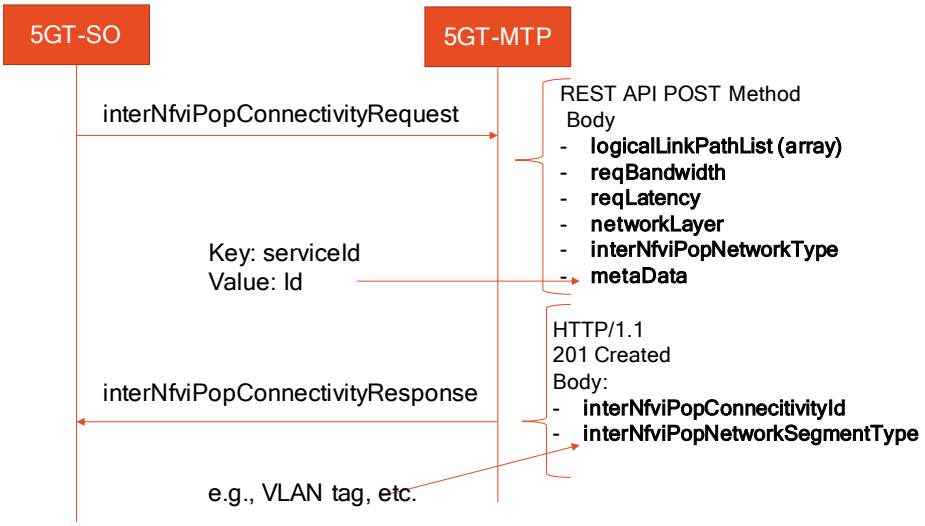
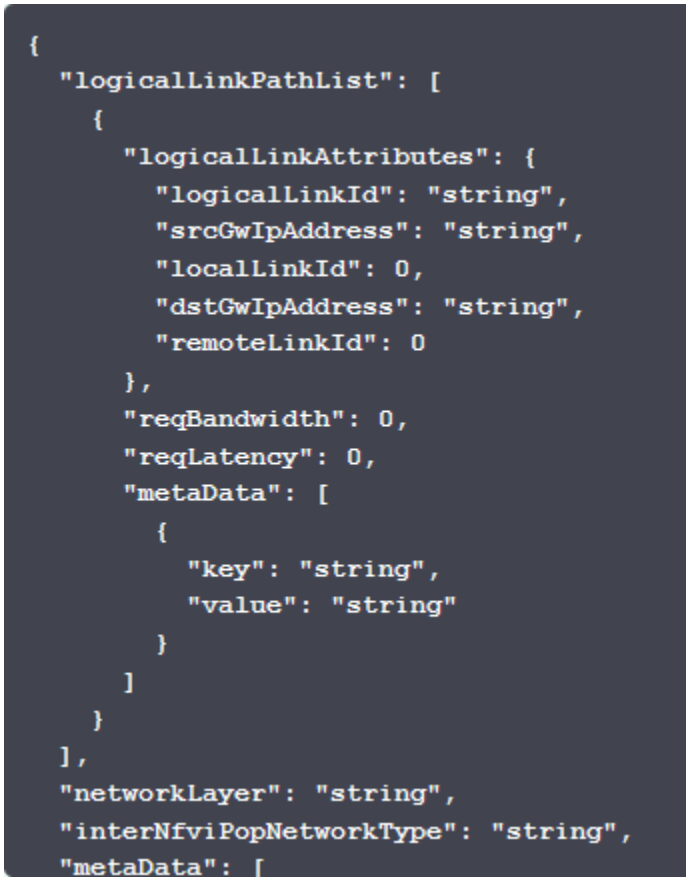


FIGURE 37: REQUEST/RESPONSE 5GT-MTP NBI FOR ALLOCATING RESOURCES ON A SET OF LLS SELECTED BY THE 5GT-SO PA



```
{
  "logicalLinkPathList": [
    {
      "logicalLinkAttributes": {
        "logicalLinkId": "string",
        "srcGwIpAddress": "string",
        "localLinkId": 0,
        "dstGwIpAddress": "string",
        "remoteLinkId": 0
      },
      "reqBandwidth": 0,
      "reqLatency": 0,
      "metaData": [
        {
          "key": "string",
          "value": "string"
        }
      ]
    }
  ],
  "networkLayer": "string",
  "interNfviPopNetworkType": "string",
  "metaData": [
```


FIGURE 38: 5GT-MTP NBI: REQUEST MESSAGE BODY FOR ALLOCATING A SET OF LLS FOR A GIVEN NETWORK SERVICE (SERVICEID)

A successful REST API response sent from the 5GT-MTP to the 5GT-SO (i.e., response code 201, Created) carries in the message body a top-level array indicating for each LL information related to the allocated resource such as the connection identifier (used to determine the data path over a given LL) and the so-called segment type (e.g., VLAN tag) being used for transporting and forwarding the data traffic over a specific LL. In other words, a network service which is determined by a *serviceID* may traverse *n* LLs. For each LL, a specific connection identifier and a segment type (which may be different) are used. Thus, at the 5GT-MTP, it is stored the *serviceId* and their associated *n* connection identifiers (referred to as *interNfviPopConnectivityId*) and the segment types (herein termed as *interNfviPopNetworkSegmentType*). Those objects are described below:

- **interNfviPopConnectivityId**: Identifier used for determining a connectivity for a given serviceId over a particular LL
- **interNfviPopNetworkSegmentType**: network selector type used to switch and forward the traffic of a given serviceId over a particular LL

The above set of attributes contained into the body of the *interNfviPopConnectivityRespose* message are shown in Figure 39 using the SWAGGER REST API editor [33].

```
[
  {
    "interNfviPopConnnectivityId": "string",
    "interNfviPopNetworkSegmentType": "string"
  }
]
```


FIGURE 39: 5GT-MTP NBI: RESPONSE MESSAGE BODY FOR ALLOCATING A SET OF LLS FOR A GIVEN NETWORK SERVICE (SERVICEID)

To complete the management of the inter-NFVI-PoP link resources, below we also provide details for releasing such network resources when a network service is being terminated. Figure 40 provides the pair of exchanged messages between the 5GT-SO and the 5GT-MTP for de-allocating the LL's resources associated to a given *serviceID*. These messages are: *deleteNfviPopConnectivityRequest* and *deleteNfviPopConnectivityResponse*. The request message body carries the *serviceID* in the so-called *interNfviPopConnectivityId* object. Additionally, a metadata object provides a placeholder for contents being considered in potential new uses. The response message does not require body information/details.

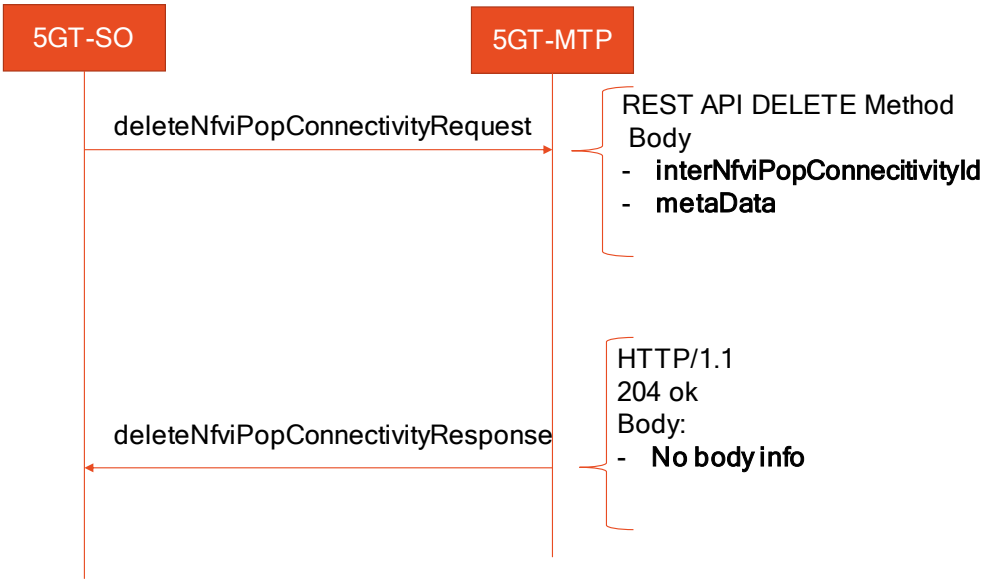


FIGURE 40: REQUEST/RESPONSE 5GT-MTP NBI FOR REMOVING THE INTER-NFVI-POP RESOURCES RELATED TO A SPECIFIC SERVICEID

The content of the body forming the *deleteNfviPopConnectivityRequest* message are shown in Figure 41 using the SWAGGER REST API editor [33].

```
{
  "interNfviPopConnnectivityIdList": [
    {
      "interNfviPopConnnectivityId": "string"
    }
  ],
  "metaData": [
    {
      "key": "string",
      "value": "string"
    }
  ]
}
```


FIGURE 41: 5GT-MTP NBI: REQUEST MESSAGE BODY FOR DE-ALLOCATING ALL NETWORK RESOURCES ASSOCIATED TO A GIVEN SERVICEID

Those objects are described below:

- **interNfviPopConnectivityIdList**: It is an array of the interNfviConnectivityIds used by a particular serviceId to be removed
  - InterNfviPopConnectivityId: Identifier used for determining a connectivity for a given serviceId over a particular LL
- **metaData**: contents not defined at the time being but reserved for future uses.

5.5.1.1.3 Allocating (and terminating) intra-Nfvi-Pop Connectivity

The allocation of the intra-NFVI-PoP connectivity entails the deployment of all the required subnets and networks to enable the connectivity of the VNFs to be instantiated into a specific NFVI-PoP. For instance, the outcome of doing that is to provide the IP address being assigned to the VNF, determining the L2-VPN labels / tags for forwarding data traffic, the connectivity between the VNF port and the NFVI-PoP's Gw for the external connectivity towards the WAN, etc. To this end, it is necessary that at the time of deploying a network service, once the NFVI-PoPs are selected to host the required VNFs, the corresponding subnets and networks are created. This operation should be triggered by the 5GT-SO using the pair of messages *AllocateNetworkResourceRequest* and *AllocateNetworkResourceResponse*. The former is attained using REST POST method with the URI set to */network_resources*. Figure 42 shows the exchanged messages between the 5GT-SO and 5GT-MTP to create the intra-NFVI-PoP connectivity where eventually the targeted VNFs should be instantiated. The contents of the *AllocateNetworkResourceRequest* are those already specified in [33]. Likewise, the successful reply message (i.e., *AllocateNetworkResourceResponse*) contains the set of parameters defined in [33]. For the sake of brevity and since those contents are not extended to cover specific 5GT architectural needs, the interested reader is invited to refer to the above ETSI IFA 005 document [33].

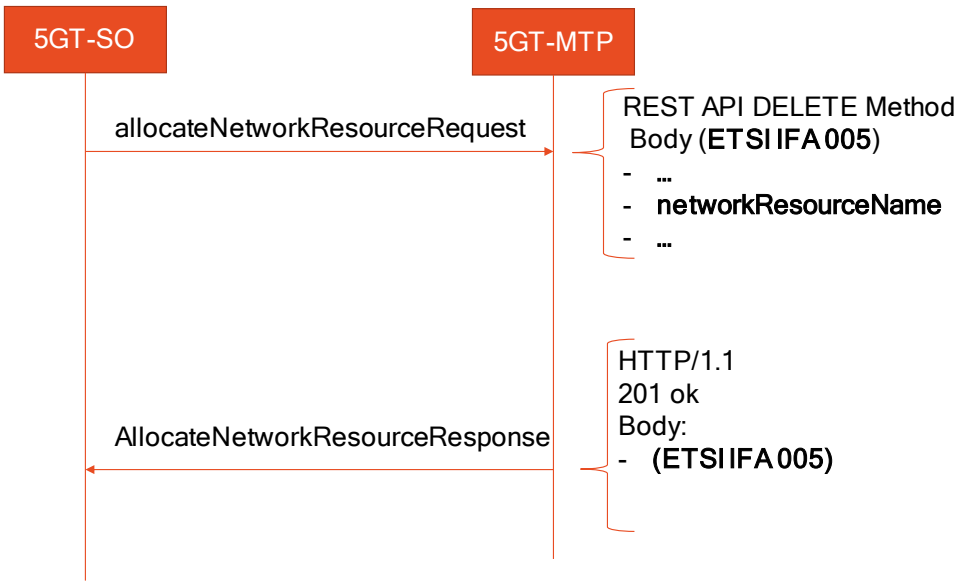


FIGURE 42: REQUEST/RESPONSE 5GT-MTP NBI FOR CREATING THE INTRA-NFVI-POP CONNECTIVITY

Moreover, the metaData contents typically defined in the IFA005 messages is exploited to carry relevant information for the configuration of the intraNfviPop network resources. This includes:

- **serviceId**: the identifier assigned by the 5GT-SO to unambiguously determine the network service being deployed within the Nfvi-Pop location
- **nfviPopId**: identifier of the NFVI-PoP
- **floating_required**: this parameter is used to eventually indicate the VIM controller (e.g., OpenStack) that the allocation of the IP addressing of the intra-Nfvi-Pop network is assigned according to a floating IP assignment mode.

The termination of the intra-NFVI-PoP connectivity is attained using the pair of messages defined in [33]. The contents and parameters carried into those messages are thoroughly addressed in the above reference.

5.5.1.1.4 Allocating (and terminating) compute resources

Requests “allocating/terminating compute resources” are used for the creation and termination of compute resources on the underlying VIM. This request is sent from the 5GT-SO to the 5GT-MTP. The 5GT-MTP interacts through the deployed 5GT-MTP plugin with the VIM controlling a specific NFVI-PoP. The request and response messages body contain the parameters reported in ETSI GS NFV-IFA 005 specification for the Allocate/Terminate Virtualised Compute Resource operation. Requests “allocating compute resources” contain the information about memory, CPU and disk resources (e.g., available, etc.), a list of elements defining the affinity or anti affinity, network interfaces, software image, list of metadata containing key-value pairs and location constraints. The request body is detailed below in Figure 43.

