Project: H2020-ICT-2014-2 5G NORMA

Project Name:

5G Novel Radio Multiservice adaptive network Architecture (5G NORMA)

Deliverable D5.2
Definition and specification of connectivity and QoE/QoS management mechanisms
Final Report

Date of delivery:	30/06/2017	Version:	1
Start date of Project:	01/07/2015	Duration:	30 months

Document Properties

Document Number:	H2020-ICT-2014-2 5G NORMA/D5.2
Document Title:	Definition and specification of connectivity and QoE/QoS management mechanisms Final Report
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Editor(s):	Marco Gramaglia, Albert Banchs (UC3M)
Contractual Date of Delivery:	30/06/2017
Dissemination level:	PU[1]
Status:	Final
Version:	1.0
File Name:	5G NORMA D5.2_v1.0.docx

Revision History

Revision	**Date**	**Issued by**	**Description**
1.0	30.06.17	5G NORMA WP5	Final version

Abstract

This document summarizes the WP5 work throughout the project, describing its functional architecture and the solutions that implement the WP5 concepts on network control and orchestration. For this purpose, we defined 3 innovative controllers that embody the network slicing and multi tenancy: SDM-C, SDM-X and SDM-O. The functionalities of each block are detailed with the interfaces connecting them and validated through exemplary network processes, highlighting thus 5G NORMA innovations. All the proposed modules are designed to implement the functionality needed to provide the challenging KPIs required by future 5G networks while keeping the largest possible compatibility with the state of the art.

Keywords

Service aware QoE/QoS control; Software-Defined Mobile Network Controller, Orchestrator, and Coordinator; SDM-C applications and interfaces; Controller's hierarchy; Mobility management; Mobility scheme design; Network slice resources management; QoE aware orchestration; VNF placement; VNF mobility

[1] CO = Confidential, only members of the consortium (including the Commission Services)
PU = Public

Executive Summary

As the expectations on what 5G Networks can finally provide to their users grow, the need for novel and flexible architectures also increases its importance. For this reason, the findings of 5G NORMA are going to have a big impact on the ongoing and future standardization activities. One of the main goal of the project was to introduce novel paradigms into the network architecture. Concepts such as Network Slicing, Multi Tenancy and Network Programmability have been fruitfully integrated into the 5G NORMA proposed architecture and, as a fundamental part of the final architecture design, also been included within theWP5 functional architecture.

As a matter of fact, the WP5 functional architecture, which has been then fully integrated within the overall WP3 architecture, takes advantage of the state of the art technologies in Network Softwarization to include the concept of network slicing as a key element. 5G NORMA hence leads the transition from the network of entities architecture to a ***network of functions-based architecture*** that leverage the recent advances in Software-Defined Networking (SDN) and Network Function Virtualization (NFV). Therefore, the main contribution of this deliverable is to summarize the work performed by 5G NORMA towards a fully specified and completely defined mobile network architecture. More specifically, WP5 focuses its effort on three main aspects: Service Aware QoE/QoS Control, Network Wide Orchestration and Enhanced Mobility Management mechanisms.

As stated above, embodying the network slicing concept into the WP5 architecture has been the largest common research effort performed by the people active in the Work Package. Therefore, all the elements that compose the WP5 architecture have a prominent and distinctive part for both Inter and Intra Network Slice operations. Being two intertwined but very heterogeneous problems (Inter Slice operation is mostly about coordination across slices, while Intra Slice operation must focus mostly on achieving the required KPIs associated to a Network Slice) each of the designed elements of the architecture has specific procedures and interfaces that deal with problems related to the control and management of VNFs belonging either to one or multiple network slices. The architectural work resulted in the definition of three enhanced controllers: the Software Defined Mobile Network Orchestrator (SDM-O), Software Defined Mobile Network Controller (SDM-C) and Software Defined Mobile Network Coordinator (SDM-X).

This document hence represents a complement to the previous deliverable D5.1, i.e., it describes the final specification of the WP5 architecture and several solutions that run on top of it. As already done for the previous version of the WP5 deliverable, we simplify the reading of this document by dividing it into two distinct parts: (i) the definition of the global architecture, and (ii) the design of the underlying algorithms and protocols.

Part I focuses on the ***architectural aspects*** of the Work Package. This includes the definition of the role of the modules, the interfaces and their final specifications. As mentioned before, specific emphasis is put on the intra and inter network slicing aspect of the different elements. More specifically, the MANO architecture, the QoE/QoS control framework, and the Shared resources control are defined in this part. Most notably, all of them provide advances to the current state of the art, while keeping almost full backward compatibility. Throughout this part, we describe the consistency of the presented functions with the overall 5G NORMA architecture and detail the definition of the interfaces among the elements. Also, we detail some operational aspects of the defined elements, describing how different common procedures can be fulfilled by using the 5G NORMA architecture and how its novel elements can be deployed or configured. Further details on the design of the various functions is available in internal documents and external publications.

The WP5 functional architecture and its use in the framework of Service Aware 5G Networks has been described in four publications that have been jointly written by all the WP partners as well as several dissemination activities like summer schools or panels at international conferences.

Part II of the deliverable puts into the spotlight the description of several mechanisms, protocols, and evaluation frameworks that take advantage of the defined functional architecture to provide specific enhancements. This includes both the definition of new algorithms that provide the functionality needed by the defined elements and their possible application to new challenging scenarios.

It is worth highlighting that most of the technical innovations presented in this document have either been published in top scientific venues, have been protected by a patent or have been pushed into standards such the ETSI, ONF or IETF.

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List of Acronyms and Abbreviations

3GPP	3rd Generation Partnership Project
AAA	Authentication Authorization Accounting
ABS	Almost Blank Subframe
ACI	Adjacent Channel Interference
AN	Access Network
ASIC	Application-Specific Integrated Circuit
BBU	Base Band Unit
BSS	Business Support System
CIO	Cell Individual Offset
CN	Core Network
CoA	Care of Address
CoMP	Coordinated Multipoint
CP	Control Plane
DMM	Distributed Mobility Management
DPDK	Data Plane Development Kit
DSAM	Dynamic Service Adaptation Model
DSP	Digital Signal Processing
eICIC	Enhanced Inter Cell Interference Coordination
EM	Element Manager
eMBB	Enhanced Mobile BroadBand
eNB	eNode B
ETSI	European Telecommunications Standards Institute
GTP	GPRS Tunnelling Protocol
HA	Home Agent
HARQ	Hybrid ARQ
HIP	Host Identity Protocol
HO	Handover
IN	Intelligent Network
InP	Infrastructure Provider
IS-RB	Inter Slice Resource Broker
JT	Joint Transmission
KPI	Key Performance Indicator
KVM	Kernel Based Virtual Machine
LMA	Local Mobility Agents
LTE	Long Term Evolution
MAC	Medium Access Control
MAG	Mobile Access Gateway
MANO	Management and Orchestration
MM	Mobility Management
MME	MM Entity

mMTC	Massive Machine Type Communication
MSP	Managed Service Provider
MPLS	Multiprotocol Label Switching
NAT	Network Address Translation
NF	Network Function
NFC	Network Function Chain
NFV	Network Function Virtualization
NFVI	Network Function Virtual Infratructure
NFVI-PoP	NFVI Point of Presence
NFVM	Network Function Virtualization Manager
NFVO	NFV Orchestrator
NSH	Network Service Header
NVGRE	Network Virtualization using GRE
ONF	Open Networking Foundation
OSS	Operation Support System
OTT	Over The Top
OVS	Open Virtual Switch
PDCP	Packet Data Convergence Protocol
PGW	Packet Gateway
PNF	Physical Network
PRB	Physical Resource Block
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Acecss Network
RAP	Radio Access Point
RCI	Resource Control Interface
RRC	Radio Resource Control
RRH	Remote Radio Header
RRM	Radio Resource Management
SDM-C	Software Defined Mobile Network Controller
SDM-O	Software Defined Mobile Network Orchestrator
SDM-X	Software Defined Mobile Network Coordinator
SDN	Software Defined Network
SFC	Service Function Chain
SFP	Service Function Path
SGW	Serving Gateway
SLA	Service Level Agreement
SON	Self Organizing Network
ToR	Top Of Rack
UHR	Ultra High Reliability
ULL	Ultra Low Latency
UP	User Plane
V2X	Vehicle to Everything
vEPCs	Virtual Evolved Packet Core

VIM	Virtual Infrastructure Manager
VM	Virtual Machine
vMNOs	Virtual Mobile Network Operator
VNF	Virtual Network Function
VNFFG	VNF Forwarding Graph
VNFM	Virtual Network Function Manager
VXLAN	Virtual Extensible LAN
WAN	Wide Area Network

Foreword

This document collects the final outcomes of WP5, describing its relationship with other Work Packages of 5G NORMA. It is the final step of WP5 work and it describe the input to the final iteration on the final architecture design phase. Also, it serves as source of knowledge for the WP6 demonstrators. This document complements and integrates D5.1, being both the full description of the WP5 work.

As already done for D5.1, this document is structured in two parts. These two parts have been written as almost independent documents on purpose, to reflect that this deliverable puts together two distinct documents into one:

- **Part I** describes the *overall architectural view* of WP5. That is, how to fulfill the identified KPIs (as defined by WP2) by designing a novel network architecture that incorporates the most promising network paradigms (such as Network Slicing, Multi Tenancy and Network Softwarization) into a modular architecture. This part also addresses the mapping of the WP5 modules into the overall 5G NORMA architecture and validates it by detailing four exemplary network processes that show how those novel concepts are going to be used by network operators to provide standard and novel functionality. This part extends and complements D5.1 Part I, avoiding the review on the requirements and the state of the art to focus just on the outcomes.
- **Part II** builds on top of Part I findings to *describe individual technology solutions* that solve specific problems, leveraging on the innovative functional architecture defined by WP5. In this part, novel algorithms, protocols, architecture o evaluation frameworks are described in detail. We put special attention to highlight how the WP5 key elements (such as the controllers or the MANO framework) play a fundamental role in the achievement of the described solutions. We also remark that most of these solutions have already been patented, pushed into standard proposals or published in scientific conferences or journals.

The two parts as a whole (including the content already provided in D5.1 that is duly referenced throughout the document, where relevant) describe hence the key innovations of 5G NORMA in the field of flexible connectivity and QoE/QoS management. Among those, we especially remark:

- The controller based architecture proposed by 5G NORMA is a pioneering effort in this area. The defined elements (SDM-C, -X, -O) have been designed to both provide novel functionality (e.g., extensive Network Function control through SDM-C, resource sharing through SDM-X) and to go one step further towards the definition of what other concepts such as network slicing or multi tenancy should be implemented in future 5G Networks. We also designed our solutions to be compatible with the current state of the art solutions, to maximize their possible impact. We also detail the main differences, when relevant.
- The specific innovations introduced by 5G NORMA WP5 are valuable pieces of work from two viewpoints: *i*) the research topic addressed within the work package are novel *per-se*, due to their bleeding edge nature, as they are part of the future 5G Network Architecture design, and *ii*) they solve compelling problems in the field of wireless and mobile networks, outperforming state of the art solutions where a comparison is possible.

The reader is referred to the Introduction section of the two parts for a complete list of the various novel contributions.

PART 1: ARCHITECTURE

1 Introduction

As explained in the Foreword, Part I of this document focuses on the description of the WP5 architecture, which complements the content of D5.1 by describing the final specification of the architecture.

1.1 Objectives

The current trends in mobile networking show a growing need for flexibility. Driven by the new business paradigms such as "5G Verticals", the future 5G network should support very heterogeneous services on the same infrastructure. Services such as Internet of Things (IoT) and Vehicular Networking require from the mobile network very different KPIs: low latency, high capacity or service continuity.

Supporting all these requirements on the same infrastructure entails a revolutionizing re-engineering of the network architecture that goes beyond the extensions of the current 3GPP-LTE one. One of the most promising approaches to such re-engineering of the network is Network Slicing [NS]. A traditional way to achieve a highly-customized network is to deploy physical infrastructure for each service (or even one for each business). This approach clearly cannot be applied in a cost-effective way and calls for technical solutions that allow for both efficient resource sharing and multi-tenant infrastructure utilization.