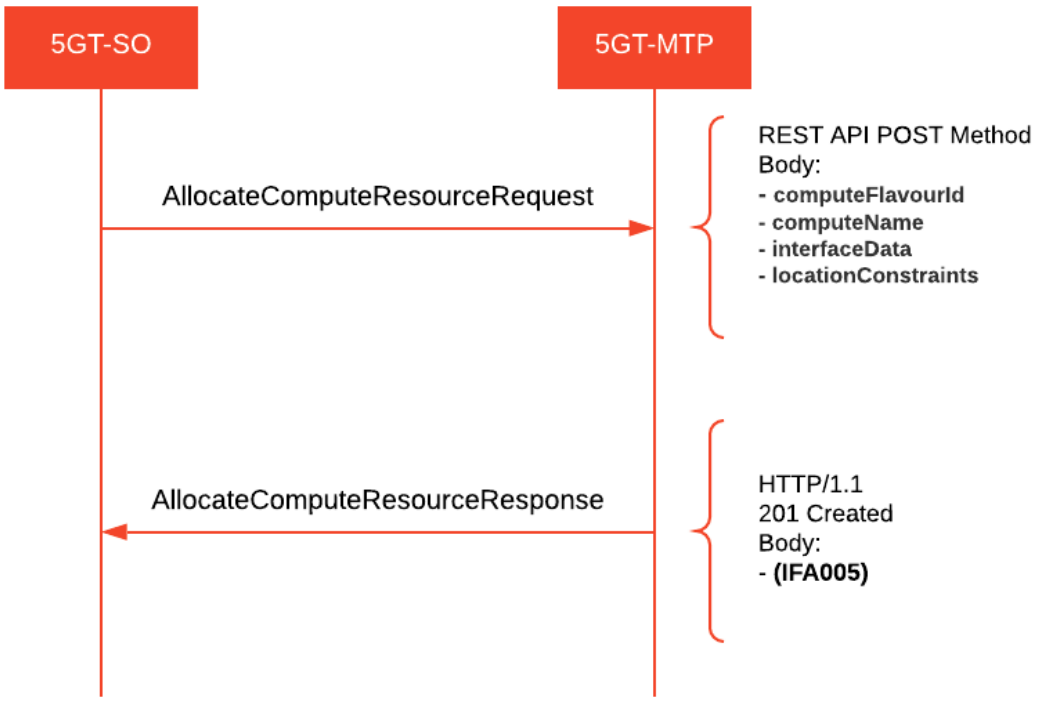


FIGURE 43: REQUEST/RESPONSE FOR ALLOCATION COMPUTE RESOURCES

AllocatingComputeResources request uses URL prefix /abstract-network-resources request body. The example of the request body is described in the Figure 44:

```
{
 "affinityOrAntiAffinityConstraints": [
  {
   "affinityAntiAffinityResourceGroup": "string",
   "affinityAntiAffinityResourceList": {
    "resource": [
     "string"
    ]
   },
   "scope": "string",
   "type": "string"
  }
 ],
 "computeFlavourId": "string",
 "computeName": "string",
 "interfaceData": [
  {
   "ipAddress": "string",
   "macAddress": "string"
  }
 ],
 "locationConstraints": "string",
 "metadata": [
  {
   "key": "string",
   "value": "string"
  }
 ],
 "reservationId": "string",
 "resourceGroupId": "string",
 "userData": {
  "content": "string",
                    "method": "string"
                              },
 "vcImageId": "string"
                             }
```


FIGURE 44: EXAMPLE OF THE COMPUTE ALLOCATION REQUEST BODY

Compute allocation request can contain a variety of fields to configure allocated compute resources accordingly. Compute allocation request parameters are described as follows:

- **affinityOrAntiAffinityConstraints** A list of elements with affinity or anti affinity information of the virtualised compute resource to allocate. There should be a relation between the constraints defined in the different elements of the list.
- **affinityAntiAffinityResourceGroup** Identifier of the producer-managed group of virtualised resources with which the actual resource is requested to be affine or anti-affine. Either affinityAntiAffinityResourceList or affinityAntiAffinityResourceGroup but not both shall be present.
- **affinityAntiAffinityResourceList** Consumer-managed list of identifiers of virtualised resources with which the actual resource is requested to be affine or anti-affine. Either affinityAntiAffinityResourceList or affinityAntiAffinityResourceGroup but not both shall be present. List of identifiers of virtualised resources.
- **scope** Qualifies the scope of the constraint. In case of compute resource: e.g. "NFVI-PoP" or "NFVI Node". In case of ports: e.g. "virtual switch or router" or

"physical NIC", or "physical network" or "NFVI Node". In case of networks: e.g. "physical NIC", "physical network" or "NFVI Node". In case of subnets: it should be ignored. Defaults to "NFVI Node" if absent.

- **type** Indicates whether this is an affinity or anti-affinity constraint.
- **computeFlavourId** Identifier of the Compute Flavour that provides information about the particular memory, CPU and disk resources for virtualised compute resource to allocate. The Compute Flavour is created with Create Compute Flavour operation
- **computeName** Name provided by the consumer for the virtualised compute resource to allocate. It can be used for identifying resources from consumer side.
- **interfaceData** The data of network interfaces which are specific to a Virtual Compute Resource instance.
- **ipAddress** The virtual network interface can be configured with specific IP address(es) associated to the network to be attached to. The cardinality can be 0 in the case that a network interface is created without being attached to any specific network, or when an IP address can be automatically configured, e.g. by DHCP.
- **macAddress** The MAC address desired for the virtual network interface. The cardinality can be 0 to allow for network interface without specific MAC address configuration.
- **locationConstraints** If present, it defines location constraints for the resource(s) is (are) requested to be allocated, e.g. in what particular Resource Zone.
- **metadata** List of metadata key-value pairs used by the consumer to associate meaningful metadata to the related virtualised resource.
- **reservationId** Identifier of the resource reservation applicable to this virtualised resource management operation. Cardinality can be 0 if no resource reservation was used.
- **resourceGroupId** Unique identifier of the "infrastructure resource group", logical grouping of virtual resources assigned to a tenant within an Infrastructure Domain.
- **userData** Element containing user data to customize the virtualised compute resource at boot-time.
- **content** String containing the user data to customize a virtualised compute resource at boot-time.
- **method** is used as transportation media to convey the content of the UserData to the virtualised compute resource. Possible values: CONFIG-DRIVE.
- **vcImageId** Identifier of the virtualisation container software image (e.g. a virtual machine image). Cardinality can be 0 if an "empty" virtualisation container is allocated.

Successfully responding the processed request, the 5GT-MTP creates a response code 201 and returns it to SO. The response body example is shown on the Figure 45.

```
{
 "accelerationCapability": [
  "string"
 ],
 "computeId": "string",
 "computeName": "string",
 "flavourId": "string",
 "hostId": "string",
 "operationalState": "string",
 "vcImageId": "string",
 "virtualCpu": {
  "cpuArchitecture": "string",
  "cpuClock": 0,
  "numVirtualCpu": 0,
  "virtualCpuOversubscriptionPolicy": "string",
  "virtualCpuPinning": {
   "cpuMap": "string",
   "cpuPinningPolicy": "string",
   "cpuPinningRules": "string"
  }
 },
 "virtualDisks": "string",
 "virtualMemory": {
  "numaEnabled": true,
  "virtualMemOversubscriptionPolicy": "string",
  "virtualMemSize": 0
 },
 "virtualNetworkInterface": [
  {
   "accelerationCapability": "string",
   "bandwidth": "string",
   "ipAddress": "string",
   "macAddress": "string",
   "metadata": "string",
   "networkId": "string",
   "networkPortId": "string",
   "operationalState": "string",
   "ownerId": "string",
   "resourceId": "string",
   "typeConfiguration": "string",
   "typeVirtualNic": "string"
  }
 ],
 "zoneId": "string"
}
```


FIGURE 45: EXAMPLE OF THE COMPUTE ALLOCATION RESPONSE BODY

The compute allocation response contains the following fields:

- **accelerationCapability** Selected acceleration capabilities (e.g. crypto, GPU) from the set of capabilities offered by the compute node acceleration resources. The cardinality can be 0, if no particular acceleration capability is provided.
- **computeId** Identifier Identifier of the virtualised compute resource.
- **computeName** Name of the virtualised compute resource.
- **flavourId** Identifier of the given compute flavour used to instantiate this virtual compute.
- **hostId** Identifier of the host the virtualised compute resource is allocated on.

- **operationalState** Operational state of the compute resource.
- **vcImageId** Identifier of the virtualisation container software image (e.g. virtual machine image). Cardinality can be 0 if an "empty" virtualisation container is allocated.
- **virtualCpu** The virtual CPU(s) of the virtualised compute.
- **cpuArchitecture** CPU architecture type. Examples are x86, ARM.
- **cpuClock** Minimum CPU clock rate (e.g. in MHz) available for the virtualised CPU resources.
- **numVirtualCpu** Number of virtual CPUs.
- **virtualCpuOversubscriptionPolicy** The CPU core oversubscription policy, e.g. the relation of virtual CPU cores to physical CPU cores/threads. The cardinality can be 0 if no policy has been defined during the allocation request.
- **virtualCpuPinning** The virtual CPU pinning configuration for the virtualised compute resource.
- **cpuMap** Shows the association of virtual CPU cores to physical CPU cores.
- **cpuPinningPolicy** The policy can take values of "static" or "dynamic". In case of "static" the virtual CPU cores have been allocated to physical CPU cores according to the rules defined in cpuPinningRules. In case of "dynamic" the allocation of virtual CPU cores to physical CPU cores is decided by the VIM.
- **cpuPinningRules** A list of rules that should be considered during the allocation of the virtual CPUs to physical CPUs in case of "static" cpuPinningPolicy.
- **virtualDisks** Element with information of the virtualised storage resources (volumes, ephemeral that are attached to the compute resource.)
- **virtualMemory** The virtual memory of the compute.
- **numaEnabled** It specifies the memory allocation to be cognisant of the relevant process/core allocation.
- **virtualMemOversubscriptionPolicy** The memory core oversubscription policy in terms of virtual memory to physical memory on the platform. The cardinality can be 0 if no policy has been defined during the allocation request.
- **virtualMemSize** Amount of virtual Memory (e.g. in MB).
- **virtualNetworkInterface** Element with information of the instantiated virtual network interfaces of the compute resource.
- **accelerationCapability** It specifies if the virtual network interface requires certain acceleration capabilities.The cardinality can be 0, if no particular acceleration capability is provided.
- **bandwidth** The bandwidth of the virtual network interface (in Mbps).
- **ipAddress** The virtual network interface can be configured with specific IP address(es) associated to the network to be attached to. The cardinality can be 0 in the case that a network interface is created without being attached to any specific network, or when an IP address can be automatically
- **configured**, e.g. by DHCP.
- **macAddress** The MAC address of the virtual network interface.
- **metadata** KeyValuePair List of metadata key-value pairs used by the consumer to associate meaningful metadata to the related virtualised resource.
- **networkId** (Reference to VirtualNetwork) In the case when the virtual network interface is attached to the network, it identifies such a network. The cardinality can be 0 in the case that a network interface is created without being attached to any specific network.

- **networkPortId** If the virtual network interface is attached to a specific network port, it identifies such a network port. The cardinality can be 0 in the case that a network interface is created without any specific network port attachment.
- **operationalState** the operational state of the virtual network interface.
- **ownerId** Identifier of the owner of the network interface (e.g. a virtualised compute resource).
- **resourceId** Identifier of the virtual network interface.
- **typeConfiguration** Extra configuration that the virtual network interface supports based on the type of virtual network interface, including support for SRIOV with configuration of virtual functions (VF).
- **typeVirtualNic** Type of network interface. The type allows for defining how such interface is to be realized, e.g. normal virtual NIC, with direct PCI passthrough, etc.
- **zoneId** If present, it identifies the Resource Zone where the virtual compute resources have been allocated.

The compute resources deletion workflow is described on the Figure 46.

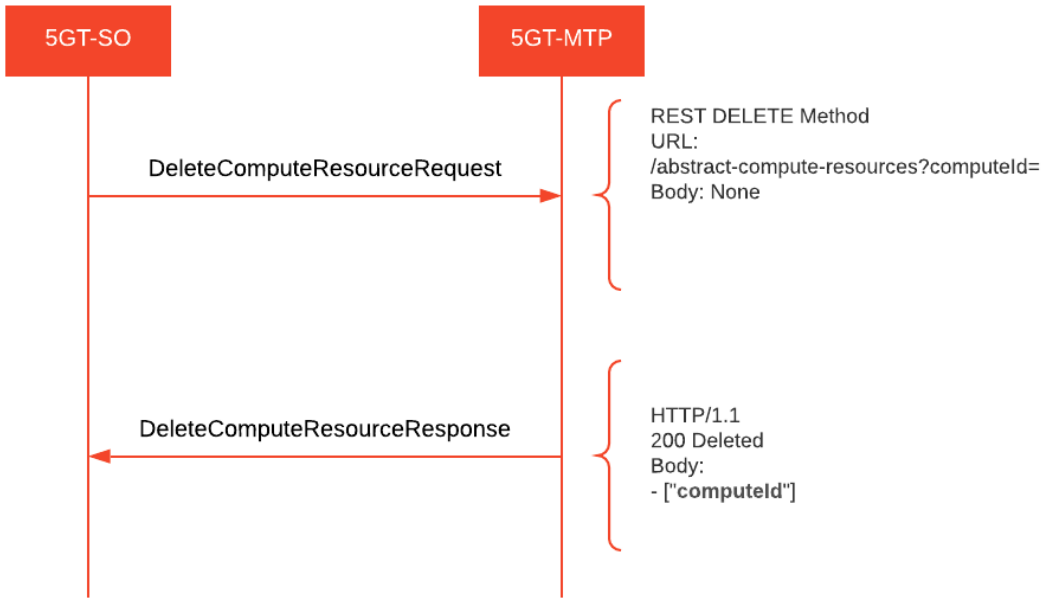


FIGURE 46: REQUEST/RESPONSE FOR TERMINATING COMPUTE RESOURCES

5GT-SO initiates DeleteComputeResourceRequest, sent to the 5GT-MTP. It refers to REST DELETE method with a compute resourceId and blank body. DeleteComputeResources request uses URI prefix /abstract-network-resources? prior to computeId key. For example: /abstract-network-resources?computeId=1, where 1 is a computeId.

5GT-MTP processes the request and answers with the 200 Delete HTTP/1.1 DeleteComputeResourceResponse, containing computeId in the body field.

5.5.2 5GT-MTP SBI

The 5GT-MTP SBI enables the interaction between the 5GT-MTP and its managed VIM, WIM, Radio and MEC domains. The following set of functionalities and/or operations are provided for each domain type:

- VIM domain
  i. Retrieving information about each available NFVI-PoP.
  ii. Retrieving the available Resource Zones for each NFVI-PoP.
  iii. Retrieving information about the various types of virtualised compute resources (memory, CPU and storage) managed by the VIM.
  iv. Retrieving capacity information for the various types of consumable virtualised compute resources managed by the VIM.
  v. Create (and terminate) VNFs on a given NFVI-PoP.
  vi. Create (and terminate) an intra-PoP connectivity on a given NFVI-PoP.
- WIM domain
  i. Retrieving information about edge gateways and virtual links managed by the WIM.
  ii. Create (and terminate) an intra-WIM connectivity between two edge gateways.
- Radio domain
  i. Retrieving information about the radio coverage area.
  ii. Create (and terminate) radio network function
- MEC domain
  i. Retrieving information about MEC regions (e.g., ID, delay).
  ii. Create (and terminate) MEC app.

All the above functionalities are supported over a specific pool of REST API messages encoded in JSON format where each domain operates as a server and the 5GT-MTP is the client.

In the following sections, specific details of the different API messages supporting those set of functionalities are provided.

5.5.2.1 VIM specific operations and functionalities

In this section VIM specific operations and functionalities are described. The implementation of such operations and functionalities are based on ETSI GS NFV-IFA 005 specification [33].

5.5.2.1.1 Retrieval of NFVI-PoPs information

This information is an on-demand basis collected by the 5GT-MTP via a GET method message where the required URI is set to */compute_resources /nfvi_pop_compute_information*. The request and response messages are named QueryComputeNFVIPoP and QueryComputeNFVIPoP (see Figure 47), respectively. The request message does not carry any content on the body, whilst a successful response (code 200) provides the details of the NFVI-PoPs (NFVIPoP List) described as a JSON encoding array where a component provides the attributes related to a given NFVI-PoP. Figure 48 shows a screenshot (via swagger REST API editor [33]) of the defined array carried in the body of the response message. The attributes describing each NFVI-PoP element are:

- **nfviPopId:** Identifier of the NFVI-PoP.

- **vimId:** Identifier of the VIM.
- **geographicalLocationInfo:** Information about the geographic location (e.g. geographic coordinates or address of the building, etc.) of the NFVI resources that the VIM manages.
- **networkConnectivityEndpoint:** Information about network connectivity endpoints (gateways) of the NFVI-PoP.

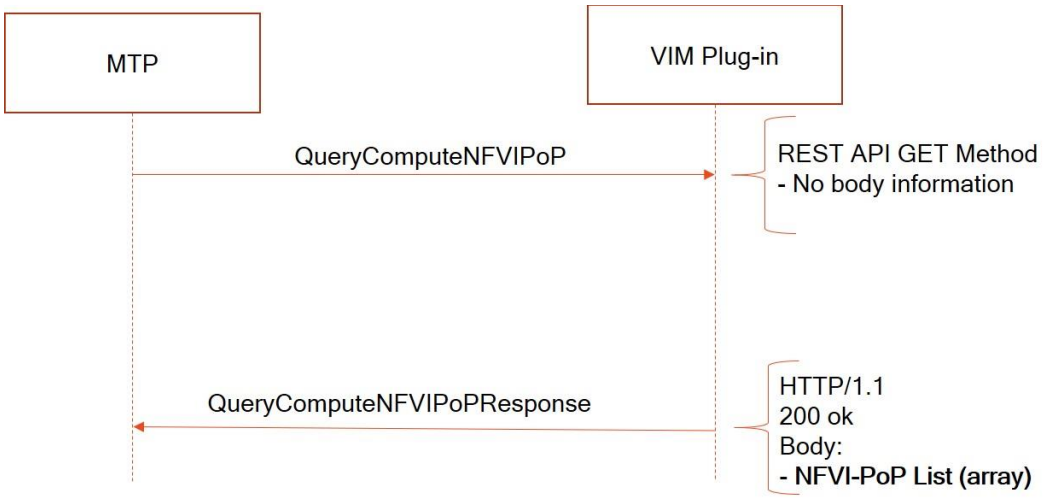


FIGURE 47: REQUEST/RESPONSE 5GT-MTP SBI FOR RETRIEVAL OF NFVI-POPS INFORMATION

```
[
  {
    "geographicalLocationInfo": "string",
    "networkConnectivityEndpoint": "string",
    "nfviPopId": "string",
    "vimId": "string"
  }
]
```

FIGURE 48: GET METHOD WITH NFVI-POPS INFORMATION

5.5.2.1.2 Retrieval of available resource zones

This information is collected upon on-demand basis by the 5GT-MTP via a GET method message where the required URI is set to */compute_resources/resource_zones*. The request and response messages are named QueryComputeZone and QueryComputeZoneResponse (see Figure 49), respectively. The request message does not carry any content on the body, whilst a successful response (code 200) provides the details of the Resource Zones (Zone List) described as a JSON encoding array where a component provides the attributes related to a given Resource Zone. Figure 50 shows a screenshot of the defined array carried in the body of the response message. The attributes describing each Resource Zone element are:

- **zoneId:** Identifier of the Resource Zone.
- **zoneName:** Name of the Resource Zone.
- **zoneState:** Current state of the Resource Zone.
- **nfviPopId:** Identifier of the NFVI-PoP the Resource Zone belongs to.

- **zoneProperty:** Set of properties that define the capabilities associated to the Resource Zone (e.g. low performance, acceleration capabilities, etc.).
- **metadata:** Metadata associated to the Resource Zone.

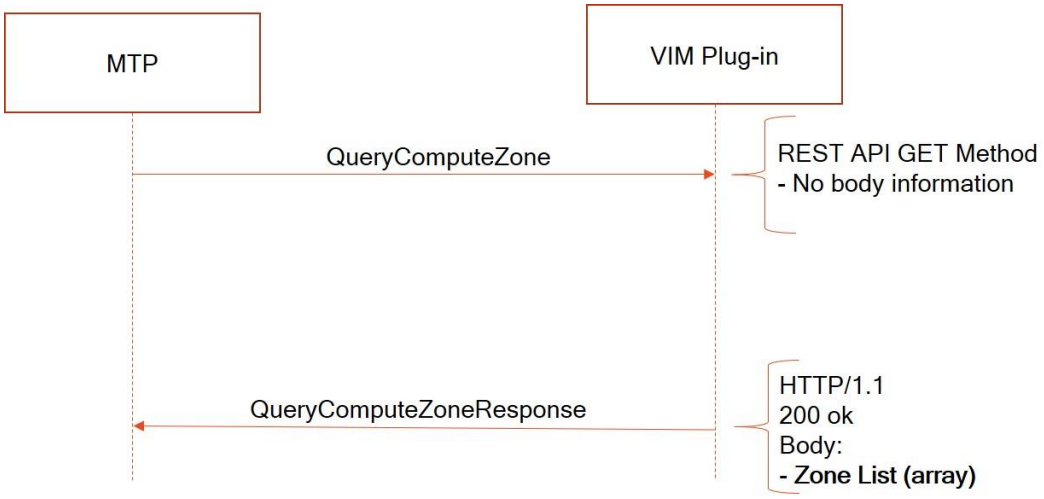


FIGURE 49: REQUEST/RESPONSE 5GT-MTP SBI FOR RETRIEVAL OF RESOURCE ZONES INFORMATION

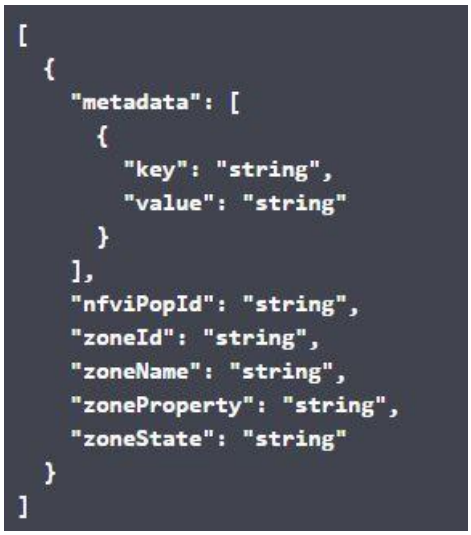


FIGURE 50: GET METHOD WITH RESOURCE ZONES INFORMATION

5.5.2.1.3 Retrieval of available virtualised compute resources

This information is an on-demand basis collected by the 5GT-MTP via a GET method message where the required URI is set to */compute_resources/information*. The request and response messages are named QueryComputeResourceInformation and QueryComputeResourceInformationResponse (see Figure 51), respectively. The request message includes the *zoneID* in the URL as query string, which identifies the resource zone for which the virtualised compute resources are requested. A successful response (code 200) provides the details of the Virtualised Compute Resources (Compute Resource List) described as a JSON encoding array where a component provides the attributes related to a given Virtualised Compute Resource (virtualCPU or virtualMemory). Figure 52 shows a screenshot of the defined array carried in the body of

the response message. The attributes describing the virtualCPU and virtualMemory resources are:

- **virtualCPU**
  - **cpuArchitecture:** CPU architecture type (e.g., x86, ARM, etc.)
  - **numVirtualCpu:** Number of virtual CPUs.
  - **cpuClock:** Minimum CPU clock rate (e.g. in MHz) available for the virtualised CPU resources.
  - **virtualCpuOversubscriptionPolicy:** CPU core oversubscription policy, e.g. the relation of virtual CPU cores to physical CPU cores/threads.
  - **virtualCpuPinningSupported:** It defines whether CPU pinning capability is available on the consumable virtualised compute resource.
- **virtualMemory**
  - **virtualMemSize:** Amount of virtual memory (e.g. in MB). **virtualMemOversubscriptionPolicy:** Memory core oversubscription policy in terms of virtual memory to physical memory on the platform. **numaSupported:** It specifies if the memory allocation can be aware of the relevant process/core allocation.

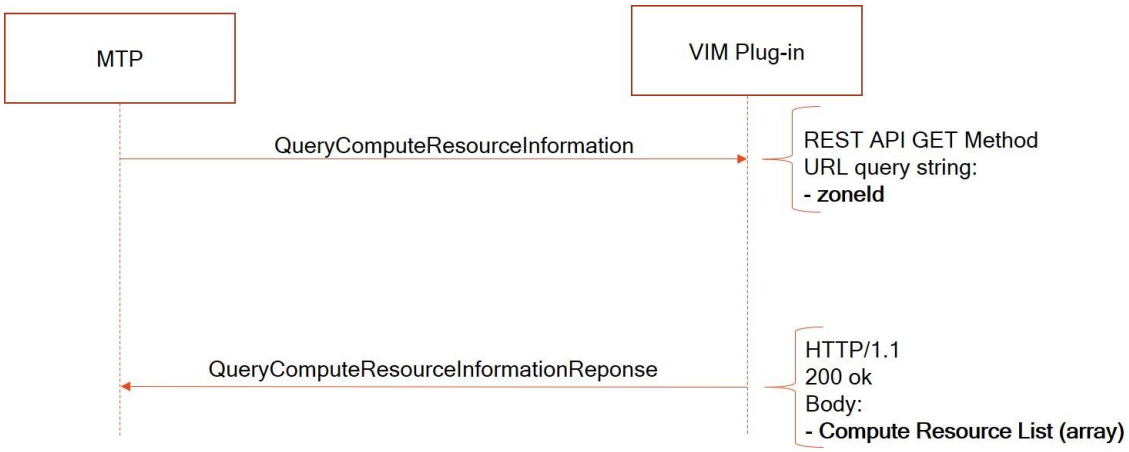


FIGURE 51: REQUEST/RESPONSE 5GT-MTP SBI FOR RETRIEVAL OF VIRTUALISED COMPUTE RESOURCES INFORMATION

```
[
  {
    "accelerationCapability": "string",
    "computeResourceTypeId": "string",
    "virtualCPU": {
      "cpuArchitecture": "string",
      "cpuClock": 0,
      "numVirtualCpu": 0,
      "virtualCpuOversubscriptionPolicy": "string",
      "virtualCpuPinningSupported": true
    },
    "virtualMemory": {
      "numaSupported": true,
      "virtualMemOversubscriptionPolicy": "string",
      "virtualMemSize": 0
    }
  }
]
```


FIGURE 52: GET METHOD WITH VIRTUALISED COMPUTE RESOURCES INFORMATION

5.5.2.1.4 Retrieval of compute capacity information

This information is retrieved upon on-demand basis by the 5GT-MTP via a GET method message where the required URI is set to */compute_resources/capacities*. The request and response messages are named QueryComputeCapacity and QueryComputeCapacityResponse (see Figure 53), respectively. The request message includes the *ResourceTypeId* in the URL as query string, which identifies the specific Virtualised Compute Resource (virtualCPU or virtualMemory) for which the capacity information is requested. A successful response (code 200) provides the capacity information of the specific Virtualised Compute Resource (virtualCPU or virtualMemory) described as a list of attributes in JSON format. Figure 54 shows a screenshot of the attributes carried in the body of the response message. The attributes describing the Capacity Information are:

- **availableCapacity:** Capacity available for allocation and reservation.
- **reservedCapacity:** Amount of reserved capacity.
- **totalCapacity:** Amount of total capacity.
- **allocatedCapacity:** Amont of allocated capacity.