Network slicing has the capability of enabling (through the network architecture) future 5G networks that encompass the required scalability and flexibility characteristics, thus supporting diverse service scenarios and services. A network slice can be broadly defined as an end-to-end logically isolated network that includes 5G devices as well as access, transport, and core network functions. In the general case, these system functions can be also shared between different slices based on pre-defined policies and business criteria. The above requires abstraction of different physical infrastructures into a logical virtual network, in which virtual network functions (created by the decomposition of physical equipment into multiple, isolated instances) are operated. More specifically, we next identify the main elements that must be provided by a mobile network architecture to support the network slicing paradigm:

- a **network slicing aware orchestration framework**, that performs both service and resource orchestration by also considering the (possibly conflicting) requirements introduced by different network slices,
- a **flexible network function control system**, that goes beyond the current definition of Element Management System (EMS) and Software-Defined Network (SDN) controller, offering thus a programmable unique control point for all the network functions belonging to a slice,
- a consistent **QoS/QoE management framework** that acts as trigger for network re-orchestration events and,
- an **enhanced mobility management algorithms** that can take optimal decision for UE (User Equipment) mobility on a per-slice base.

The requirements and the research challenges related to the introduction of these elements were already analyzed and discussed in D5.1. This document focuses on how the network slicing paradigm as one of the fundamental building blocks of future 5G networks as currently being targeted by the 5G NORMA project.

1.2 Structure of Part I

This part of the document describes the outcome of the Work Package 5 (WP5) architecture, which is composed by the following elements: Network Wide Orchestration, the service-aware QoE/QoS Control and the flexible service-tailored mobility management. Still, to further emphasize the overreaching role of Network slicing in our architecture, we describe the architecture by detailing each defined module in according to its relationship with the Network Slicing concept. More in details Part I of this document follows this outline.

We first describe the building blocks of the WP5 architecture in Section 2.1, how they relate with the current technology trends in network softwarization (that were thoroughly reviewed in [D5.1]) and how they can be used to provide the enhanced functionality that new requirements such as Network Slicing, Multi Tenancy and Network Programmability deem. Here we first introduce our enhanced controllers SDM-C, SDM-X and SDM-O.

Then we discuss about the two main extents of the WP5 architecture in Section 2.1.1 and 2.1.2: the inter- and intra-network slice management and control. By means of specific example we explain how the 5G NORMA approach is useful to solve problems related to network control and orchestration, handling of shared resources (either physical ones or VNFs), service aware orchestration and multi-tenant management. Specific attention is devoted to one of the main building blocks of the architecture, the QoE/QoS framework. This framework has already been defined in [D5.1], so in this document we focus on its operational aspects. Finally, we discuss about the fitting of the WP5 key elements in the WP3 architecture, detailing how they fit into the overall architectural view in Section 2.1.3.

The main content of Section 2 is the description of the enhanced controllers that we have defined in 5G NORMA: the Software Defined Mobile Network Orchestrator (SDM-O), Software Defined Mobile Network Controller (SDM-C) and Software Defined Mobile Network Coordinator (SDM-X). In this document, we integrate the definitions already provided in [D5.1] with the full specification of the extent of each logical interface, stating e.g., their relationship with the state of the art solutions for network orchestration and controllers such as the ETSI NFV MANO.

In Section 2.3 we describe how a mobile network is managed through four exemplary processes that make use of the defined enhanced controllers to solve both routinary tasks related to the novel requirements of network slicing and network softwarization and activities that directly involve new features introduced by them, such as how to employ SDM-C to control network functions and how the SDM-X can manage shared resources among slices.

Finally, we discuss in Section 3 different aspects related to the real-world implementation of the 5G NORMA WP5 concepts and elements, as a part of the migration path from the current architecture to the future one. How to deploy the WP5 novel controllers, perform VNF movement and monitoring the QoE/QoS parameters within a slice are some of the topics addressed in this section.

1.3 Key contributions of Part I

As explained above, the main contributions of part I are the definition of an architecture composed by three innovative elements (SDM-C, SDM-O and SDM-X), the discussion of how those elements are beneficial from a network operation perspective and how they can be deployed into a real network underlining the alignment with the current trends and technologies in the field of 5G Networks. That is, the besides the individual “vertical” innovations described in Part II, the WP5 functional architecture itself is already having a big impact on the most prominent academic, industrial and standardization fora. We briefly summarize here the achieved impact:

- The main guidelines behind the WP5 architecture, including the key concepts behind the WP5, the main building blocks of the architecture and their interaction, have been published in two subsequent editions of the International Workshop on 5G Architecture which focuses precisely on the design of novel architecture for 5G.
- The key ideas behind the SDM-C concept, including the novelty of the concept and its application to QoS/QoE, have been published in the Cloud Technologies and Energy Efficiency in Mobile Communication Networks workshop which focuses on the design of cloud-based architectures for mobile network.

- The main concept of network sharing through SDM-X have been published in a paper at the CoCoa Workshop held at the European Workshop. The aim of the workshop was on Competitive and Cooperative Approaches for 5G networks
- The overall WP5 orchestration concept has been pushed as an IETF draft in which we propose some use cases that include service chains with access functions. This is a critical aspect behind the flexible function allocation innovative concept of 5G NORMA and the Network orchestration concept of WP5.
- The concept of the enhanced Software Defined Controller embodied by the SDM-C has been integrated into a white paper that is going to be published by the ONF (one of the most relevant bodies in the field) soon.
- Some of the concepts devised within WP5 have been showcased in a Demo shown at the ICC Conference in Paris during May 2017. Indeed, the strong integration of WP5 and WP6 is one of the most important contributions of WP5.

The reader is referred to the introduction of Part II (Section 5) for a list of the most relevant contributions behind WP5.

2 WP5 Functional Architecture

The 5G NORMA WP5 functional architecture, builds on top of enabling technologies such as SDN and NFV to provide novel functionalities required by future 5G Networks. The whole roadmap that has been followed by WP5 is depicted in Figure-2-1.

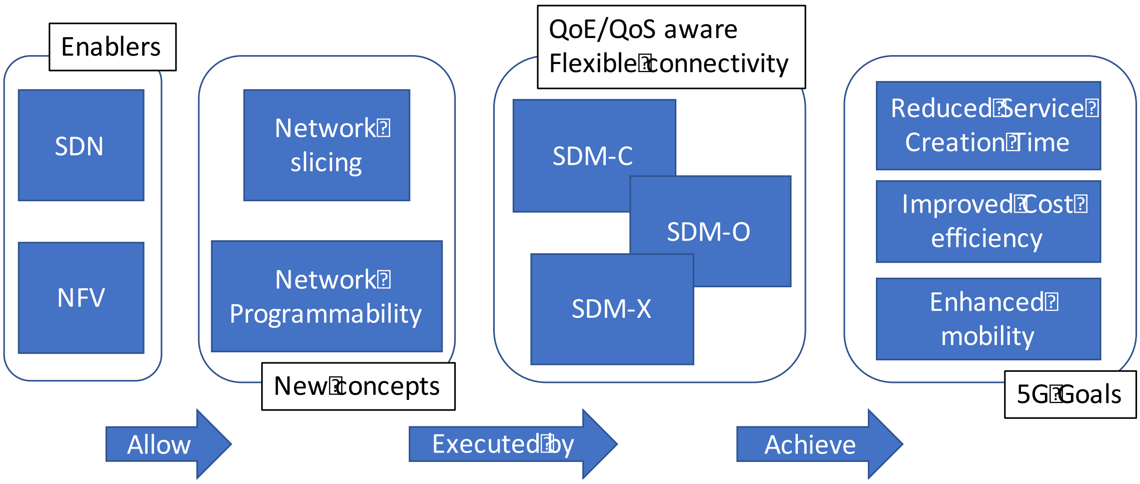

Figure-2-1: Design principles for the WP5 architecture

The cloudified elements of the WP5 functional architecture have to necessarily rely on the state of the art technologies for network softwarization: i.e., SDN and NFV. Those are the needed enablers that can be used to introduce novel concepts of Network Slicing and Network Programmability into the architecture, something that is much more difficult to achieve with the current physical and rather monolithic network architecture. Therefore, within the framework of 5G NORMA WP5 we first devised a functional architecture capable of providing such innovative concepts (see [D3.2] for a more detailed description of the innovative concepts), then we elaborated different technical contributions that leverage on the defined architecture. The concepts of network programmability and network slicing are embodied in the WP5 architecture by means of three enhanced controllers: SDM-C, SDM-X and SDM-O. These entities, described next, are designed to exploit network programmability to provide inter and intra network slice functionalities. Specifically, we develop the concept of SDM-C and SDM-X application that are a fundamental building block for network modularity, one of the emerging trends in future 5G Networks, that are experiencing a transition from a network of entities to a network of functions. That is, by exploiting the extreme versatility of the software defined approach, VNF-based network may be adapted to the changing environments that they will face. As discussed in D3.2 and D2.2, the Network Architecture defined by 5G NORMA should be able to support network slices with very heterogeneous KPIs running on the same infrastructure. Additionally, the architecture should be able to adapt to different stakeholder scenarios in order to be future-proof.

2.1 Architectural Building Blocks

The WP5 architecture covers functions for management, orchestration and control of NFs. Generally, such functions either have a slice-specific scope (“intra-slice”) or a cross-slice scope (“inter-slice”), cf. Figure-2-2.

In the 5G NORMA MANO layer, dedicated NFV MANO functions (NFVO, VNFM, VIM) and slice-/domain-specific application management functions orchestrate the dedicated part of network slices. This “intra-slice domain” comprises slice-specific SDM-C, Mobility Management, QoS control, and other applications as well as the required infrastructure resources. The associated procedures in both MANO and control layer are constrained such that they do not interfere with similar procedures in other network slice instances.

For inter-slice procedures, a shared set of inter-slice functions orchestrates and controls NFs that are common among slice instances. On the MANO layer, the Inter-slice Resource Broker prioritizes the requirements of different slices against each other, e.g., w.r.t. inter-slice resource orchestration as well as configuration of shared functions. According decisions (incl. potentially remaining margins) are communicated to and executed by inter- and intra-slice NFVOs as well as the inter- and intra-slice application management. On the control layer, usually realized as VNFs, inter-slice applications and policies (access and mobility management, QoS control, RRM, etc.) operate on top of the SDM-X northbound interface (NBI) to enforce the desired behaviour of shared (V)NFs.

As depicted in Figure-2-2, the WP5 architecture is compatible with ETSI NFV MANO framework and implements the respective reference points. It extends the framework to multi-domain and multi-tenant 5G NORMA networks introducing two major extensions: (1) the Inter-slice Resource Broker that manages functions and resources across slices according to SLAs. In the ETSI NFV MANO reference architecture, this function would be part of the OSS block. (2) Domain-specific application management functions that apply domain-specific knowledge (e.g., 3GPP or enterprise network domain) and rules to configure, optimize, and trouble-shoot 5G NORMA functions and SDM-C applications via the new *Am-Nf* reference point. In the ETSI NFV MANO architecture, these functions would be mapped partially to the OSS block and partially to the EMS functions. Accordingly, the interfaces between NFVO and Inter-slice Resource Broker as well as between NFVO and domain-specific application management functions would be subsumed by the ETSI NFV MANO reference point *Os-Ma-Nfvo*. Moreover, the *Am-Nf* reference point depicted in Figure-2-2 partially comprises the 5GNORMA-SDMO-SDMC/X reference points explained in Section 2.2.2.

Together with the NFVO, Inter-slice Resource Broker and domain-specific application management realize the 5G NORMA paradigm of application-aware software-defined mobile network orchestration (SDMO). The following subsections further elaborate on inter- and intra-slice functions and procedures within WP5 and the relationship to the overall 5G NORMA architecture.