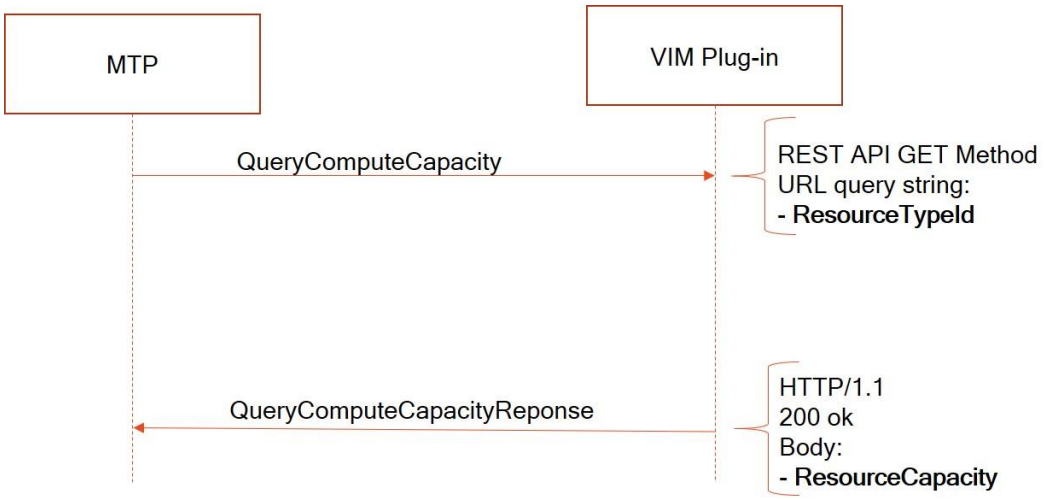


FIGURE 53: REQUEST/RESPONSE 5GT-MTP SBI FOR RETRIEVAL OF COMPUTE CAPACITY INFORMATION

```
{
  "allocatedCapacity": "string",
  "availableCapacity": "string",
  "reservedCapacity": "string",
  "totalCapacity": "string"
}
```

FIGURE 54: GET METHOD WITH COMPUTE CAPACITY INFORMATION

5.5.2.1.5 VNF instantiation/termination

This operation requested by the 5GT-MTP and processed by a VIM domain triggers the instantiation/termination of a VNF on a given NFVI-PoP. The instantiation of a VNF relies on the REST POST method with the URI set to */compute_resources*, whereas the termination of a VNF uses the REST DELETE method with the same URI.

Figure 55 shows the exchanged messages (i.e., *VnfInstatiationRequest* and *VnfInstatiationResponse*) between the 5GT-MTP and a specific VIM domain to instantiate a VNF. The request and response messages body contain the attributes reported in ETSI GS NFV-IFA 005 specification for the Allocate Virtualised Compute Resource operation. The metadata attribute is used to specify the identifier of the NFV-NS (serviceId) for which the VNF is instantiated.

Figure 56 shows the exchanged messages (i.e., *VnfTerminationRequest* and *VnfTerminationResponse*) between the 5GT-MTP and a specific VIM domain to terminate a VNF. The request and response messages contain the attributes reported in ETSI GS NFV-IFA 005 specification for the Terminate Virtualised Compute Resource operation. Specifically, the request message includes the *computeId* in the URL as query string, which identifies the specific VNF to terminate. A successful response (code 200) contains the identifier (*computeId*) of the VNF correctly terminated.

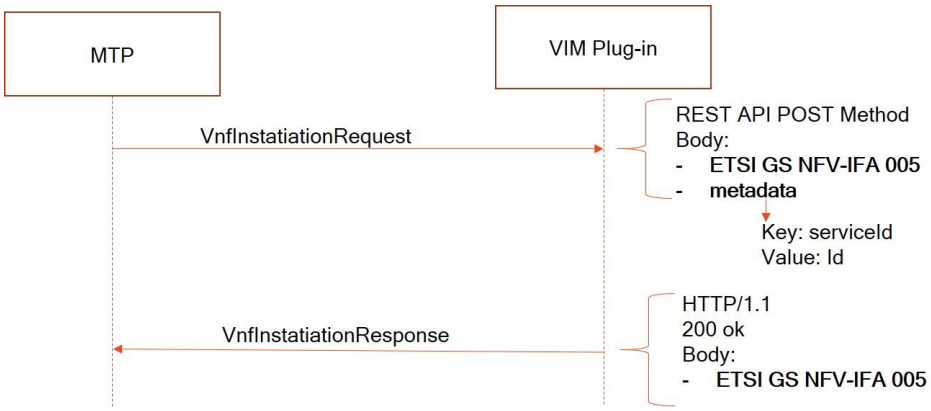


FIGURE 55: REQUEST/RESPONSE 5GT-MTP SBI FOR INSTANTIATION OF A VNF

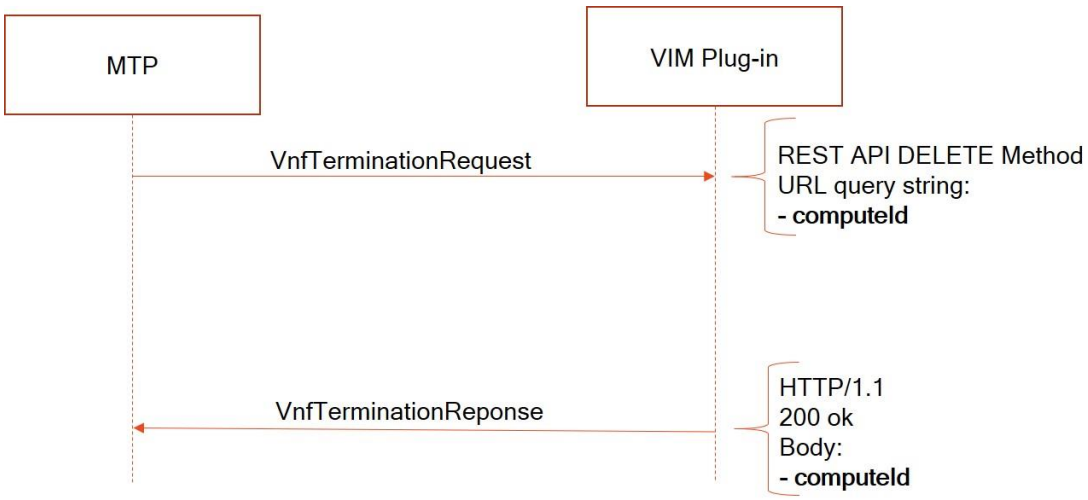


FIGURE 56: REQUEST/RESPONSE 5GT-MTP SBI FOR TERMINATION OF A VNF

5.5.2.1.6 Intra-NFVI-PoP connectivity instantiation/termination

This operation requested by the 5GT-MTP and processed by a VIM domain triggers the instantiation/termination of an intra-NFVI-PoP connectivity. The instantiation of an intra-NFVI-PoP connectivity relies on the REST POST method with the URI set to */network_resources*, whereas the termination uses the REST DELETE method with the same URI.

Figure 57 shows the exchanged messages (i.e., *IntraPopNetworkInstatiationRequest* and *IntraPopNetworkInstatiationResponse*) between the 5GT-MTP and a specific VIM domain to instantiate an intra-NFVI-PoP connectivity. The request and response message bodies contain the attributes reported in ETSI GS NFV-IFA 005 specification to support the Allocate Virtualised Network Resource operation. The metadata attribute is used to specify the identifier of the NFV-NS (serviceId) for which the intra-NFVI-PoP connectivity is instantiated.

Figure 58 shows the exchanged messages (i.e., *IntraPopNetworkTerminationRequest* and *IntraPopNetworkITerminationResponse*) between the 5GT-MTP and a specific VIM domain to terminate an intra-PoP connectivity. The request and response messages contain the attributes reported in ETSI GS NFV-IFA 005 specification to support the Terminate Virtualised Network Resource operation. Specifically, the request message

includes the *networkResourceId* in the URL as query string, which identifies the specific virtualised network resource to terminate. A successful response (code 200) contains the identifier (*networkResourceId*) of the virtualised network resource correctly terminated.

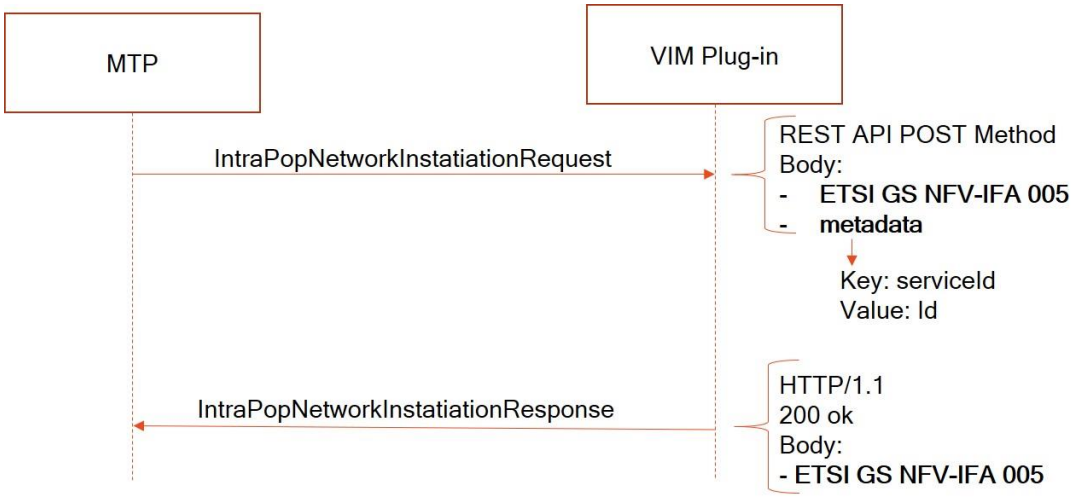


FIGURE 57: REQUEST/RESPONSE 5GT-MTP SBI FOR INSTANTIATION OF AN INTRA-POP CONNECTIVITY

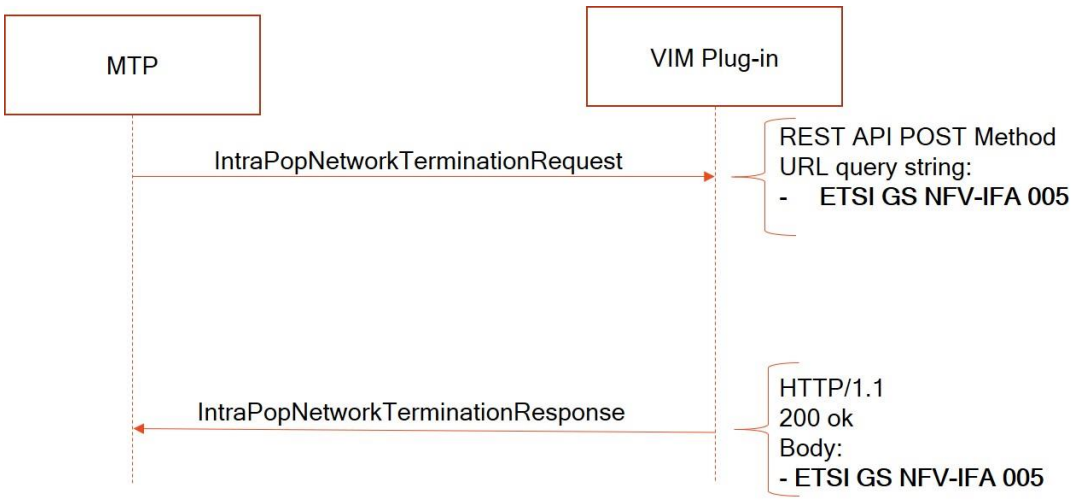


FIGURE 58: REQUEST/RESPONSE 5GT-MTP SBI FOR TERMINATION OF AN INTRA-POP CONNECTIVITY

5.5.2.2 WIM specific operations and functionalities

In this section WIM specific operations and functionalities are described.

5.5.2.2.1 Retrieval of edge gateways and virtual links information

This information is gathered upon an on-demand basis by the 5GT-MTP via a GET method message where the required URI is set to */abstract-network*. The request and response messages are named QueryWanResources and

QueryWanResourcesResponse (see Figure 59), respectively. The request message does not carry content on the body, whilst a successful response (code 200) provides the details of WAN aggregated resources (gateways and virtualLinks) described as two JSON encoding array where a component provides the attributes related to a given element. Figure 60 shows a screenshot (via swagger REST API editor [33]) of the defined array carried in the body of the response message. The attributes describing gateway and virtual-link elements are:

- **Gateway**
  - **geographicalLocationInfo:** information about the geographic location (e.g. geographic coordinates or address of the building, etc.) of the NFVI resources that the WIM manages.
  - **wimId:** Identification of the WIM.
  - **networkConnectivityEndpoint (array)**
    - **netGwIpAddress:** Edge gateway IP address.
    - **netGwInterfceId:** References the edge gateway interface over which the WAN is reachable.
  - **gatewayId:** Identifier of the edge gateway.
- **virtualLink**
  - **virtualLinkId:** Identifier of the virtual link.
  - **totalBandwidth:** total bandwidth of the virtual link (in Mbps).
  - **availableBandwidth:** available bandwidth of the virtual link (in Mbps).
  - **networkQoS**
    - **linkCostValue:** Cost of the virtual link.
    - **linkDelayValue:** Delay of the virtual link.
    - **packetLossRate:** Packet loss rate of the virtual link.
  - **srcGwId:** References the source edge gateway.
  - **srcLinkId:** References the source edge gateway interface.
  - **dstGwId:** References the destination edge gateway.
  - **dstLinkId:** References the destination edge gateway interface.
  - **networkLayer:** Describes the network layer capabilities of the gateway, i.e., Layer 2 (L2) or Layer 3 (L3), e.g. Ethernet, IP, IP/MPLS [29]

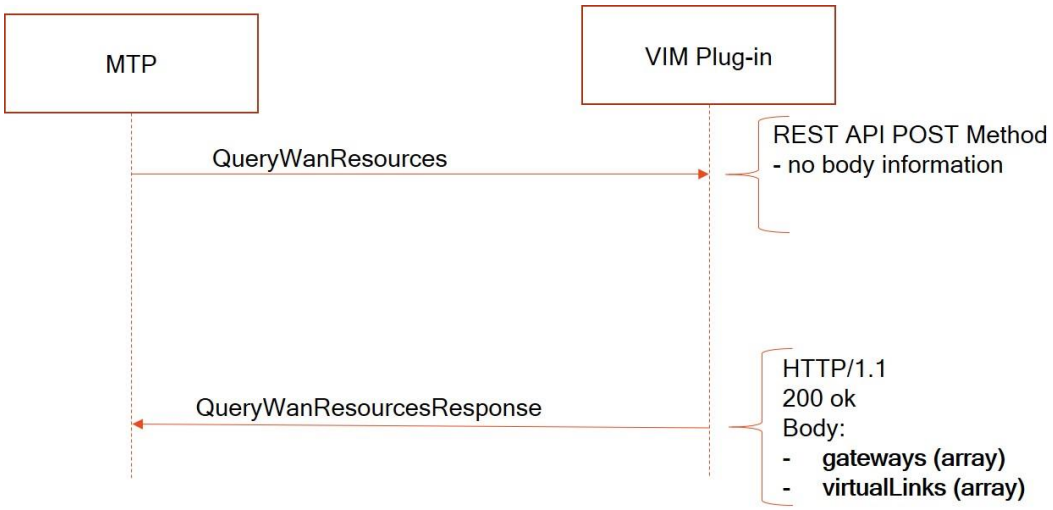


FIGURE 59: REQUEST/RESPONSE 5GT-MTP SBI FOR RETRIEVAL OF WAN AGGREGATED RESOURCES INFORMATION

```
{
  "gateways": [
    {
      "gatewayAttributes": {
        "geographicalLocationInfo": "string",
        "wimId": "string",
        "networkConnectivityEndpoint": [
          {
            "netGwIpAddress": "string",
            "netGwInterfceId": 0
          }
        ],
        "gatewayId": "string"
      }
    }
  ],
  "virtualLinks": [
    {
      "virtualLink": {
        "virtualLinkId": "string",
        "totalBandwidth": 0,
        "availableBandwidth": 0,
        "networkQoS": {
          "linkCostValue": 0,
          "linkDelayValue": 0,
          "packetLossRate": 0
        },
        "srcGwId": "string",
        "srcLinkId": 0,
        "dstGwId": "string",
        "dstLinkId": 0,
        "networkLayer": "string"
      }
    }
  ]
}
```

FIGURE 60: GET METHOD WITH WAN AGGREGATED RESOURCES INFORMATION

5.5.2.2.2 Intra-WIM connectivity instantiation/termination

This operation requested by the 5GT-MTP and processed by a WIM domain triggers the instantiation/termination of an intra-WIM connectivity. The instantiation of an intra-WIM connectivity relies on the REST POST method with the URI set to */network_resources*, whereas the termination uses the REST DELETE method with the same URI.