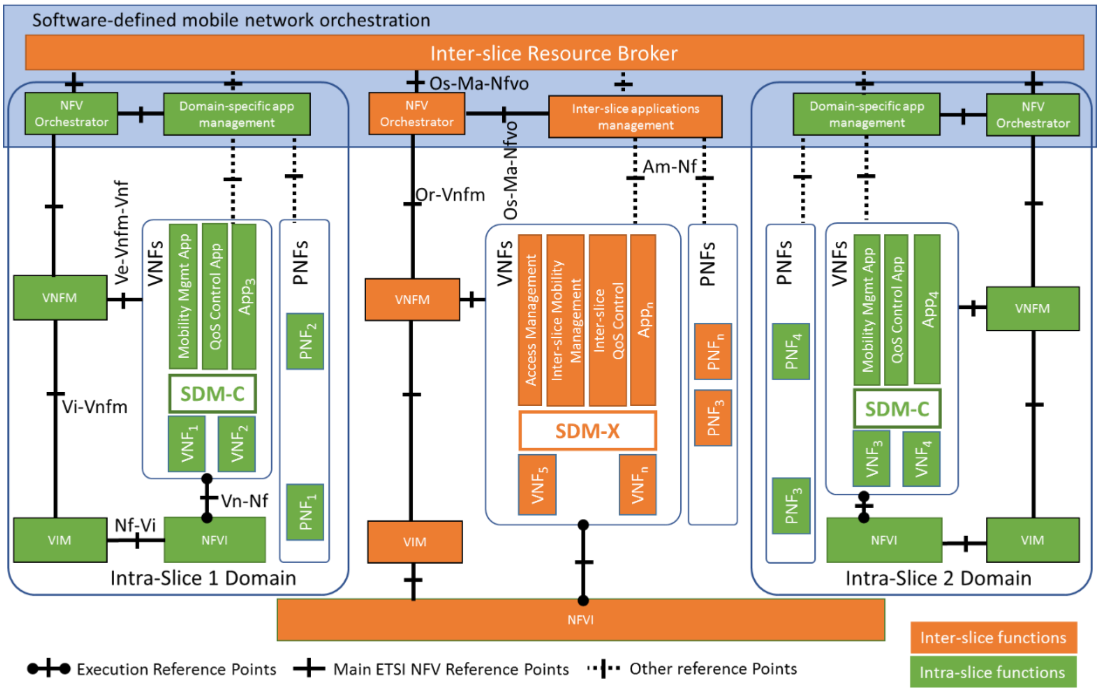

Figure-2-2: Inter- and intra-slice management, orchestration, and control

2.1.1 Inter-slice management and control

The paradigm of software-defined mobile network orchestration (SDM-O) enables the inter-slice management and orchestration, and thus it has a fundamental role in realizing multi-service and multi-tenant aspects of 5G NORMA network. The responsibilities of SDM-O is to map the slice templates representing the slice requirements along with the corresponding tenants' SLAs to the available network resources. The decision upon which network functions can be shared among slices/tenants as well as their placement in the network will be carried out by the software-defined mobile network orchestration. E.g. for a V2X slice with a stringent latency requirements the SDM-O might tend to deploy the network functions closer to the network edge. On the other hand, for eMBB slice with relaxed latency requirements the network functions might be placed in the central cloud.

The SDM-O has a complete (inter-slice) view on different slices and tenants' requirements as well as corresponding resources for slice realization. Moreover, the SDM-O incorporates the domain-specific knowledge, i.e. the logic of network functions that it orchestrates. Having such cross-slice knowledge the SDM-O can efficiently decide on rules/instructions that need to be conveyed to other 5G NORMA MANO entities, control applications and 5G NORMA controllers in order to properly orchestrate, manage and control the network functions and resources of slices.

The network functions and resources can be shared among different network slices and tenants. Such multiplexing improves the network resource utilization and reduces the cost of network service deployment. Inter-slice control of 5G NORMA enables efficient sharing of such resources and network functions. The sharing rules are derived by SDM-O from slice templates and SLAs and implemented on top of inter-slice controller (SDM-X) in the form of applications. Typical SDM-X applications involve RAN functions but, e.g. different Virtual Mobile Network Operators (vMNOs) can have dedicated implementations of virtualized EPCs (vEPCs) but the (S)Gi-LAN functions such as Firewall, Parental Control, DPI, etc. can be common (shared) among all vMNOs. The control of such shared (S)Gi-LAN will be done by SDM-X as depicted in Figure-2-3

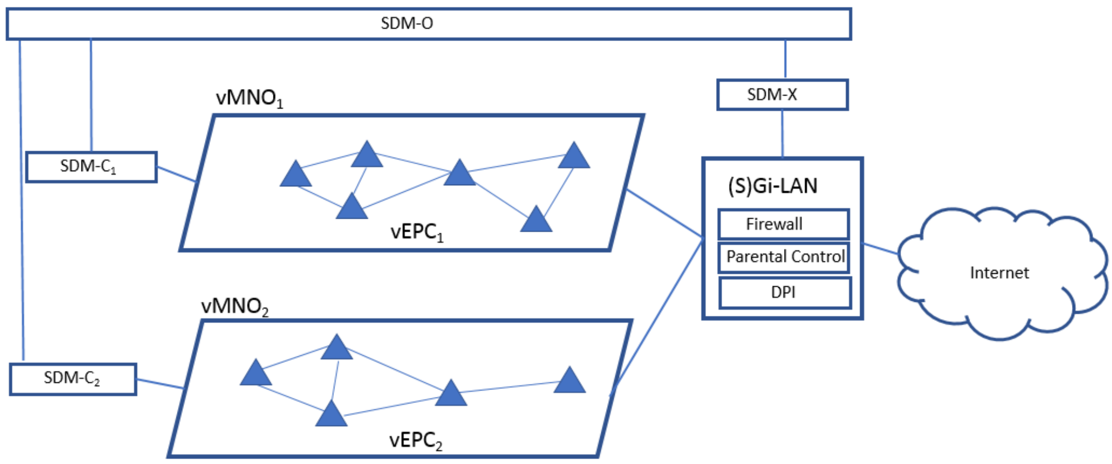

Figure-2-3: An example of shared network functions (Firewall, Parental Control, DPI, etc.) under the control of SDM-X.

2.1.2 Intra-slice management and control

Intra-slice QoE/QoS control is performed using the QoE/QoS control framework already defined in Deliverable D5.1 [D5.1] and reported in [D3.2] and [EuCNC-17], which is depicted in the following Figure-2-4:

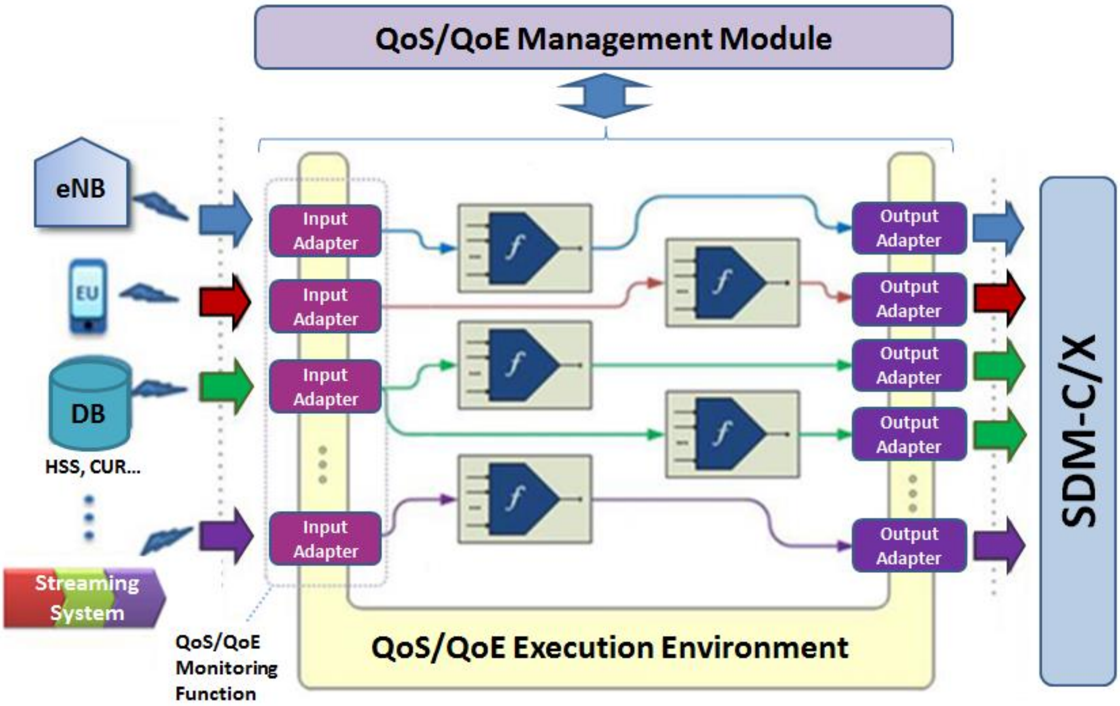

Figure-2-4: 5G NORMA QoE/QoS Framework.

The reader may find more information about this framework in [D5.1]. Instead, in this deliverable, our main interest will be to explain how this framework can be applied to implement the specific QoE/QoS control requirements inside each specific slice, including also the associated management operations. Of course, for doing that, we need to focus also in the interaction with the main 5G NORMA architectural control components (SDM-C and SDM-X) and how the necessary information could be propagated towards the main orchestration block (SDM-O). In this section, we will provide a high-level approach, while in Section 2 (Solutions), more detailed information about possible practical implementations will be provided.

As described in [D5.1], depending on each slice specific requirements, the intra-slice QoE/QoS control could be practically implemented in very different ways, although always according the framework in the previous Figure-2-4. If we watch that figure in detail, we can see the QoE/QoS Monitoring and Control function is split into three different relevant subsystems:

1. What we could call the *QoE/QoS Assessment subsystem*, which is indeed composed by four elements:
   a) The *QoE/QoS Monitoring Function*, composed by the set of all purple blocks in the left side (i.e., the Input Adapter blocks to collect all the relevant data from different elements in the network).
   b) The *QoE/QoS Mapping Functions*, composed by the '*f*' labelled blocks right inside the U-shaped yellow element.
   c) The *Output Adapter blocks*, to transform the output generated by the mapping functions into a semantic model that can be interpreted by the external systems receiving their QoE/QoS signals (mapping functions could be diverse and heterogeneous, so we need a common communication model towards the associated external systems).
   d) The QoE/QoS Execution Environment, where all those elements are deployed and executed. Depending on the required complexity, this execution environment could be local to one single node, or distributed across multiple hosts.

2. The QoE/QoS Management system (the elongated purple rectangle on top). This system should be integrated in the 5G NORMA Management and Orchestration layer (it should be part of the SDM-O), and basically should be used for two different things:

a) To manage and configure all QoE/QoS functional blocks deployed on the QoE/QoS execution environment (i.e., Input/Output Adapters and Mapping Functions deployed into the U-shaped yellow block in the figure).
b) To configure the QoE/QoS related parameters in the SDM-C (or SDM-X) to make it able to properly process the messages coming from the Output Adapter blocks. These parameters should be defined in some way in the SLA for each slice, and should be used to trigger re-orchestration requests from the SDM-C/X towards the SDM-O when necessary (e.g.: if certain Output Adapter produces an output below certain threshold, then change the flavour of certain VNF from *medium* to *large*).

3. The QoE/QoS Control System itself, composed by the 5G NORMA main control blocks, i.e. the SDM-C (for the slice specific resources) and the SDM-X (to control shared resources). In the case that we are considering here, for inter-slice QoE/QoS control, just the SDM-C should be interfaced. As suggested just before in item 2b, with regard to QoE/QoS control, the SDM-C (or X) would behave as a rule-based control system receiving the QoE/QoS relevant parameters defined in the SLA and triggering re-orchestration requests towards the SDM-O when certain rules apply to fulfil the slice-specific QoE/QoS requirements (we understand these re-orchestration requests would be scaling operations mostly); i.e., the QoE/QoS control loop is closed propagating the triggers generated into the Assessment system towards the SDM-C, which in turn request to the SDM-O the necessary re-orchestration actions; after re-orchestrating new resources are allocated, bringing back the system to acceptable levels of QoE/QoS.

The following sequence diagram shows what could be a typical flow to deploy and configure the relevant elements defined in this framework, and also, the basic interactions among the main functional blocks to get the intra-slice QoE/QoS control:

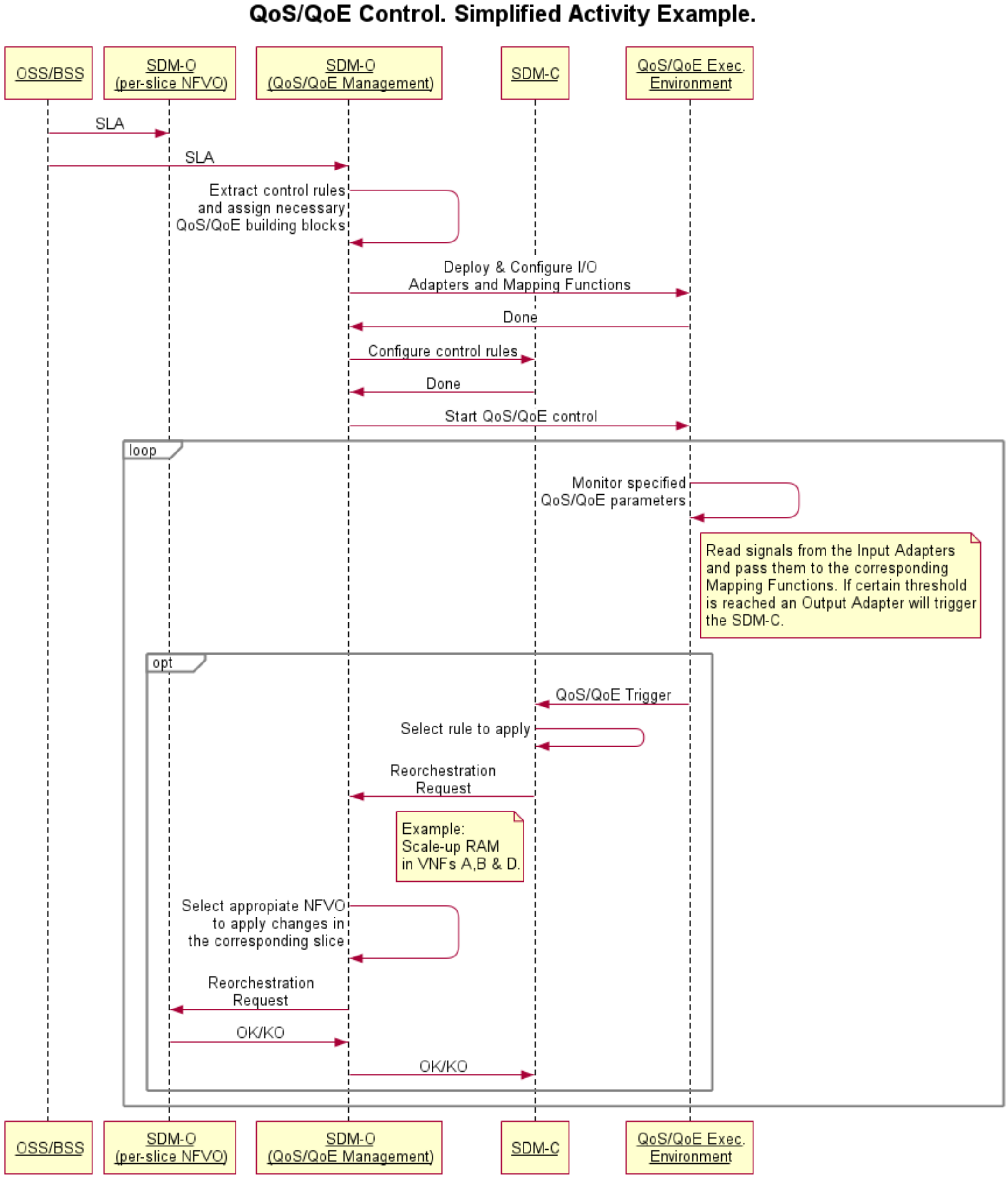

Figure-2-5: QoE/QoS Sequence Diagram.

But besides the functionality of each single block in the QoE/QoS framework, another important point is how to perform the deployment of all these elements in a realistic scenario. Since each slice could have very different requirements regarding the QoE/QoS control, different solutions should be provided without breaking down the QoE/QoS framework that we've defined. In the WP4 [D4.2] two different QoE/QoS control entities are considered: one associated to the SDM-C, and another one associated to the SDM-X; of course, these entities should be implemented using the 5G NORMA framework (see Figure-2-6 below).

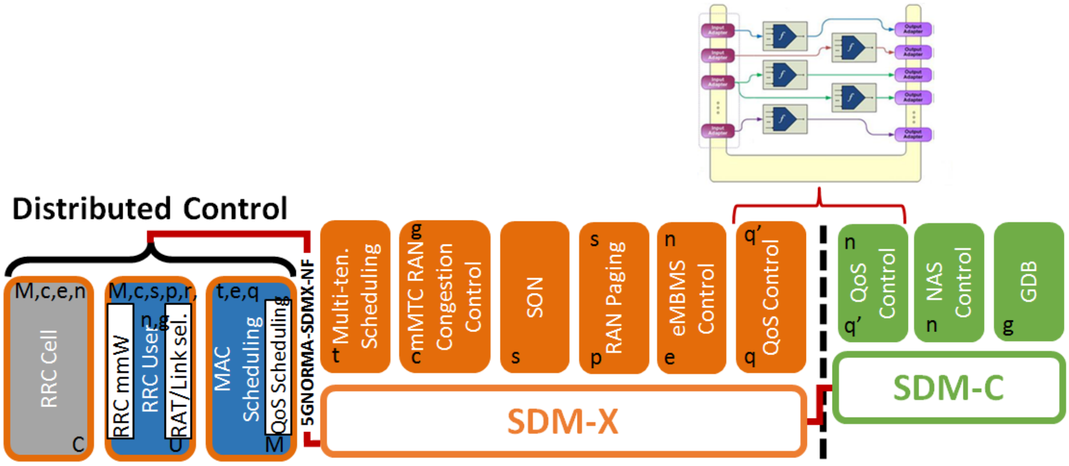

Figure-2-6: QoE/QoS Control System in WP4.

If we consider how this could be implemented in practice, we can see that our QoE/QoS is flexible enough to make possible different approaches.

Looking the previous figure, the first most evident approach would be to deploy two different instances of the QoE/QoS platform: one for the common resources QoE/QoS Control (orange block labelled as *q*) and another one for the slices specific resources (the green *q'*) to implement the intra-slice QoE/QoS control. Each instance would be a single node (or a cluster of nodes) running two different QoE/QoS execution environments: one hosting the common I/O adapters and Mapping Functions and interfacing the SDM-X, and another one with the Adapters and Mapping functions for the different slices in the network; i.e., this second instance would allocate components belonging to different tenants into a single execution environment. The deployment should be something like the one represented in the following Figure-2-7

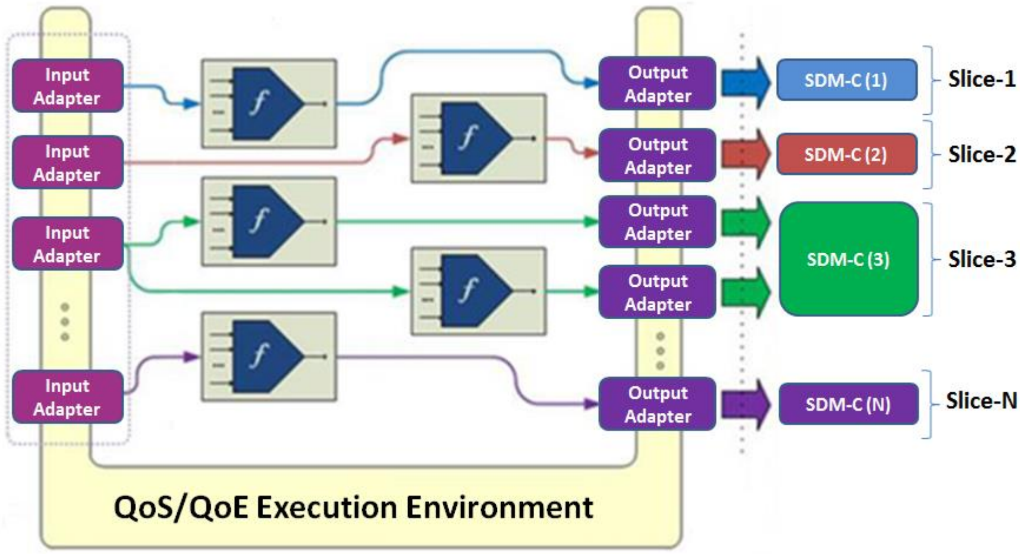

Figure-2-7: Common QoE/QoS Execution Environment for different slices.

In this case, each tenant should be granted with permission to manage and configure just those blocks in their specific slices, enabling security means (through the QoE/QoS management block) to forbid access to those resources belonging to other tenants.

However, this approach could not be well accepted for some tenants, since in certain manner it breaks the principle of slice isolation (although the QoE/QoS specific components are independent for each slice, they are executed on a *common* execution environment). This leads to a second approach, consisting on providing a separate execution environment for each slice; the following Figure-2-8 illustrates this idea.

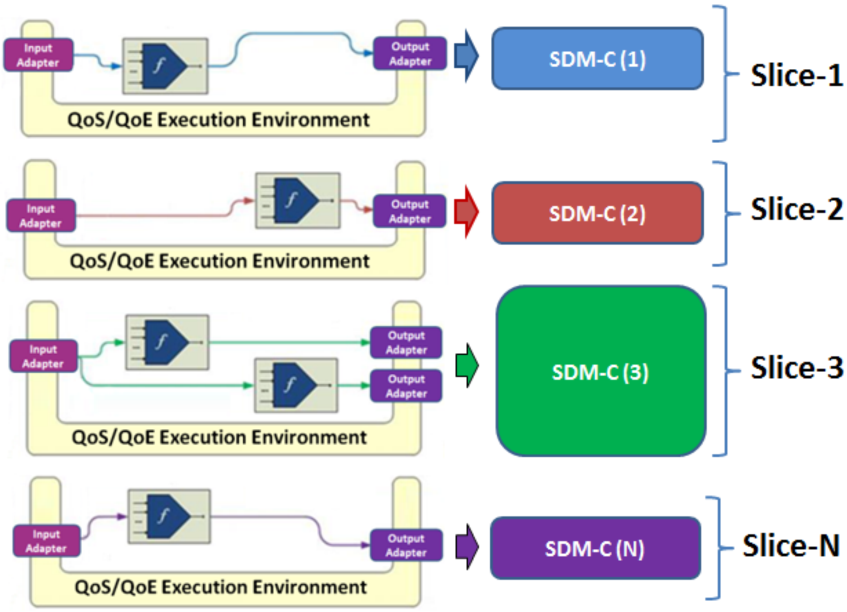

Figure-2-8: Separate QoE/QoS Execution Environments for different slices.

Between these two approaches probably there is no an absolute best one from a design point of view. This would depend on the infrastructure provider policies and the type of service he would like to offer to their customers. Still, our vision here is to provide a framework flexible enough to cover all necessities, since probably, the best approach for a InP would be to support different implementations of the QoE/QoS framework depending on the specific requirements of each tenant; so, the first approach could be adopted by tenants that would accept to share the common execution environment with others, while the second one could be offered to those tenants having very strict slice isolation requirements.

For example, for tenants with high-demanding requirements (e.g., services requiring multi-site deployments with high QoE/QoS requirements) it would be possible to deploy the QoE/QoS Assessment module (the execution environment with the I/O adapters and the mapping functions) as a dedicated service in the InP network. The complexity of such service would be variable based on the tenant requirements (it could be a single centralized node or a more complex deployment with a distributed set of nodes). Still, the basic idea would be the same: the service should implement the interface for the SDM-C and the corresponding interfaces for the monitoring and the management modules.

For medium-scale solutions, the QoE/QoS Assessment system could be deployed also into specific NFs (physical or virtual) of a slice (i.e., besides the NFs specifically required by the tenant to implement its service, the InP could deploy specific NFs implementing the required QoE/QoS control functions). Also, that NF should implement the required interfaces defined in the QoE/QoS framework.

Also, for small-scale solutions, it could be feasible to implement the QoE/QoS Assessment functionality into the SDM-C itself. We consider that, for some cases, it could be simpler to have a kind of “monolithic” SDM-C including the basic or most commonly requested QoE/QoS Assessment capabilities. This way the QoE/QoS Assessment Module would work as an internal SDM-C module, although preserving its functional independence.