Figure 61 shows the exchanged messages (i.e., *IntraWimNetworkInstatiationRequest* and *IntraWimNetworkInstatiationResponse*) between the 5GT-MTP and a specific WIM domain to instantiate a WIM connectivity. Figure 62 shows a screenshot of the attributes carried in the body of the request message. As shown in Figure 61, the metadata attribute is used to specify the identifier of the NFV-NS (serviceId) for which the virtualised network resource is instantiated.

The attributes of the request message are described below:

- **locationConstraints:** it defines location constraints for the resource(s) is (are) requested to be allocated, e.g. in what particular Resource Zone.
- **reservationId:** Identifier of the resource reservation applicable to this virtualised resource management operation.
- **typeNetworkData:** The network data provides information about the particular virtual network resource to create.
- **affinityOrAntiAffinityConstraints:** A list of elements with affinity or anti affinity information of the virtualised network resource to allocate.
- **typeNetworkPortData:** Information about the particular network port to create.
- **resourceGroupId:** Unique identifier of a logical group of virtual resources assigned to a tenant within the WIM domain.
- **metadata:** List of metadata key-value pairs used by the consumer to associate meaningful metadata to the related virtualised resource.
- **networkResourceType:** Type of virtualised network resource. Possible values are: "network", "subnet" or network-port.
- **networkResourceName:** Name provided by the consumer for the virtualised network resource to allocate.
- **typeSubnetData:** Information about the particular sub-network resource to create.
- **bandwidth:** Minimum virtual network bandwidth (in Mbps).
- **delay:** virtual network delay.
- **networkType:** Type of network that maps to the virtualised network, e.g., "local", "vlan", "vxlan", "gre", "l3-vpn", etc.
- **segmentType:** Isolated segment for the virtualised network. For instance, for a vlan networkType, it corresponds to the vlan identifier; and for a gre networkType, this corresponds to a gre key.
- **networkQoS:** Information about QoS attributes that the network must support
- **isShared:** It defines whether the virtualised network is shared among consumers.
- **sharingCriteria:** Sharing criteria (if any) for this network.
- **layer3Attributes:** This attribute allows setting up a network providing defined layer 3 connectivity.
- **portType:** Type of network port, e.g., regular port, trunk port, etc.
- **networkId:** Identifier of the network that the port belongs to
- **segmentId:** The isolated network segment the port belongs to. For instance, for a VLAN, it corresponds to the VLAN tag/identifier.

- **ingressPointIPAddress:** The ingress point IP address.
- **ingressPointPortAddress:** The ingress point port (interface) address.
- **egressPointIPAddress:** The egress point IP address.
- **egressPointPortAddress:** The egress point port (interface) address.
- **wanLinkId:** Identifier of the logical link.

Figure 61 shows the exchanged messages (i.e., *IntraWimNetworkTerminationRequest* and *IntraWimNetworkTerminationResponse*) between the 5GT-MTP and a specific WIM domain to terminate a WIM connectivity. The request message includes the *networkId* in the URL as query string, which identifies the specific virtualised network resource to terminate. Similarly, a successful response (code 200) contains the identifier (*networkId*) of the virtualised network resource successfully terminated.

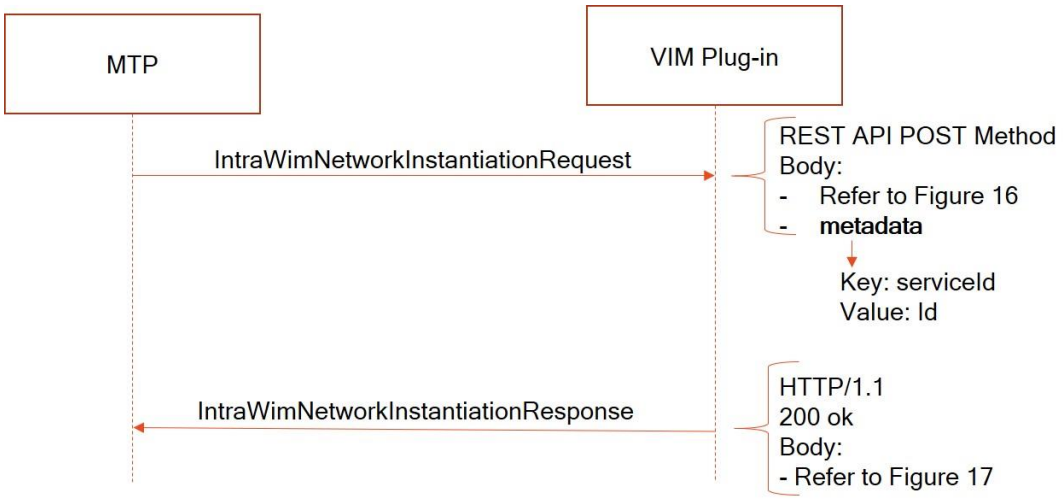


FIGURE 61: REQUEST/RESPONSE 5GT-MTP SBI FOR INSTANTIATION OF WAN NETWORK RESOURCE

```
{
  "locationConstraints": "string",
  "reservationId": "string",
  "typeNetworkData": "string",
  "affinityOrAntiAffinityConstraints": "string",
  "typeNetworkPortData": "string",
  "resourceGroupId": "string",
  "metadata": "string",
  "networkResourceType": "string",
  "networkResourceName": "string",
  "typeSubnetData": "string",
  "bandwidth": 0,
  "delay": "string",
  "networkType": "string",
  "segmentType": "string",
  "networkQoS": "string",
  "isShared": true,
  "sharingCriteria": "string",
  "layer3Attributes": "string",
  "portType": "string",
  "networkId": "string",
  "segmentId": "string",
  "ingressPointIPAddress": "string",
  "ingressPointPortAddress": "string",
  "egressPointIPAddress": "string",
  "egressPointPortAddress": "string",
  "wanLinkId": "string"
}
```


FIGURE 62: POST METHOD INPUT PARAMETERS


```
{
  "networkId": "string",
  "networkType": "string",
  "segmentType": "string"
}
```


FIGURE 63: POST METHOD OUTPUT PARAMETERS

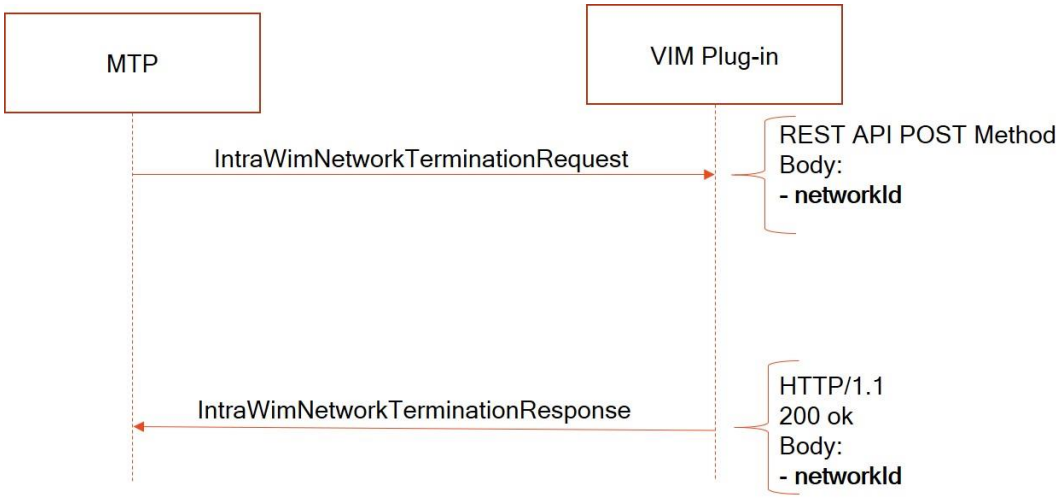


FIGURE 64: REQUEST/RESPONSE 5GT-MTP SBI FOR TERMINATION OF WAN NETWORK RESOURCE

5.5.3 MEC SBI

This section presents the interface exposed by the MEC 5GT-MTP plugin. The MEC plugin aims to abstract the operation of the MEC platform with respect to traffic rule management, DNS handling, and MEC service dependencies. It should be noted that the MEC plugin does not manage application instances. It is assumed that the interactions with the underlying VIM with respect to their onboarding, instantiation, and other lifecycle management operations are handled by the VIM plugin, as would be the case if the instance was a regular VNF.

The MEC plugin provides a REST HTTP interface to the 5GT-MTP, which is specified using OpenAPI v2.0 [35]. This API implements the following functions:

1. List MEC service requests per region
2. List MEC service requests across all regions
3. Create a MEC service request
4. Delete a MEC service request
5. Retrieve information about a specific service request

Figure 65 shows the API endpoints of the MEC plugin, including information on the HTTP method used and the path for each function.

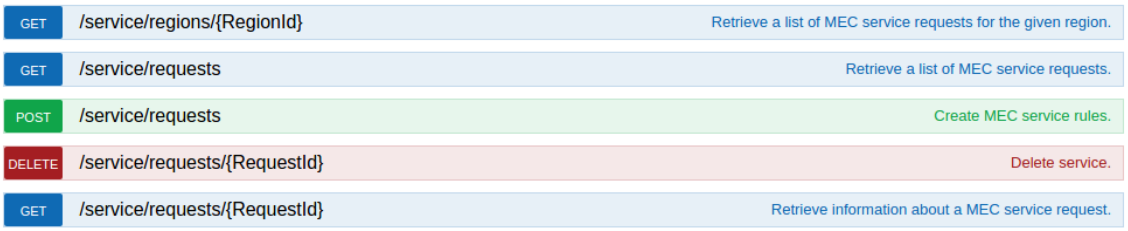


FIGURE 65: AVAILABLE MEC PLUGIN REST API CALLS

The MEC plugin is implemented in python and is based on the flask library. On its SBI, it communicates with the MEC platform managing each region's MEC over the MEP's REST API. In practice, the MEC plugin translates specific information elements included in a MEC service request from a format that complies with ETSI MEC 10-2 to a format compatible with the MEP's API for service registration and discovery, and traffic and DNS rule management. In particular, the MEC plugin receives with a MEC service request, specific information elements which are extracted from the MEC application descriptor (AppD):

- **appTrafficRule**: This field contains a list of traffic steering directives, i.e., rules that specify how traffic flows of a specific service, identified by information such as the destination IP address, the port and the transport protocol used, will be offloaded to MEC application instances.
- **appDNSRule**: The MEC application provider may specify a list of DNS rules to be added to the MEC DNS subsystem. The typical use of this field is so that DNS requests of UEs for specific domain names are resolved to the IP addresses of MEC application instances. This can find typical use in CDN scenarios, to implement DNS-based content request routing to edge caches, or in cloud robotics settings, where robots need to discover and connect to a command-and-control application instance deployed at the edge.
- **appServiceProduced**: This field is used to specify whether a MEC application is itself exposing a MEC service via the MEP to other applications.

- **appServiceRequired**: When this information element is present in the AppD, it means that the MEC application needs access to a specific service (e.g., RNIS).

It should be noted that above elements are supplied by the MEC application package provider at package onboarding time. Therefore, the information included there is not complete in order for the MEP to apply, e.g., traffic redirection, since the IP address of the instance is not known in advance to its creation. For this purpose, before communicating with the MEC plugin, the 5GT-MTP has to complement the appTrafficRule and appDNSRules that it receives over its NBI with the IP address information that it has received from the VIM plugin after the successful creation of an instance.

Figure 66 shows an example MEC service creation request, which includes both a traffic and a DNS rule. In this example, the 5GT-MTP requests the MEC plugin to apply a rule that matches a UE traffic flow towards destination IP address 195.251.255.142 and TCP port 80 and transparently redirects it to IP address 172.24.248.5, which corresponds to a MEC application instance. It also registers a DNS rule to resolve a specific domain name to the same IP address.


```
{
  "RegionId": "2",
  "appTrafficRule": [
    {
      "trafficRuleId": "c4c19d1a-2a7d-4424-bb54-9bd28d624cc4",
      "filterType": "FLOW",
      "priority": 100,
      "trafficFilter": [
        {
          "srcAddress": ["208930100001114"],
          "dstAddress": ["195.251.255.142"],
          "dstPort": ["80"],
          "Protocol": ["tcp"]
        }
      ],
      "action": "FORWARD",
      "dstInterface": [
        {
          "interfaceType": "IP",
          "dstMACAddress": "00:11:22:33:44:55",
          "dstIPAddress": "172.24.248.5"
        }
      ]
    }
  ],
  "appDNSRule": [
    {
      "dnsRuleId": "3f7ba638-5332-4db7-bbc6-eb38eb78183b",
      "domainName": "pfrag.gr",
      "ipAddressType": "IP_V4",
      "ipAddress": "172.24.248.5",
      "ttl": 0
    }
  ]
}
```


FIGURE 66: EXAMPLE OF A SERVICE CREATION REQUEST OVER THE MEC PLUGIN API.