The following Figure Figure-2-9 represents these possibilities.

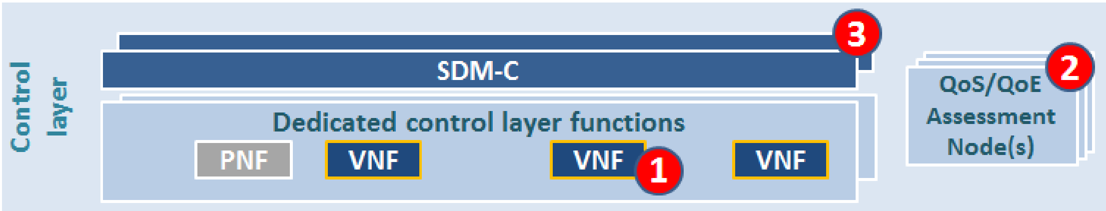

Figure-2-9: Possibilities for the placement of the QoS/QoE assessment modules.

Therefore, to get this while preserving the QoE/QoS framework structure could be challenging; the emphasis should be not only on the implementation of each functional block, but also, on the interfaces used to communicate the different blocks one with another.

General availability and degree of support for mobility of devices, services, sessions, and/or flows is seen as specific characteristic for a logical 5G network slice differentiating thus e.g. between eMBB with and mMTC without support of mobility, or between eMBB and V2X with simple and sophisticated MM, respectively. In this section, taking MM as exemplary modular NF, the potential design principles and granularities of modularization for the mobility feature of a slice are described as well as underlying criteria summarized. The relation to the preceding section on NF control is visualized from a specific mobility point of view (e.g. how the MM specific C/U-plane sub-functions are controlled and addressed) and the coordination with QoE/QoS framework (which interfaces and criteria are required to derive which mobility trigger from an expected/detected QoE/QoS violation proactively) is addressed. Detailed information on 5G NORMA achievements on MM selection and scheme design is provided in part 2, section 4, of this document.

Assuming throughout this section that each slice is just configured to efficiently provide a single service with specific mobility demands and corresponding performance laid down in policies or SLAs and monitored by QoE/QoS framework as described above here the case of a slice specific MM scheme to best fit the tenants' requirements is chosen.

Management and control within the slice is handled by MANO and SDM-C taking care of proper provision of resources to enable NF operation according to the expectation. MM is then represented as a corresponding Application interfacing SDM-C in the ETSI NFV [ETSI_GS_NFV] nomenclature (i.e. SDM-C App communicates to SDM-C via RESTful interface, API, or OF) to translate mobility demands into corresponding VNF configurations.

Furthermore, the MM App can translate a slice specific mobility management demands along with SLAs agreed with the tenant into the RAN specific configurations to be enforced. One example of such role of MM App is the definition of a size of User-centric Connection Area (UCA) [UCA] which minimizes the signalling towards the core network due to inactivity/activity change of a UE. By this means the MM App plays a role in joined RAN-core optimization. More detailed description of slice-aware MM design and joined RAN-core optimization is given in Section 4.4 of this document.

In the framework of MM the SDM-C is controlling/interfacing entities within the NFVI i.e. c-plane NFs (e.g. for location/paging) and u-plane (V)NFs (e.g. for anchoring, forwarding, enforcement, etc.). This case of a dedicated MM-App conveying slice-specific mobility requirements via SDM-C to NFs being fully under control of one SDM-C is the ideal representation of an intra-slice management and control. One of specific 5G NORMA challenges, however, is the inclusion of PNFs and VNFs under SDM-C control, e.g. when the equipment at a radio access site is included in mobility operations (e.g. via provision of lower layer information to enhance mobility decisions). In the latter case (since radio frequency in general is assumed to be a shared resource) the PNF would be controlled by SDM-X. Such an aspect as well as the question whether also a Mobility driven orchestration may have to be considered thus requiring also SDM-O interface for MM-App is related to the preceding Section 2.1.1.

Contrary to the assumption above the exceptional use case demanding for inter-slice MM is handled briefly in the following (for more detailed description please see [COCOA]):

We have to differentiate between the MM-App representing a slice specific MM scheme and the controlled NFs which may be shared (as RAPs or jointly accessed data bases for e.g. user subscription profiles and policies). This case may be denoted as hybrid MM, while the situations depicted in Figure-2-2 describe dedicated MM as both MM-App and all related NFs residing within same slice – vs. common MM where MM-App and all related NFs are shared between multiple slices and thus under SDM-X control. In [COCOA]: examples for application and use cases for all three variants are described.

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2.1.3 Relationship with the 5G NORMA Overall Architecture

WP5 inter- and intra-slice procedures and the associated functions cover the three layers of the 5G NORMA overall architecture, as depicted in Figure-2-10: (1) Management & Orchestration (MANO) layer, (2) Control layer, and (3) Data Layer.

The SDM-O 'Inter-Slice Resource Broker', NFV Orchestrator (NFVO), and domain-specific application management (DSAM) reside in the MANO layer. With the exception of the Inter-Slice Resource Broker, there can be dedicated MANO entities per network slice, e.g., a dedicated NFV MANO stack instance for each network slice.

While the Inter-Slice Resource Broker interfaces with the Service Management and also determines if and how resources and functions are shared across network slices, NFVO and DSAM interact with the (dedicated or common) control layer, in particular the controllers (SDM-C and SDM-X) and the distributed control functions that do not implement the SDM-C approach (cf. RAN architecture of WP4). The NFVO, together with the other NFV MANO functions VNFM and VIM, performs lifecycle management tasks (instantiation, scaling, re-location, termination) for network slices, i.e., it orchestrates all virtualized functions and links of a network slice including control applications, SDM-C/-X and Data layer functions. Further, the NFV MANO functions are responsible NFV infrastructure management. In a complementary fashion, DSAM configures the domain-specific (e.g., 3GPP) parameters of all NFs of a network slice and manages the application-specific hardware, e.g., ASIC, DSPs, active antenna systems, monolithic (non-decomposed) eNBs, etc.

The control applications for SDM-C and SDM-X, e.g., the mobility management or QoS control applications outlined in the previous subsection, as well as the controllers themselves reside in the Control layer. The controllers expose northbound APIs (e.g., RESTful interfaces) to-wards the applications and use tailored control primitives on the southbound to abstract the technology and implementation particularities of the controlled network functions in both Control and Data layer. SDM Cs can make reconfiguration or resource allocation requests towards SDM-X that in turn prioritizes multiple such requests according to the rule set supplied by the SDM-X control applications.

The key functional elements of WP5, i.e., SDM-O for management and orchestration, and SDM-C and SDM-X for control, are further analysed in the following section.

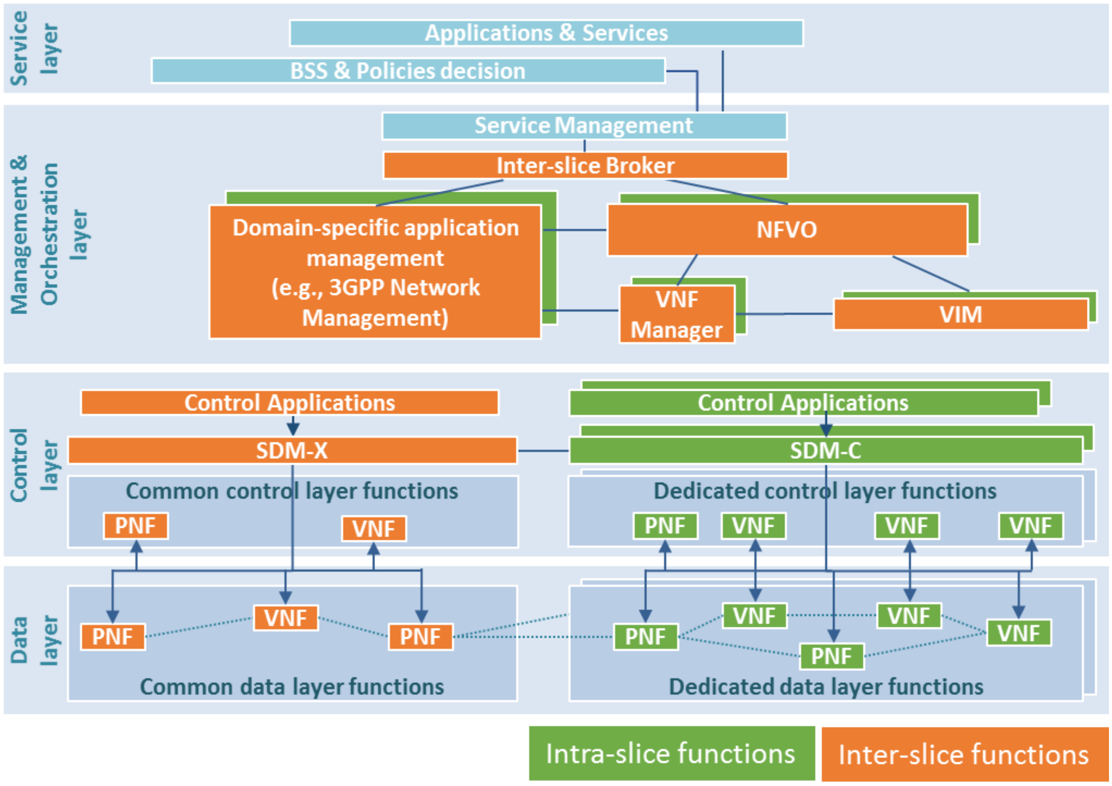


Figure-2-10: 5G NORMA overall architecture.

2.2 5G NORMA WP5 Key Functional Elements

As discussed before, future 5G Networks are going to heavily rely on enhanced controllers that extend the SDN capabilities [ONF]. Therefore, the functional architecture defined within the WP includes three fully softwarized elements that provide the intra- and inter-slice control and management functionalities introduced before.

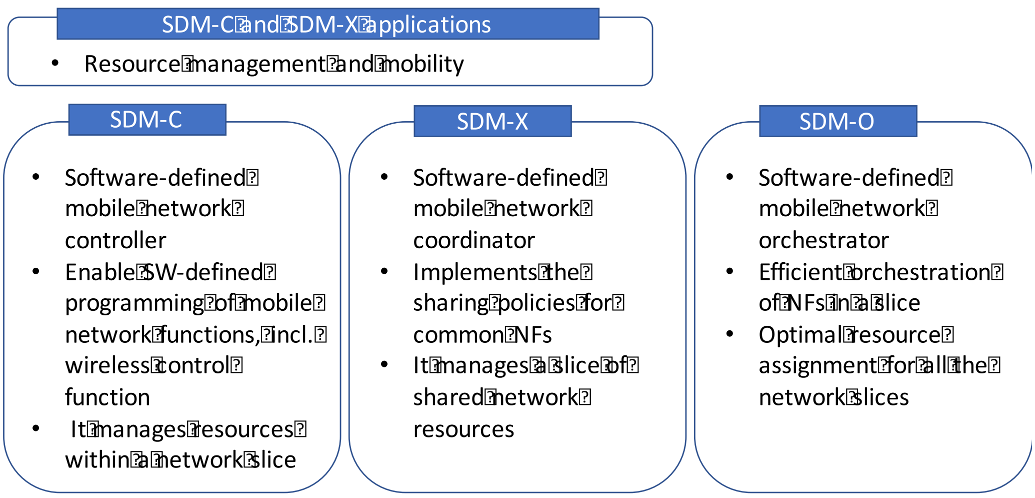


Figure-2-11: The Controller design rationale.

The rationale behind this choice, as depicted in the above Figure-2-11 is to have a specific element for each of the main problems introduced in Section 2.1. That is, we defined a specific element that takes care of i) applying extensive SW driven control to all the NF embedded into a Network Slice, ii) coordinating shared resource requests and utilizations across network slicing and iii) efficiently orchestrating resources across network slices over multiple infrastructure domain. Therefore, we introduced the Software Defined Mobile Network Controller (SDM-C), the Software Defined Mobile Network Coordinator (SDM-X) and Software Defined Mobile Network Orchestrator (SDM-O).