5.5.4 5GT-MTP monitoring interface

The 5GT-MTP monitoring interface is offered by the Monitoring Configuration Manager (Config Manager) [11] and consumed by the 5GT-MTP in order to receive real-time information and alerts regarding the managed infrastructure.

There are three entities whose lifecycle is controlled through this interface: exporter jobs, alerts and dashboards. Exporter jobs are the logical representation of Monitoring data collection jobs, and they are usually in a 1-1 relationship with the monitored entities, although multi-entity aggregated jobs are possible. Alerts represent the logical bundle of a communication channel between the Monitoring platform and a notification consumer, together with the rules for notification generation at the Monitoring Platform. Finally, a dashboard is a web page representing – in real time – several monitored timeseries in plot format; it is a diagnostic and "active" (i.e. requiring direct user scrutiny) monitoring tool.

The exporter API allows the consumer to create, modify, delete and query exporter jobs. Each exporter jobs contains the configuration of a polling job performed by the Monitoring platform towards a data source, and it contains the information required to reach the source endpoint, i.e. IP address and port, on top of the job's configuration.

This API will usually be invoked at infrastructure deployment time, to connect the Monitoring platform to the data plane monitoring sources such as the VIM(s), WIM(s) and the data plane hardware.

The alert API allows the consumer to create, query, configure and delete notifications related to breaches of thresholds imposed on the monitored data. Each alert specifies a – potentially complex – query extracting a single value from any number of timeseries, a label and a severity parameter to report in case of a breach to ease the parsing of the notification at the notification consumer, the threshold value and the comparator (e.g. greater than, lower than, greater or equal, etc.) and the target which should be notified of the breach, in the form of a URL accepting POST requests.

This API might be called at infrastructure deployment time, to setup a baseline notification system, or at runtime in order to more closely monitor some problematic piece of the infrastructure, or to tighten the notification net when anticipating a heavy load or some other external difficulty, in order to have more time to react.

Finally, the dashboard API allows the consumer to create, read, update and destroy monitoring dashboard. After creation, a dashboard is assigned a URL the consumer can point their browser to in order to visualize a graphical report of the status of any part of the 5GT-MTP infrastructure.

The dashboard API requires to specify the users authorized to access the dashboard (if access control is required), some general configuration for the plots (time plotted and refresh frequency), and a list of panels. Each panel represents one plot window, and allows to specify the title of the window, the query that should be plotted in the window itself and the size of the window related to the browser window.

This API is meant to be invoked at infrastructure deployment time in order to generate one or more dashboard for general admin infrastructure monitoring, and at runtime for ad-hoc reporting of specific parts of the infrastructure or of some specific data for diagnosing issues.

5.5.5 5GT-MTP placement interface

This purpose of this API is to provide a means where a myriad of PA algorithms to be executed at the 5GT-MTP level can be triggered attaining a more granular decision (in terms of both cloud and networking resources) with respect to the result accomplished by the PA launched at the 5GT-SO level. Recall that in the 5GT hierarchical architecture, the cloud and networking infrastructure details being passed from the 5GT-MTP towards the 5GT-SO is generically abstracted. In light of this, the output of 5GT-SO's PAs typically describes a set of NFVI-PoPs (to host the required VNFs) and a set of LLs (enabling the inter-NFVI-PoP connectivity). Consequently, executing the 5GT-MTP's PA algorithm over the output of the 5GT-SO's PA aims at achieving a more accurate decision of both the cloud and the networking resources that eventually will be allocated. The rationale behind this is that the 5GT-MTP operates with a more detailed view of the all the resources compared to the 5GT-SO.

The 5GT-MTP PA could target multiple and heterogeneous objective functions as addressed in Section 5.3.4.1. The goal is that the 5GT-MTP relies on a common API to request executing a particular PA algorithm. This allows more flexibility and modularity to the 5GT-MTP architecture where conceiving a new PA algorithm can be easily integrated into the 5GT-MTP as long as the API is used. A schematic view of the interworking between the 5GT-MTP and a pool of potential PAs to be used is depicted in Figure 67.

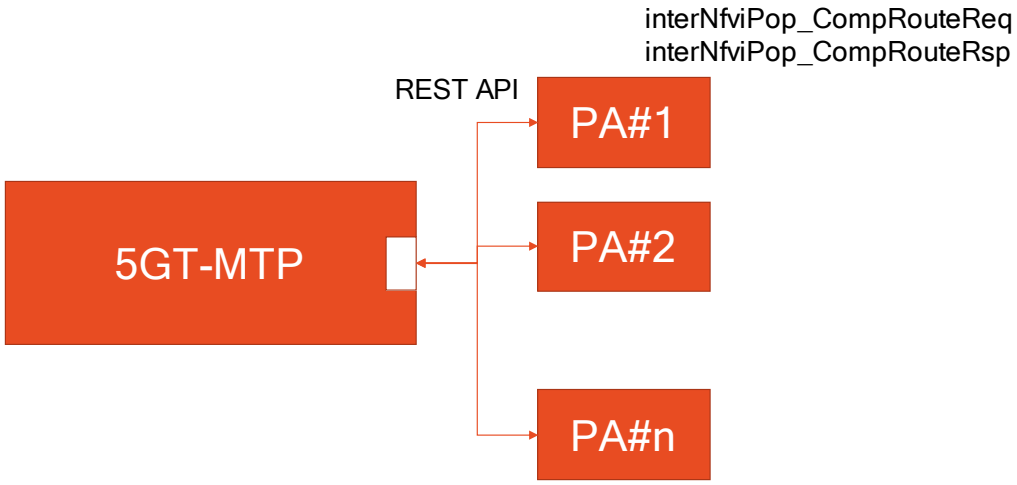


FIGURE 67: INTERWORKING BETWEEN THE 5GT-MTP AND THE PAS USING THE DEFINED API

At the time of writing, the defined API is mostly devoted to enable that a networking-oriented PA extends the selection of a LL previously made by the 5GT-SO PA. In other words, the 5GT-SO provides the set of the LLs interconnecting the NFVI-PoPs to accommodate a network service (see Section 5.5.1.1.2). For each the LL, the API allows requesting the PA to select the inter-NFVI-PoP (i.e., WAN) resources satisfying the LL requirements in terms of bandwidth and delay. In this regard, the API has been defined using a REST protocol where the contents are encoded using JSON format.

The 5GT-MTP PA API supports a pair request/response messages where the 5GT-MTP operates as a client and the PA as the server. Those messages are referred to as *interNfviPopCompRouteRequest* and *interNfviPopCompRouteResponse*. The URI of both messages is */compRoute*. For the former message the URI is completed with the

selected *interNfviConnectivityId* which is used by both the 5GT-MTP and the selected PA server to associate a specific compute request to its particular response.

Before detailing the contents of the above API messages, it is worth to rely on an example where it is detailed the view and the operations to allocated inter-NFVI-PoP network resources being made at the 5GT-MTP. Using Figure 68, let's assume that for a network service, the 5GT-SO selects the LL interconnecting both NFVI-PoP#1 and NFVI-PoP#3. Once the 5GT-MTP receives the allocation message (Section 5.5.1.1.2) from the 5GT-SO specifying that LL, the 5GT-MTP should trigger the PA to allocate the resources. The vision of the 5GT-MTP has not only the NFVI-PoP's Gws but also the Provider Edge (PE) nodes attached to those NFVI-PoPs Gws as well as border nodes of all the WANs being managed by the 5GT-MTP. Herein it is considered that internal WAN details are hidden to the 5GT-MTP (for the abstraction purposes) and should be afterwards handled by the specific WIM controller governing every WAN domain. Thus, the minimum topological information used by the 5GT-MTP and usable by the PA includes the connectivity between NFVI-PoPs'Gws and PEs (e.g., Gw#1 and PE#11, Gw·3 and PE#33) along with the links connecting PEs between two different WAN domains (e.g., PE#12 and PE#31 in the example). For those links, specific information about the used identifiers, metric, available bandwidth, delay, etc. are known by the 5GT-MTP.

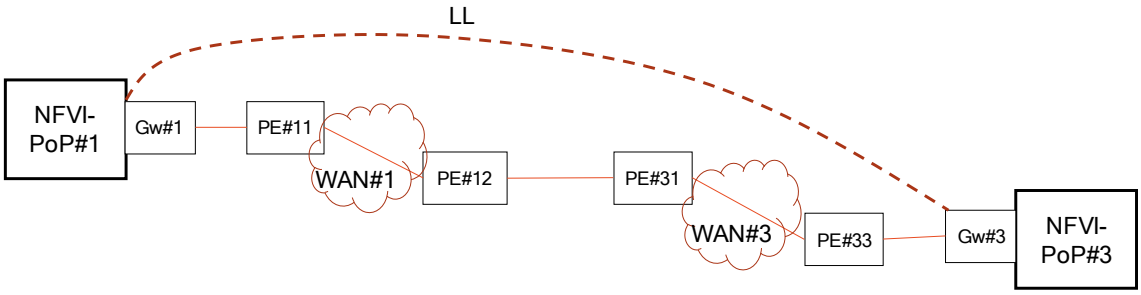


FIGURE 68: 5GT-MTP VIEW PROVIDING INTER-NFVI-POPS CONNECTIVITY

The above considerations about the 5GT-MTP (inter-NFVI-PoP) topology information view have been used to define the 5GT-MTP PA API. The following details the contents of the two messages, that is the request and response operations for computing and selecting the networking resources related to a specific LL. It is worth noting that the API is designed to operate on per LL basis. In other words, for a network service entailing *n* LLs, the PA should be triggered *n* times requiring *n* request/response message exchanges between the 5GT-MTP and the PA.

interNFVIPopCompRouteRequest

The request message is intended to trigger the execution of a particular PA. Basically, it carries relevant information to assist the PA execution, which is summarized in the following set of requirements:

- Specifying the pair of source and destination endpoints, i.e., PEs attached to the associated NFVI-PoP's Gws to the targeted LL (in Figure 68, PE#1 and PE#3)
- Determining the PA identifier. This is used to explicitly indicate a particular PA to be triggered. All potential PAs having their own objective functions are identified by an individual and unique identifier.
- Description of the 5GT-MTP topology details used as input for the PA. The topology information includes the whole 5GT-MTP vision of the all the underlying network infrastructure: i) QoS and identifiers attributes of the connectivity

between WAN domains; ii) abstracted WAN encompassing specific details in terms of nodes and links and their related identifiers and QoS parameters.
- Specifying the QoS constraints that should be guaranteed by the route computation: minimum bandwidth and maximum latency / delay

To deal with the above requirements, the contents of the *interNFVIPopCompRouteRequest* carried into the body a REST POST method are encoded with the following JSON objects:

- **paId**: identifier of the PA to be executed
- **srcPEId**: id. of the source PE attached to ingress NFVI-PoP's Gw of the requested LL
- **dstPEId**: id. of the destination PE attached to egress NFVI-PoP's Gw of the requested LL
- **interWanLinks**: array describing the link connectivity between a pair of PEs bordering two separated WAN domains (e.g., PE#12 - PE#31 link in Figure 67)
- **aWimId**: ingress WIM Id controller of the inter-WAN link
- **zWimId**: egress WIM id controller of the inter-WAN link
- **aPEId**: ingress border PE Id of the inter-WAN link
- **zPEId**: egress border PE Id of the inter-WAN link
- **aLinkId**: link id (32-bit positive integer) attached to aPEId of the inter-WAN link
- **zLinkId**: link id (32-bit positive integer) attached to zPEId of the inter-WAN link
- **networkLinkQoS**: object describing the QoS parameters associated to the inter-WAN link
    - **linkCostValue**: metric associated to the inter-WAN link
    - **linkDelayValue**: delay (in ms) associated to the inter-WAN link
    - **linkAvailBwValue**: available bandwidth (in Mb/s) of the inter-WAN link
- **absWanTopo**: array describing for each WAN element abstracted intra-WAN topology details
- **wimId**: WIM Id controller handling the WAN
- **nodes**: array listing all the nodes forming the abstracted WAN topology
    - **nodeId**; node Identifier
- **edges**: array providing for each abstracted intra-WAN link/edge specific details (i.e., identifiers and QoS parameters). Such edges provide the specific connectivity between pairs of the intra-WAN nodes listed above
    - **aNoded**: ingress node Id of the intra-WAN link
    - **zNodeId**: egress node Id of the intra-WAN link
    - **aLinkId**: link id attached aNodeId of the intra-WAN link
    - **zLinkId**: link id attached to zNodeId of the intra-WAN link
    - **networkLinkQoS**: object describing the QoS parameters associated to the intra-WAN link
    - **linkCostValue**: metric associated to the intra-WAN link
    - **linkDelayValue**: delay (in ms) associated to the intra-WAN link
    - **linkAvailBwValue**: available bandwidth (in Mb/s) of the intra-WAN link
- **networkLayer**: specifies the switching capability supported by the intra-WAN link
- **qosCons**: object used for declaring the QoS constrains that the PA should deal with

- **bandwidthConsValue**: specifies the demanded bandwidth to be allocated
- **delayConsValue**: specifies the maximum tolerated latency to be satisfied