In a nutshell, their behaviour is as follows. The SDM-C is the core of the network slice: it applies the SDN principle everywhere in the NFs belonging to a slice, managing the QoE and QoS perceived by the users, eventually triggering re-orchestration requests to SDM-O. Following the SDN spirit, all the network functionality is implemented in a SDM-C Application, a piece of software that implements the logic of each network function. For example, one of the most important procedures of a mobile network, the mobility management, is performed as SDM-C application.

The efficient utilization of the resources shared among different network slices is managed by SDM-X. As scarce resources such as spectrum or fronthaul and backhaul bandwidth are likely going to be shared among slices, their efficient management and control is paramount to guarantee that QoS and QoE KPIs are fulfilled in the network. By applying different policies, SDM-X can steer the shared NF behaviour to the most appropriate ones according to the scenario.

Finally, how to orchestrate resources among network slices within the same (possibly multi-domain) resource infrastructure is a task accomplished by SDM-O. Its fundamental task is interoperating different slices, each one having its own requested KPI, assigning resources accordingly. The SDM-O architecture is an extension of the ETSI MANO NFV to the multi-slice, multi-tenant scenario. Still, we defined the SDM-O for the sake of clarity: it is in fact a bounding box that contains all the specific functionalities needed for multi-slicing orchestration.

Within 5G NORMA WP5 we also defined high level mechanisms that drive how standard processes will be carried out using the defined controllers in the proposed architecture. Common operation such as Mobility Management, Intra and Inter Slice Handovers, the re-orchestration triggers or the network slice onboarding.

We next detail each of the defined elements, highlighting their distinctive features before introducing the designed processes. The interfaces between the WP5 functional elements are intended to be functional interfaces, that enable the exchange of the needed information between elements. Some of them can be mapped to (possibly enhanced) version of already standardized interfaces (e.g., the northbound and southbound interfaces of SDM-C). Others may enrich the functionality currently available across several reference points (e.g., the interfaces between SDM-O and SDM-C can be implemented by joining the functionality of different reference points defined by ETSI NFV)

2.2.1 SDM-O

The SDM-O is a key component in the 5G NORMA Management and Orchestration architecture. Although this component has been conceptually there since the initial definitions in the 5G NORMA project [D5.1] [D3.1], it has been necessary to perform different design iterations (in a joint effort in WPs 3 & 5) to define its functionality in a more specific way.

The role of this core component in the 5G NORMA MANO architecture has been already outlined in the previous Section 2.2 (see Figure-2-9 and associated text). Here we will describe this component in more detail. The following shows a block diagram with the internal blocks forming this component and the main interfaces with other elements in the 5G NORMA architecture[2].

[2] The name and role of some of these internal blocks has changed during the project evolution, so what we present here could not be fully aligned with other references or descriptions in previous documents. What we present here is the last updated version, which comes from a common agreement in WPs 3 & 5.

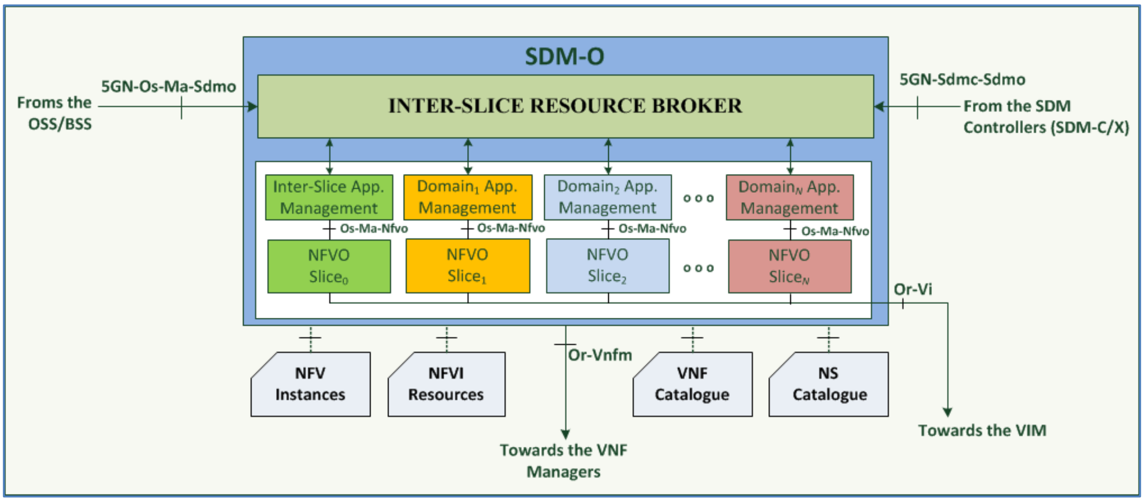


Figure-2-12: SDM-O interfaces.

As we see the SDM-O works basically as an aggregator of NFVO blocks. These NFVOs are the orchestration blocks defined in the ETSI NFV MANO framework [MANO]. As described in Section 2.2, we have a complete ETSI NFV MANO stack per slice, so these are the orchestration elements for each of those stacks. As shown, the central element in the SDM-O is the "Inter-Slice Resource Broker" (IS-RB) block. This block implements the following interfaces:

- **5GN-OS-MA-SDMO**. Used to communicate the SDM-O with the OSS/BSS systems. In some way, this can be seen as a natural extension of the ETSI NFV MANO 'OS-MA-NFVO' reference point to support multi-slicing in our 5G NORMA architecture; i.e., this is interface is basically used for the same exchanges that those defined in [MANO] for the 'OS-MA-NFVO' reference point (network services instantiation, service querying, provide usage records, SLA parameters definition…), but with the necessary extensions to specify the stakeholder requesting the operations and the specific network slice where those operations should be performed (the stakeholders could the InP itself, or any tenant requiring access to manage its own slices). So, besides the information elements already defined in the 'OS-MA-NFVO' reference point, this new '5GN-OS-MA-SDMO' interface should include the corresponding slice specific information elements (e.g.: slice and stakeholder identifiers).
  As we see, the requests from/to the remote OSS/BSS systems are primarily processed by the IS-RB block, which propagates the information from/to the necessary slices using the corresponding Application Management block. As we see, these Application Management blocks are working as a kind of 'internal' OSS/BSS system for each slice, interfacing with the different NFVO blocks (one per slice) by implementing the actual 'OS-MA-NFVO' reference point already defined in [MANO].
  As we can see, we have two different types of Application Management blocks: the Inter-Slice Application Management (green) and the Domain Specific ones (orange, blue and red). The first one is available only to the InP to manage all the infrastructure, while the others are available to the different tenants to manage their own domains for each slice.
- **5GN-SDMO-SDMC**. This interface, already defined in [D3.2, Section 4.4], is used by the 5G NORMA control elements (SDM-C and SDM-X) to request re-orchestration operations (for example, when certain QoE/QoS parameters are beyond the specified limit). The idea is that, in the case the SLA targets cannot be met, the SDM-C/X can directly trigger the re-orchestration request on the SDM-O. This is a totally new interface introduced in the 5G NORMA architecture, so a full definition of their information elements is necessary. To process the requests from this interface the IS-RB should be able to decide the re-orchestration operation to be performed (typically it will be a scaling operation) and the specific slice on which that operation should be performed; once

decided, that operation should be communicated to the corresponding Application Management module, which will interface the corresponding NFVO block.

- **OR-VI** and **OR-VNFM** interfaces. These are the same as the ones already defined in the ETSI NFV MANO framework. The interface is directly performed between the VIM and the VNFM functional blocks for each slice.
- **Catalogues interfaces**. Also, the same as those defined in the ETSI NFV MANO framework. The idea is to have a full set of catalogues per slice, so the interface is also between the catalogues themselves and the NFVO blocks.

2.2.2 SDM-C

The Software Defined Mobile Network Controller (SDM-C) aims to be the one of the key elements of future 5G Networks. The overall idea of the module is to enforce the split between the control logic of a NF. By acting as an enhanced SDN controller that applies this split across all the network functions in a slice, the SDM-C is the core of a network slice as it is the centralized control point in which all the NF logic is executed. Due to the intrinsically more heterogeneous operation of the controller this enhanced controller needs a larger number of interfaces compared to the ONF counterpart. Still, we tried to align as much as possible the functionality of such interfaces (at least from a high-level perspective) with the principle of Software Defined Networking.

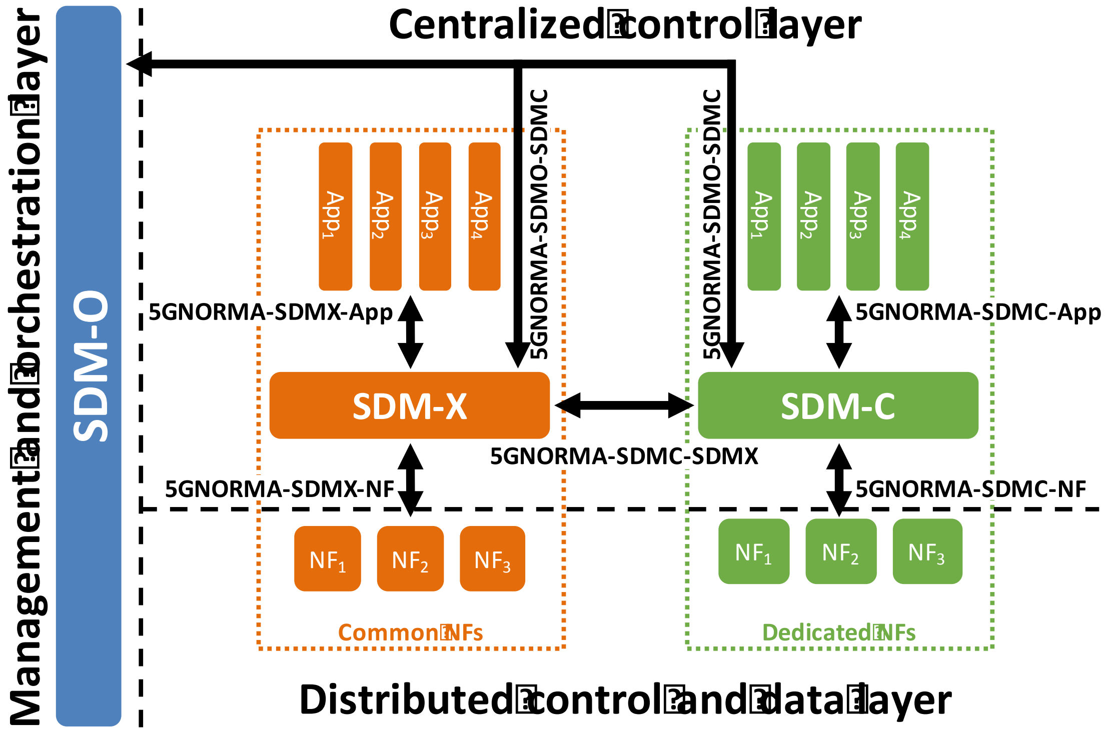


Figure-2-13: SDM-C SDM-X interfaces in the C-D layer architecture.

In a nutshell, there are three categories of interfaces: northbound interfaces towards the application logic, southbound interfaces to the different NFs and the management interfaces. They are detailed next. In Figure-2-13 we show how the SDM-C interacts with the other components of the architecture (i.e., SDM-X and SDM-O). The detailed extent of each interface is described next.

Interface 5GNORMA-SDMO-SDMC: this is a management interface, used by the SDM-O (see Sec. 2.2.1 for more details) to provide application management through the SDM-C controller. To some extent, this interface provides all the functionalities related to the configuration of OSS BSS and EM.

This interface is used to convey the Control Application-specific information derived during the translation from high-level tenant requests and established SLAs into the network slice resource provisioning, NFs logic, and lifecycle parameters. E.g., with respect to Mobility Management (MM) Application, this interface can convey the information about the most suitable MM scheme and corresponding network slice template with respect to the agreed SLA and service policies. Depending on the QoS service requirements attached to the network slice, a corresponding mapping onto latency, bandwidth, computing and storage requirements, QoS thresholds to monitor, etc. can be conveyed to the QoE/QoS Appli-cation via this interface.

Interface 5GNORMA-SDMC-APP: This interface is used to enforce the conditions defined by the Control Applications that must be realized for a given traffic identifier on dedicated functions and resources to fulfil the targeted SLA. E.g. via this interface the MM Application can convey to SDM-C the exact network slice configuration (with right VNFs type selection and right composition and configuration of different VNFs) based on selected network slice blueprint. On the oth-er hand, this interface can convey the information regarding the current slice performance which is reported back to the corresponding Control Application.

Interface 5GNORMA-SDMC-NF: It controls and configures parameters of the dedicated P/VNFs which implement the NFs on the data path. The 5GNORMA-SDMC-NF interface is hence used to configure and control these (Physical or Virtual) Network Functions. A list of the available NF that can be controlled is listed in D3.2 and D4.2. The main category of controllable NF is SDN-compatible routers (forwarders), building the path(s) that connect the VNFs of a service chain. In this case, the interface is equivalent to the southbound interface of an ONF-type SDN controller.

Interface 5GNORMA-SDMC-SDMX: is used for interaction between the SDM-C and SDM-X controllers in a peer communication mode. Based on the resource management policies provided by the SDM-O, the negotiation between SDM-X and SDM-C is established to decide how to fulfil the demands of several partially competing network slices simultaneously. E.g. the SDM-X decides based on the SDM-O policies whether it is necessary or not to modify a network slice’s shared resources upon a request coming from SDM-C

These interfaces are used to perform common task in the mobile network operation. Some of them are revised in Section 2.3 below.

2.2.3 SDM-X

While the SDM-C represents the functional core of a single dedicated network slice, the Software Define Mobile Coordinator (SDM-X) is the pillar of the novel 5G NORMA architecture as it manages heterogeneous accesses (by multiple tenants) to a shared network resource, e.g., spectrum or shared network functions. This implies advanced sharing mechanisms in order to e.g., prevent (competitors) tenants from selfishly acquiring sensitive unauthorized data while still keeping affordable multiplexing gains.

Shared resources might be collected in a common pool before being dedicated to specific network slices. Such a common pool is dynamically managed by the SDM-X in charge of providing QoS guarantees to each network slice traffic flow. However, an admission control mechanism should be developed and formerly applied (at the SDM-O level) to avoid network congestions and, in turn, unexpected SLA violations. The key idea relies on the interaction between a single SDM-X and multiple SDM-C, corresponding to multiple network slices willing to get shared resources. In this context, 5G NORMA framework envisages a bi-directional communication between SDM-X and SDM-C. In particular, the SDM-X will promptly notify the resource availability per slice (based on inter-slice policies which might be enforced by the SDM-O). Resource availability might change over time based on the real slice resources utilization. For instance, SDM-C might issue an amended SLA request due to a traffic burst (for its own slice traffic flow), which may be efficiently accommodated at expenses of unused shared resources. This automated negotiation introduces flexibility and efficiency in the shared resource management process without establishing a master-slave hierarchy between SDM-X and SDM-C instances. Applications running on top of those controllers may easily interact each other and choose the best scheduling option while satisfying the overall slice requirements. This interaction is performed through the **5GNORMA-SDMC-SDMX** interface. In the next section, we provide a detailed interaction between different 5G NORMA controllers based on given network processes.

2.3 5G NORMA WP5 Processes

The functional architecture described in the previous sections incorporates novel concepts of Network Slicing and Network Programmability that are certainly beneficial for achieving the goals described by the most important 5G stakeholders associations. We already described the role of the three major elements in the WP5 functional architectures: this entails the redesign of most of network procedures that are currently performed by the management elements of the network (e.g., EM, OSS/BSS) and the definition of new ones that regard the novel concepts we introduced, such as SDM-C and SDM-X application. In this section we describe four exemplary processes that will be relevant for the deployment and operation of 5G NORMA based networks.

We first describe two processes that are related to the network management: how to set up and deploy a network slice and how to re-orchestrate the resources associated to a network slice.

2.3.1 Network Slice Set Up and Deployment

The first part of the process describes how external tenants can specify requests for communication services at an MSPs customer portal and an annotated network slice template is generated from the provided input.

Actors	**Triggering actor:** - Tenant application/human operator **Involved actors:** Service Management, Inter-Slice Resource Broker
Preconditions:	• none
Postconditions:	• An annotated network slice template has been created and provided to the Inter-Slice Resource Broker
Frequency of Use:	Daily/weekly
Normal Course of Events:	1. Tenant application/human operator invokes the customer portal (part of MSP's BSS in 5G NORMA service layer) for requesting a communication service 2. Tenant application/human operator provides the required input vector, e.g., o Duration of the communication service o Expected traffic characteristics (total, distribution in space and time, uplink/downlink distribution) o Geographical area / coverage o Number of subscribers o Latency, jitter o Qualitative attributes (service availability and reliability, privacy, access control, encryption and integrity protection requirements, etc.) 3. The Service Management utilizes the input vector from the customer portal to select the most appropriate template from the network slice template repository as follows

	o Each available template is associated with the same parameter vector and, per parameter, the value (or value range) that the template can support o Based on a pre-defined distance metric, the best matching template is selected 4. The Service Management further annotates the selected template by adding further information regarding (non-exhaustive list) o Inter-slice prioritization information o SLA information o Slice identifiers and UE association rules o Resource dimensioning for each NF o Transport network performance requirements (links between NFs) o Initial configuration information for each NF o Monitoring policies o Lifecycle management policies (thresholds, etc.) o Deployment flavor parameters o Local affinity (anti-affinity) rules o etc. 5. Service Management hands-off the annotated template to the Inter-Slice Resource Broker

The second part describes how the 5G NORMA MANO layer entities create a network slice instance based on the annotated slice template. This process comprises

- allocation of physical as well as virtualized resources,
- creation of dedicated MANO layer functions,
- instantiation of major control functions like SDM-C, control applications, and dedicated control layer VNFs,
- instantiation and configuration of dedicated VNFs, and
- establishing connectivity between virtualization containers and PNFs.

Actors	**Triggering actor:** - Service Management **Involved actors:** Service Management, Inter-slice Resource Broker, NFVO, domain-specific application management, SDM-X/-C, VNFM, VIM
Preconditions:	• An annotated slice template has been received by the Inter-Slice Resource Broker • Information on infrastructure resource utilization is available
Postconditions:	• Network slice has been instantiated and activated • Tenant application/human operator is given control over the network slice • Network slice is ready to handle user traffic
Frequency of Use:	Daily/weekly
Normal Course of Events:	1. The Inter-Slice Resource Broker receives an annotated slice template from Service Management 2. The Inter-Slice Resource Broker creates a new NFV MANO functions (and/or associates existing ones) for the new slice instance and allocates NFVI resources for dedicated VNFs 3. The Inter-Slice Resource Broker creates new domain-specific application

	management functions (and/or associates existing ones) for the new slice instance 4. For shared NFs that become part of the new slice instance, the Inter-Slice Resource Broker updates the according NFV MANO and application management functions 5. The inter-slice application management functions reconfigure SDM-X entities to consider the new slice in the control of shared functions/ resources. 6. The NFVO triggers the responsible VNFMs to instantiate the slice-specific SDM-C, the respective control applications, and all other NFs that are part of the network slice. 7. The VNFMs instruct the appropriate VIM(s) to instantiate the SDM-C, control applications, and other NFs for the new network slice. 8. VIM(s) instantiate SDM-C, control applications, and other NFs. 9. The NFVO and application management functions set up the interconnections between Virtual Containers as well as to PNFs and to common VNFs. 10. Application management functions provide network function configurations to SDM-C 11. Network slice is activated by Inter- Slice Resource Broker, confirmation is sent to Service Management
Exceptions:	If the network slice deployment is not feasible due to lack of infrastructure resources, all affected catalogs (annotated slice templates, infrastructure resources) shall be reverted to their initial state before the process was started. The initiating tenant application/human operator receives an error message explaining the reason for slice deployment failure. (As long as the infrastructure and resource situation does not change, a new slice deployment request may only be successful if it is done using a different/modified network slice template.)

2.3.2 Network Slices resource re-orchestration

Resources re-orchestration is a fundamental problem for cloudified network. As a matter of fact, one of the most appealing features of softwarized network is their ability to auto-scale and self-adapt to the changing conditions, both inside and outside the extent of a network slice, Therefore, in the framework of WP5 we defined our controllers to be a central part of these procedures.

To correctly perform the re-orchestration procedures, we divided them into two categories: re-orchestration due to lack of IT resources and re-orchestration due to QoS requirements. Broadly speaking, both IT resources (i.e., disk, RAM, CPU) and network resources (i.e., spectrum, fronthaul bandwidth, scheduling patterns) should be managed in a unified way. Shortages in any of the two realms should be considered for re-orchestration triggers. However, as they are intrinsically very different, we defined two re-orchestration paths. We define the re-orchestration due to IT resource shortage as follows:

Actors	**Triggering actor:** - VIM **Involved actors:** VNFM, NFVO, Inter- Slice Resource Broker
Preconditions:	• Lack of IT resources
Postconditions:	• Network slice is scaled up/out

Frequency of Use:	Daily/weekly
Normal Course of Events:	1. Each VNF deployed in a network slice has associated triggers regarding the needed amount of IT resources (CPU, RAM, storage) needed in his VM container to properly provide the designed functionality 2. When one or more triggers associated to the VNF are fired, the information is passed to the VNFM that has to take one of the following decision: to scale out or up the VM(s) building a network slice. 3. Before taking the decision, the VNFM contacts the NFVO of the network slice, that checks if one of the selected operation is possible (there are enough resources) or other decision better fulfill the VM replacement (e.g., move the VNF to another container of NFVI) 4. If additional resources are needed, the Inter- Slice Resource Broker is involved, as the NFVI share of the tenant that runs the network slice has to be resized to perform the scale out/up operation 5. The VIM is instructed to perform the operation

The process above is very similar to the one currently defined by the ETSI NFV MANO, for scaling in/out or up/down VNF. Now, in order to perform a similar operation triggered by QoS parameters, we have to involve two more actors in the procedure: the SDM-C (or X, in case of shared resources) and the QoS Framework. It is detailed next. For the sake of simplicity, we detail the use case for dedicated resources, but the process is analogous for shared ones.

Actors	**Triggering actor:** - SDM-C/SDM-X - QoS Framework **Involved actors:** VNFM, NFVO, Inter- Slice Resource Broker, VIM
Preconditions:	• QoS levels not fulfilled
Postconditions:	• Network slice is re-orchestrated
Frequency of Use:	Daily/weekly
Normal Course of Events:	1. The QoS framework reports to the SDM-C the relevant metrics for the monitored NF 2. The SDM-C app checks if the shortage can be countered by a reconfiguration of the VNF in the SFC. 3. If not, the information is sent to the SDM-O (NFV-O) through the 5GNORMA-SDMC-SDMO interface. Relevant side information, such as the current QoS levels (also not related to the monitored NF is provided to the SDM-O). As explained in Section 2.2, this logical interface may span different reference points already defined by ETSI NFV MANO architecture. 4. The final decision is taken by the NFVO of the network slice, that checks if one of the selected operation is possible (there are enough resources) or other decision better fulfill the VM replacement (e.g., move the VNF to another container of NFVI). Also, different assignment of network resources (e.g., spectrum), or an update to the SFC is a valid option.

	5. If additional or different resources are needed, the Inter- Slice Resource Broker is involved, as the NFVI share of the tenant that runs the network slice must be resized to perform the scale out/up operation. 6. The VIM is instructed to perform the operation (in case more VNFs are needed) and the SDM-C is informed about the new extent of the network slice.

2.3.3 SDM-X applications

As described in Section 2.2.3, the SDM-X is in charge of handling shared applications over multiple slices/tenants. Among others, it is responsible to allocate scarce and expensive radio resources to slices in an optimized manner to guarantee efficient usage of those. It needs to control the needed functionality of the service chain via policy based de-/activation patterns to satisfy the defined slice/SLA requirements. SDM-X was introduced in [D5.1] and its functionality is further described in [D3.2, COCOA] In the following, an overview of necessary requirements on signalling and policy rules are described, while specific technical solutions of SDM-X controlled functionalities are explained in detail in Part 2, Section 3.