The content of the body forming the *interNFVIPopCompRouteRequest* message are shown in Figure 69 using the SWAGGER REST API editor [33].

```
{
  "paId": 0,
  "srcPEId": "string",
  "dstPEId": "string",
  "interWanLinks": [
    {
      "aWimId": "string",
      "zWimId": "string",
      "aPEId": "string",
      "zPEId": "string",
      "alinkId": 0,
      "zlinkId": 0,
      "netwLinkQoS": {
        "linkCost": "string",
        "linkCostValue": 0,
        "linkDelay": "string",
        "linkDelayValue": 0,
        "linkAvailBw": "string",
        "linkAvailBwValue": 0
      }
    }
  ],
  "absWanTopo": [
    {
      "wimId": "string",
      "nodes": [
        {
          "nodeId": "string"
        }
      ],
      "edges": [
        {
          "aNodeId": "string",
          "zNodeId": "string",
          "alinkId": 0,
          "zlinkId": 0,
          "netwLinkQoS": {
            "linkCost": "string",
            "linkCostValue": 0,
            "linkDelay": "string",
            "linkDelayValue": 0,
            "linkAvailBw": "string",
            "linkAvailBwValue": 0
          },
          "networkLayer": "string"
  "qosCons": {
    "bandwidthCons": "string",
    "bandwidthConsValue": 0,
    "delayCons": "string",
    "delayConsValue": 0
  }
}
```


FIGURE 69: 5GT-TMP PA API: REQUEST MESSAGE BODY FOR REQUESTING A NETWORK COMPUTE ROUTE TO A SPECIFIC PA

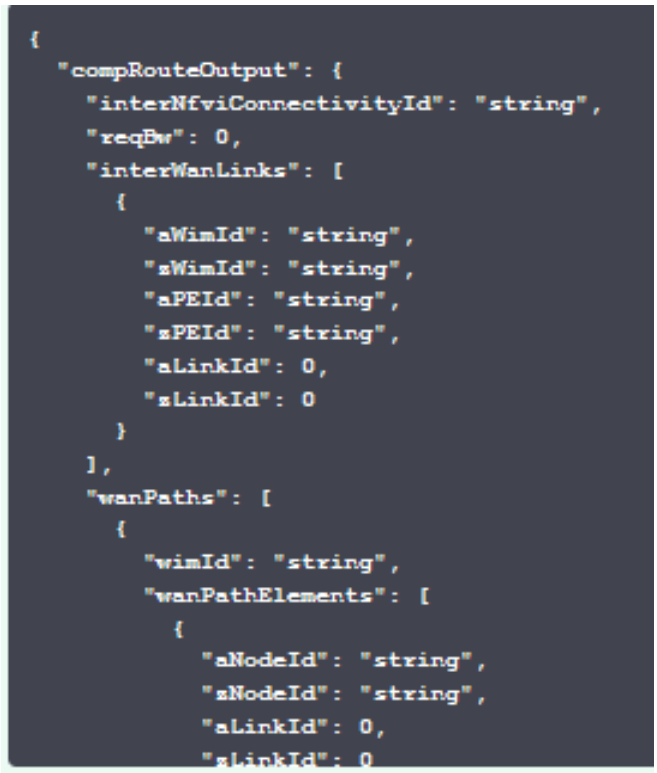
interNFVIPopCompRouteResponse

If the selected PA succeeds on the computing a route between the specified endpoints (i.e., *srcPEId* and *dstPEId*) satisfying the demanded *qosCons*, the PA server sends a REST response message whose body details the explicit path (i.e., nodes and links) to allow the 5GT-MTP then commanding the allocation operations via the related WIM plugins of the underlying network infrastructure. Observe that the output, i.e. computed route, may be divided into: i) intra-WAN paths segments; ii) list of inter-WAN links. Bearing this in mind and for the sake of easing the corresponding processing at the 5GT-MTP, the format used for presenting the computed path is passed on the basis of the above route segmentation. Thus, the following JSON objects are included in the PA response message:

- **compRouteOutput**: main object including the detailed computed route
- **interNfviConnectivityId**: determines the connectivity Id for a LL fir which a route has been computed
- **reqBw**: specifies the bandwidth (i.e., in Mb/s) to be allocated
- **interWanLinks**: array with the set of inter-WAN links to be traversed by the computed route. For each of these links
    - **aWimId**: see above
    - **zWimId**: see above
    - **aPEId**: see above
    - **zPEId**: see above
    - **aLinkId**: see above
    - **zLinkId**: see above

- **wanPaths**: array detailing for each traversed WAN, the explicit route within that WAN
    - **wimId**: see above
    - **wanPathElements**: array with the ordered set of nodes and links to be traversed on a specific WAN (controlled by the WIM Id)
        - **aNodeId**: see above
        - **zNodeId**: see above
        - **aLinkId**: see above
        - **zLinkId**: l

The content of the body forming the *interNFVIPopCompRouteResponse* message are shown in Figure 70 using the SWAGGER REST API editor [33].



```
{
  "compRouteOutput": {
    "interNfviConnectivityId": "string",
    "reqBw": 0,
    "interWanLinks": [
      {
        "aWimId": "string",
        "zWimId": "string",
        "aPEId": "string",
        "zPEId": "string",
        "aLinkId": 0,
        "zLinkId": 0
      }
    ],
    "wanPaths": [
      {
        "wimId": "string",
        "wanPathElements": [
          {
            "aNodeId": "string",
            "zNodeId": "string",
            "aLinkId": 0,
            "zLinkId": 0
```


FIGURE 70: 5GT-MTP PA API: RESPONSE MESSAGE BODY PROVIDING THE COMPUTE PATH WHICH MAY ENCOMPASS MULTIPLE WANS

5.6 5GT-MTP workflow descriptions

In this section, the workflows for the creation and termination of the logical link and VNF will be presented. The instantiation and termination of MEC and Radio resources, instead is still under discussion and will be described in future deliverable (D5.5).

5.6.1 Non-nested network service instantiation

This section presents the 5GT-MTP internal workflow for instantiating an incoming non-nested NFV-NS (network service) received from the 5GT-SO via the NBI. The flow is composed of two steps. The first step is to allocate virtualized network resources on logical links for the connectivity network needed for the NFV-NS as long as two or more remote NFVI-PoPs are involved. The second step is to instantiate the VNFs on each particular NFVI-PoP.

We consider the special case where the NFV-NS is composed a logical link connecting two VNFs located in different VIM domains.

Extensions to different cases are straightforward.

5.6.1.1 Logical link instantiation

Figure 71 shows the 5GT-MTP internal workflow for instantiating a virtual network resource on a logical link. The workflow is triggered by the Logical Link Allocation Request for the NFV-NS's connectivity network from the NFVO in the 5GT-SO to the 5GT-MTP-NFVO-RO SLPOC also referred to as the Network Functions Virtualization Orchestrator – Resource Orchestrator (NFVO-RO). The subsequent operations of the 5GT-MTP are listed below.

1. NFVO (at 5GT-SO) sends a request to the 5GT-MTP-NFVO-RO SLPOC to allocate network resources on a logical link using the POST method to the resource named */abstract-network-resources* within WIMNetworkResources tag of the 5GT-SO SBI (5GT-MTP NBI). The request parameters include the identifier of the logical link (LogicalLinkID), the identifier of the NFV-NS (ServiceID) and the remaining network request parameters referred to as NetServParam (e.g., bandwidth and maximum latency). Starting from logical link (LogicalLinkID) selected by the 5GT-SO, the RO module of the 5GT-MTP orchestrates the connectivity across its controlled domains, i.e., transport WIMs, VIMs and radio WIMs. The orchestration follows the basic rule described in ETSI IFA022 [29]. First the connectivity inside the WIM is created and then it is stitched with the intra-VIM and RAN connectivity.
2. 5GT-MTP-NFVO-RO SLPOC via SBI requests from the correct transport WIM plugin to instantiate the network connectivity inside the WAN using the method POST to the resource named */network-resources* within WIMNetworkResources tag of the 5GT-MTP SBI.
3. WIM plugin requests from WIM controller the allocation of network resources inside the WAN for the NFV-NS's connectivity network.
4. WIM controller instantiates the WAN network connectivity.
5. WIM controller acknowledges completion of network resource allocation to the WIM plugin. The acknowledge message includes the identifier (WanNetworkResourceID) of allocated resource as well as the ingress and egress forwarding rules for the adjacent domains (VIM and radio). In the example the forwarding rules are VPN tags. The RO inside 5GT-MTP uses the forwarding rules to configure the adjacent domains.
6. WIM plugin acknowledges completion of WAN network resource allocation to the 5GT-MTP-NFVO-RO SLPOC.
7. 5GT-MTP-NFVO-RO SLPOC requests from VIM1 plugin the instantiation of intra-VIM network resources for the NFV-NS's connectivity using the method POST to the resource named */network_resources* within virtualisedNetworkResources tag (IFA005 interface) of the 5GT-MTP SBI. The request includes the identifier of the NFV-NS (ServiceID) and ingress forwarding rule provided by the WIM.
8. VIM1 plugin forwards the instantiation request to the VIM1 controller
9. VIM1 controller creates a virtual network (VN) for connecting to the WAN.
10. VIM1 controller acknowledges completion of network resources allocation to the VIM1 plugin. The acknowledge message includes the identifier (Vim1NetworkResourceID) of allocated resource.

11. VIM1 plugin acknowledges completion of intra-VIM network resource allocation to the 5GT-MTP-NFVO-RO SLPOC.
12. 5GT-MTP-NFVO-RO SLPOC requests from VIM2 plugin the instantiation of intra-VIM network resources for the NFV-NS's connectivity using the method POST to the resource named */network_resources* within virtualisedNetworkResources tag (IFA005 interface) of the 5GT-MTP SBI. The request carries the identifier of the NFV-NS (ServiceID) and egress forwarding rule provided by the WIM for connecting to the WAN.
13. VIM2 plugin forwards the instantiation request to VIM2 controller.
14. VIM2 Controller creates the virtual network (VN) for connecting to the WAN.
15. VIM2 controller acknowledges completion of network resource allocation to the VIM2 plugin. The acknowledge message includes the identifier (Vim2NetworkResourceID) of allocated resource.
16. VIM2 plugin acknowledges completion of network resource allocation to the radio plugin.
17. 5GT-MTP-NFVO-RO SLPOC returns result of NFV-NS's connectivity network allocation back to NFVO. The acknowledge message includes the identifier (InterNfviPoPConnectivityID) of allocated network resources.

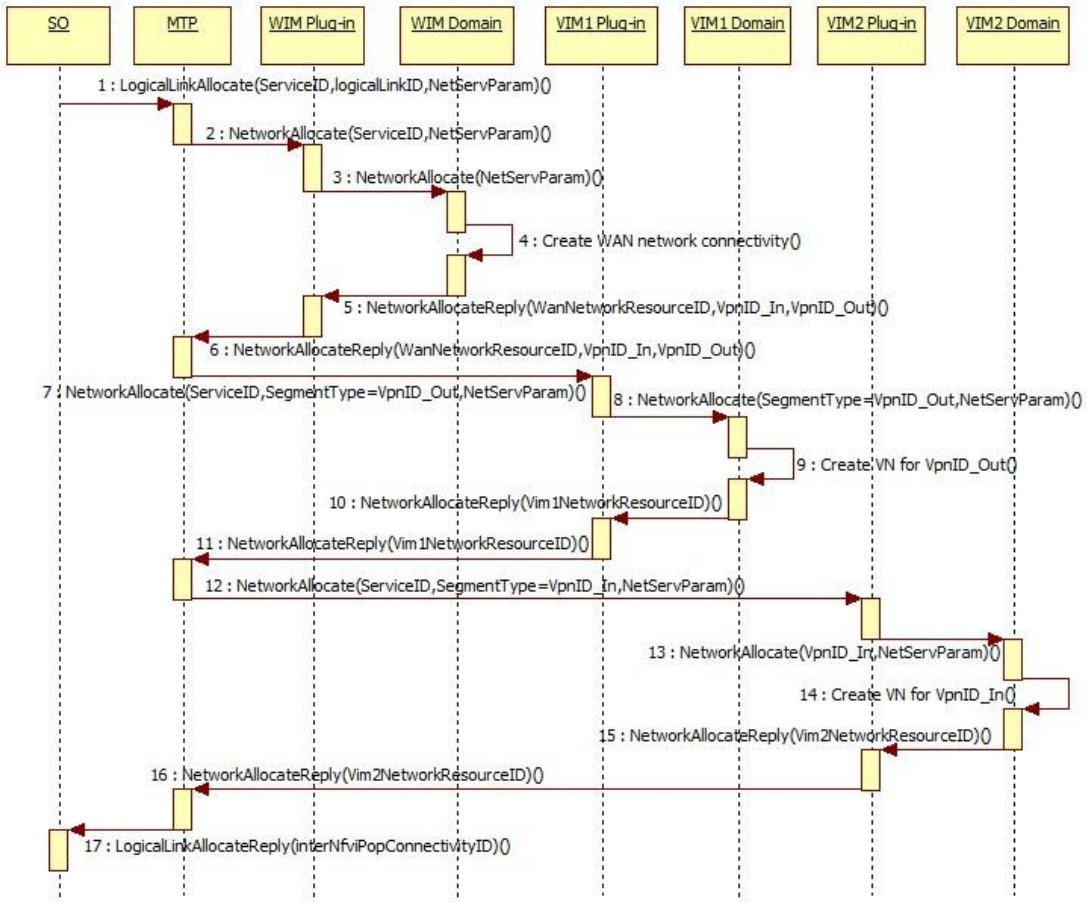


FIGURE 71: LOGICAL LINK INSTANTIATION

5.6.1.2 VNF instantiation

Figure 71 presents the 5GT-MTP workflow for instantiating a VNF. The VNF instantiation workflow is triggered by the Compute Allocation Request for a new VNF instance from the NFVO to the 5GT-MTP- NFVO-RO SLPOC. The subsequent operations of the 5GT-MTP are listed below.

1. NFVO sends a request to the 5GT-MTP- NFVO-RO SLPOC for allocation of a VNF within an NFVI-PoP using the POST method to the resource named */abstract-compute-resources* within abstractResources tag of the 5GT-SO SBI (5GT-MTP NBI). The request parameters include identifier of the NFV-NS (ServiceID), the identifier (AbstractNfviPopId) of abstract NFVI-PoP where to put the VNF and remaining compute service request parameters referred to as ComputeServParam. If VNF is a MEC application the request contains specific MEC service parameters referred to as MecServiceParam. 5GT-MTP uses the ServiceID to associate compute and network request operation to the same service. Indeed, the ServiceID is sent to VIM plugin and it allows the plugin to associate the VNF with the VN created during logical link instantiation.
2. 5GT-MTP- NFVO-RO SLPOC via 5GT-MTP SBI requests from the VIM plugin to instantiate the VNF using the method POST to the resource named */compute_resources* within virtualisedComputeResources tag of the 5GT-MTP SBI.
3. VIM plugin forwards the instantiation request to the VIM controller.
4. VIM controller creates the VM and attaches it to the VN.
5. VIM controller acknowledges the completion of resource allocation back to VIM plugin. The acknowledge message includes the identifier (ComputeResourceID) of allocated resource.
6. VIM plugin acknowledges the completion of resource allocation back to 5GT-MTP- NFVO-RO SLPOC.
7. If VNF is a MEC application, 5GT-MTP- NFVO-RO SLPOC via 5GT-MTP SBI requests from the MEC plugin to create the needed MEC service rules.
8. MEC plugin forwards the request to the VIM controller.
9. VIM controller applies traffic redirection rules, activates the MEC application and provides the required MEC services.
10. VIM controller acknowledges completion of request to the MEC plugin. The acknowledge message includes the identifier (RequestID) of the MEC service request.
11. MEC plugin acknowledges completion of request to 5GT-MTP- NFVO-RO SLPOC.
12. 5GT-MTP-NFVO-RO SLPOC returns result of VNF allocation request back to NFVO. The acknowledge message includes the identifier (ComputeResourceID) of allocated compute resource.

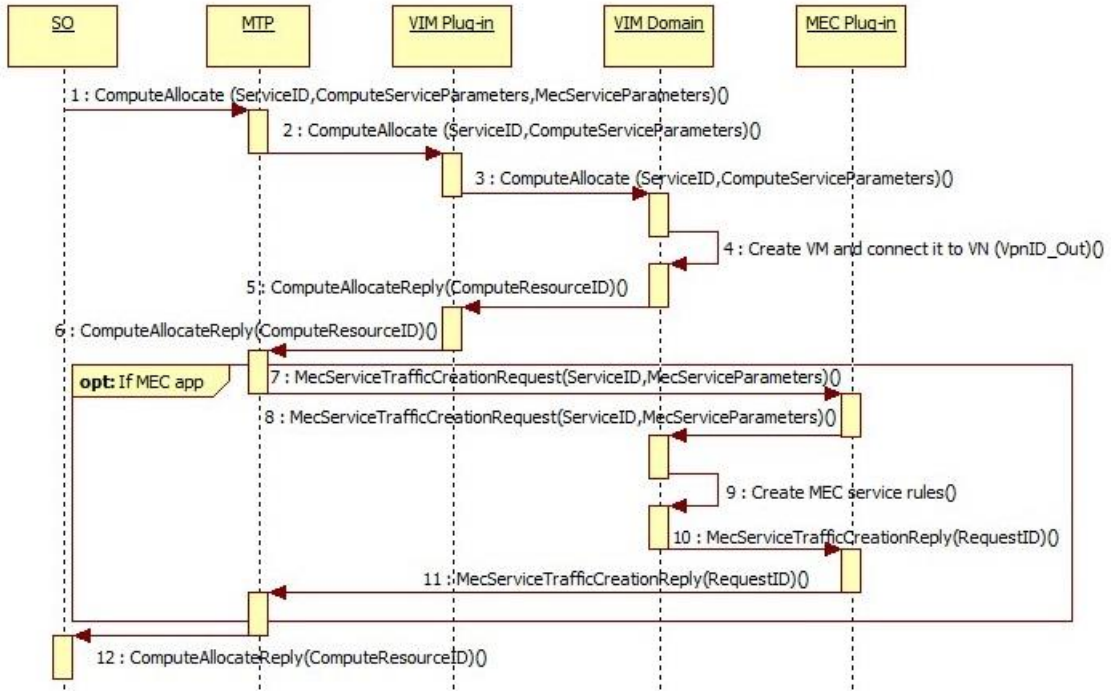


FIGURE 72: VNF INSTANTIATION

5.6.2 Non-nested network service termination

This section presents the 5GT-MTP workflow for terminating a non-nested network service. This flow is composed of two steps. The first step is to terminate the VNFs of the NFV-NS. The second step is to delete the network resources allocated on logical links for the connectivity network of the NFV-NS.

Similarly, to the non-nested network service instantiation workflow, we consider the special case where the NFV-NS is composed by a logical link connecting two VNFs located in different VIM domains.

Extensions to different cases are straightforward.

5.6.2.1 VNF Termination

Figure 73 presents the 5GT-MTP workflow for terminating a VNF. The termination workflow is triggered by the Compute Termination Request for a VNF from the NFVO to the 5GT-MTP-NFVO-RO SLPOC. The subsequent operations of the 5GT-MTP are listed below.

1. NFVO sends a request to 5GT-MTP- NFVO-RO SLPOC for deletion of a VNF instance using the DELETE method to the resource named */abstract-compute-resources* within abstractResources tag of the 5GT-SO SBI (5GT-MTP NBI). The request includes the identifiers (ComputeResourceID) of the VNF to be terminated.
2. 5GT-MTP-NFVO-RO SLPOC forwards the resource termination request to the appropriate VIM plugin.
3. VIM plugin forwards the resource termination request to the VIM controller.
4. VIM controller deletes the VM of the VNF instance.
5. VIM controller acknowledges the completion of resource release back to VIM plugin. The acknowledge message includes the identifier (ComputeResourceID) of released resource.

6. VIM/WIM acknowledges the completion of resource release back to 5GT-MTP-NFVO-RO SLPOC.
7. If the VNF is a MEC application, 5GT-MTP- NFVO-RO SLPOC via 5GT-MTP SBI requests from the MEC plugin to delete the traffic redirection rules and MEC services of the VNF. The request includes the identifier (RequestID) of the MEC service request to be terminated.
8. MEC plugin forwards the request to the VIM controller.
9. VIM controller deletes traffic redirection rules and MEC services of the VNF.
10. VIM controller acknowledges completion of request to the MEC plugin.
11. MEC plugin acknowledges completion of request to 5GT-MTP-NFVO-RO SLPOC.
12. 5GT-MTP-NFVO-RO SLPOC acknowledges the completion of resources release back to NFVO. The acknowledge message includes the identifiers (ComputeResourceID) of released resource.

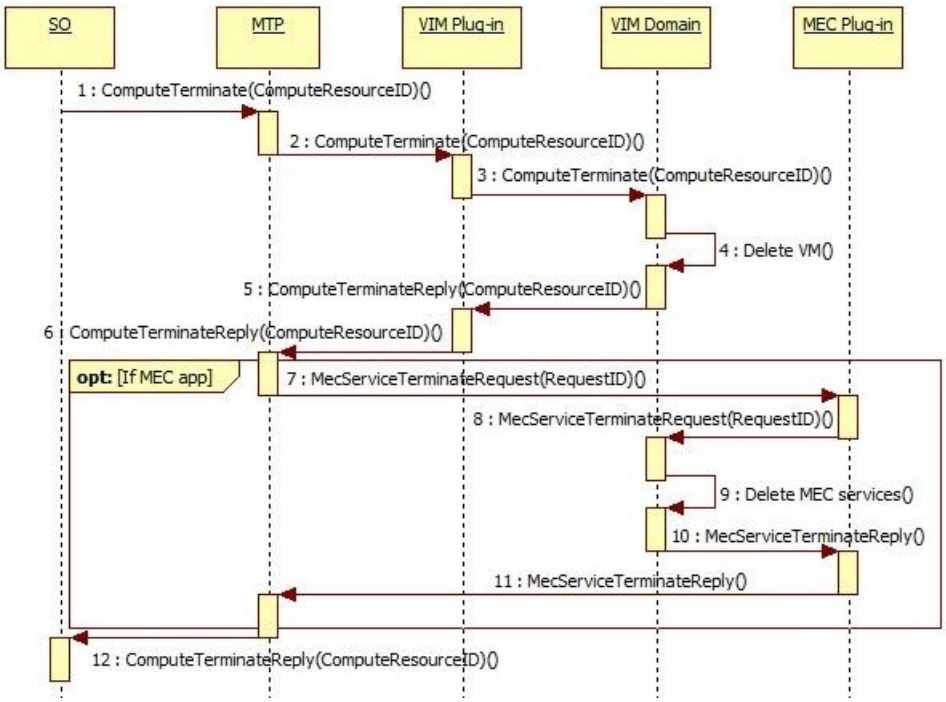


FIGURE 73: VNF TERMINATION WORKFLOW

5.6.2.2 Logical link termination

Figure 74 shows the 5GT-MTP internal workflow for terminating a virtual network resource on a logical link. The workflow is triggered by the Logical Link Termination Request from the NFVO in the 5GT-SO to the 5GT-MTP-NFVO-RO SLPOC. The subsequent operations of the 5GT-MTP are listed below.

1. NFVO sends a request to the 5GT-MTP-NFVO-RO SLPOC to terminate network resources on a logical link using the DELETE method to the resource named /abstract-network-resources within abstractResources tag of the 5GT-SO SBI (5GT-MTP NBI). The request parameters include the identifier of the virtualized network resource (InterNfviPopConnectivityID) to terminate. Starting from the knowledge of InterNfviPopConnectivityID, the RO module of MTP retrieves the information about the virtualised network resources of its own managed domains that need to be terminated.

2. 5GT-MTP-NFVO-RO SLPOC requests from VIM2 plugin the termination of the virtual network (VN) used by the NFV-NS's network connectivity. The request includes the identifier (VIM2NetworkResourceID) of the virtualised network resource to terminate.
3. VIM2 plugin forwards the resource termination request to VIM2 controller.
4. VIM2 controller deletes radio network resource of NFV-NS's connectivity network.
5. VIM2 controller acknowledges completion of release request to VIM2 plugin.
6. VIM2 plugin acknowledges completion of release request to the 5GT-MTP-NFVO-RO SLPOC.
7. 5GT-MTP-NFVO-RO SLPOC requests from VIM1 plugin the termination of the intra-VIM network resource of the NFV-NS's network connectivity. The request includes the identifier (Vim1NetworkResourceID) of the virtualised network resource to terminate.
8. VIM1 plugin forwards the resource termination request to the VIM1 controller.
9. VIM1 controller deletes intra-VIM virtualised network resource of NFV-NS's connectivity network.
10. VIM1 controller acknowledges completion of release request to the VIM1 plugin
11. VIM1 plugin acknowledges completion of release request to the 5GT-MTP-NFVO-RO SLPOC.
12. 5GT-MTP-NFVO-RO SLPOC requests from WIM plugin the termination of the WAN virtualized network resource of the NFV-NS's network connectivity. The request includes the identifier (WanNetworkResourceID) of the virtualised network resource to terminate.
13. WIM plugin forwards the resource termination request to the WIM controller
14. WIM controller deletes the WAN virtualised network resource of NFV-NS's connectivity network.
15. WIM controller acknowledges completion of release request to the WIM plugin.
16. WIM plugin acknowledges completion of release request to the 5GT-MTP-NFVO-RO SLPOC.
17. 5GT-MTP-NFVO-RO SLPOC acknowledges the completion of resource release back to NFVO.

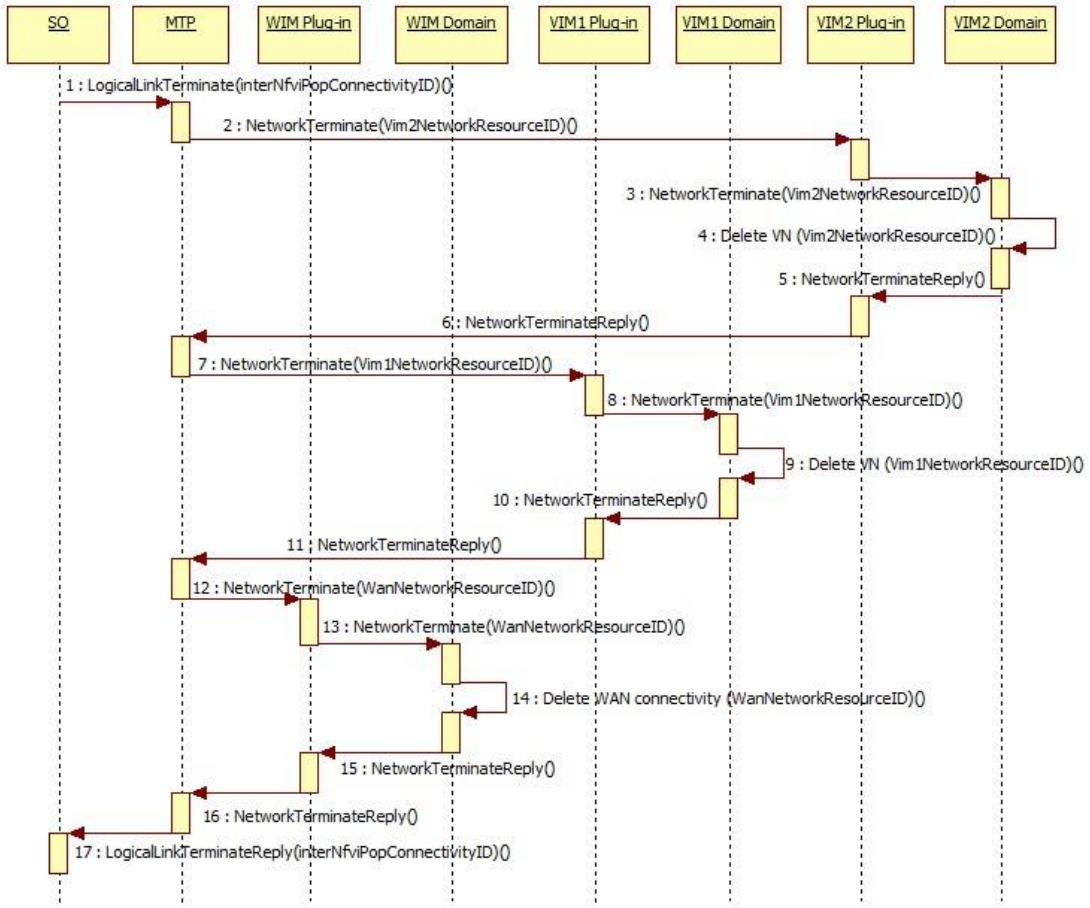


FIGURE 74: LOGICAL LINK TERMINATION WORKFLOW