	SDM-X as Trigger	**SDM-X as Receiver**
SDM-O	Re-orchestration request	Policy enforcement after orchestration
SDM-C	Monitoring request	Additional resource request
P/VNFs	Policy based de-/activation, modification	Problem detection

Figure-2-14: Triggers and interactions of SDM-X.

Figure-2-14 gives an overview on identified triggers and interactions of the SDM-X to control shared applications and P/VNF during runtime of multiple slices. The shared resource control is triggered by the orchestrator via policies when shared resources must be managed, e.g., spectrum or shared network functions. The SDM-X enforces the provided policies for shared applications. Furthermore, shared applications at the SDM-X entity will be supported by (multiple) SDM-C functional blocks through the 5GNORMA-SDMC-SDMX interfaces. This ensures communication levels between SDM-X and SDM-C and prevents master/slave communications. The SDM-X needs to be able to trigger a re-orchestration request to SDM-O to prevent an SLA violation. SDM-X needs to e.g., activate and deactivate shared applications based, such as ICIC and scheduler policies which dynamically change the behaviour/functionalities of the instantiated shared applications. For instance, it might switch between the locally instantiated scheduling metrics of a BS cluster to improve the overall slice performance. Furthermore, the SDM-X needs to be triggered by SDM-C if additional resources are required. SDM-X needs to receive monitoring information of the slice specific QoS monitoring entity of the SDM-C and SDM-X needs to receive additional control data, such as resource requests by SDM-C.

2.3.4 SDM-C applications

This section describes the process of slice and service specific selection of an SDM-C controlled network functionality or service in charge of mobility of (active or idle) session endpoints which can be seen as SDM-C App(lication) or VNF and is denoted by MM-App. More details on available versions of such MM schemes and the selection are given in Part 2 (section 4, NS MM)

As described in Part 2 the SDM-C App will be responsible for correct c-plane and u-plane VNFs and PNFs as (dynamically chosen by the SDM-O) anchor points for routing and forwarding u-plane traffic and enforcement points to check correct QoS handling, policy or AAA issues. Other functionality to be addressed may be to initiate RAN Paging for unknown location of a device in case of mobile terminated session request. In case this control is executed directly the MM-App has to know which functions how to address and these states have to be available to each App instance. Alternatively, SDM-C does this (e.g. in terms of a shared data layer and thus allowing for stateless operation of the App) via the **5GNORMA-SDMC-NF** interface to control and configure parameters of dedicated P/VNFs. Then the MM-App needs to convey this information via the **5GNORMA-APP-SDMC** interface used to enforce conditions defined by Control Applications that have to be realized for a given traffic identifier on dedicated functions and resources in order to fulfil targeted SLA. In other words, via this interface MM-App can deliver to SDM-C exact network slice configuration (with right specific VNFs configuration) regarding MM features to be supported based on selected network slice blueprint. On other hand, this interface can relay information regarding current slice performance reported back to corresponding Control Application (e.g. from QoE/QoS Moni-App).

During the slice set-up or re-configuration Control Application-specific information derived during the translation from high-level tenant requests and established SLAs into network slice resource provisioning are communicated through the **5GNORMA-SDMO-SDMC** interface. Information such as NFs logic, and lifecycle parameters are communicated to the MM-App pool for selection through the controller or E.g., information about most suitable MM scheme and corresponding network slice template with respect to agreed SLA and service policies are retrieved.

MM-App as exemplary SDM-C App must consider limitations and restrictions given by existing agreements on service provisioning – enforcement here is to be understood as the usual translation of c-plane information into verification on u-plane at the enforcement points (i.e. NFs on u-plane level).

As already mentioned in preceding section (SDM-X policies) the SDM-C App may also be operated in a shared mode, i.e., a MM scheme is operated jointly for different slice instantiations (e.g. vehicular slice for different car manufacturers) or slices with identical mobility requirements (e.g. mMTC and residential BB access). In this case, the App similarly to the dedicated slice case will via **5GNORMA-SDMX-APP** interface enforce conditions defined by Mobility Control Application to be realized for given traffic type on shared resources and functions in order to fulfil the targeted SLA with respect to relevant service policy. Alternatively, this is done via SDM-C and the respective interface depicted in Figure-2-13: SDM-C SDM-X interfaces in the C-D layer architecture.

3 Deployment Considerations for WP5 functional architecture

This section will discuss and describe the rationale and the deployment considerations for the placement of the NORMA controllers i.e., SDM-X and SDM-C within the 5G NORMA architecture. The discussion will provide the overview of various possible deployment options of the controllers at various levels of the 5G NORMA architecture and briefly describe the pros and cons of each deployment option with respect to 5G NORMA functional and operational imperatives.

Moreover, this section will also describe the interaction between the MANO layer and the SDM-C and SDM-X controllers for different purposes. For example, inter/intra-slice orchestration and lifecycle management of the slices including mobility management and QoE/QoS management are discussed next.

3.1 Controllers Placement

This section will provide an overview of the rationale and design considerations that were considered when determining the placement options of the 5G NORMA controllers. As mentioned before, one of the innovative aspects of the 5G NORMA architecture was the employment of the SDN concepts within the overall scheme of slice management. The aim is to leverage on the SDN and NFV concepts in order to develop a novel mobile network architecture that shall provide the necessary adaptability in a resource efficient way able to handle fluctuations in traffic demand resulting from heterogeneous and dynamically changing service portfolios and to changing local context. From the NFV perspective 5G NORMA extends the NFV MANO framework to support multi-tenancy and manage service slices that may be extended over multiple sites. From the SDN perspective, it defines two SDN-based controllers, SDM-C for the management of network functions local to a mobile network service slice, and SDM-X for the management of network functions that are common/shared between mobile network service slices. These controllers leverage on the concept of SDN controller and translate decisions of the control applications into commands to VNFs. The main design challenge was to determine the deployment option of these two controllers that are crucial to the effective management of the mobile network slices and their management.

In line with the base design principles of following ETSI NFV architecture and extending it as per the use case requirements, the decision on the controller placement has also been made keeping in line with the ETSI NFV recommendations regarding the SDN usage in the NFV architectural framework [SDN-NFV].

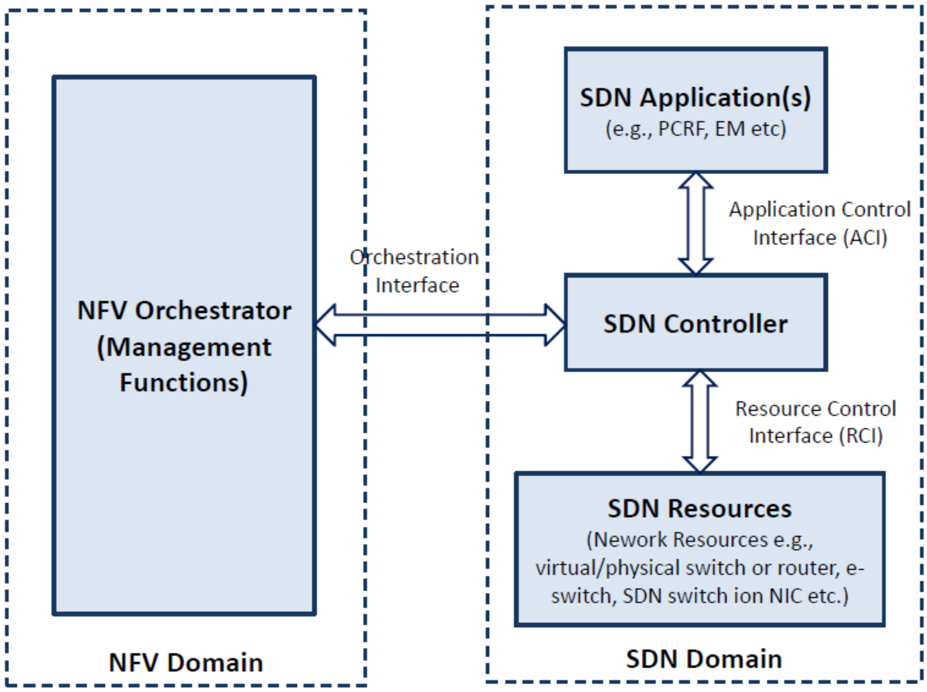


Figure-3-1: ETSI NFV Perspective of interfacing with the SDN domain [SDN-NFV].

3.1.1 NFV Considerations and Recommendations

ETSI NFV provides a very precise architectural framework for a very clear purpose, and that is to manage and orchestrate NFVI resources, typically located in data centres, that are utilized and consumed by Telco related functions and services. In this context ETSI NFV specifies features and functions it requires from SDN. They then look into various possibilities of positioning SDN in the larger scope of NFV.

From this perspective, the ETSI NFV system as per today's requirements uses the services of SDN to provide a programmable platform for establishing links between VNFs and/or VNFCs, and to support enhanced functions such as policy based management of traffic between VNFs and/or VNFCs, or dynamic bandwidth management. Thus, the NFV system realizes a fully programmable end-to-end network services (NS) within the NFV domain.

When integrating the SDN functional components within the NFV infrastructure, it must take into consideration the SDN interfaces relevant for its requirements. Figure-3-1 gives a high-level overview depicting ETSI NFV perspective on interfacing with the SDN domain [SDN-NFV]. As shown, ETSI NFV is in the process of specifying the *"Orchestration interface(s)"* for interfacing the SDN controller with the NFV MANO system. These specifications take the interfaces internal to the SDN domain into account. That is, the Application Control Interface (ACI) that provides to the VNFs an application programmatic control of abstracted network resources [SDN-NFV], and the Resource Control Interface (RCI) for controlling the NFVI network resources (e.g, physical/virtual routers and switches, and networks connecting VNFs).

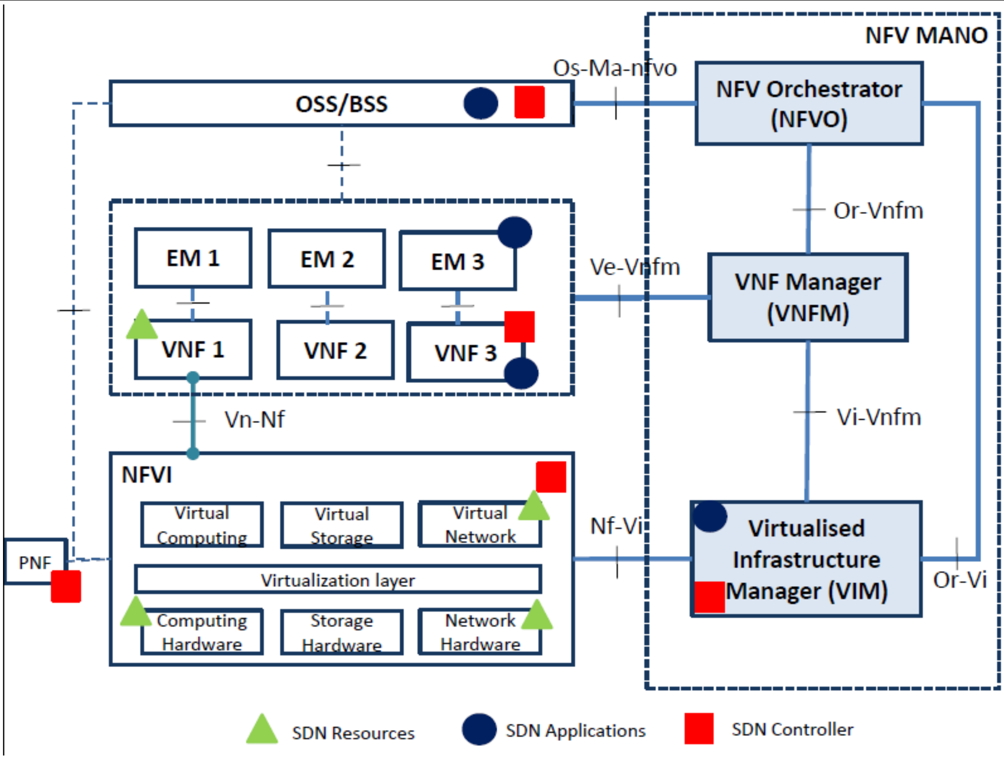


Figure-3-2: Overview of SDN controller deployment options with respect to SDN Applications and SDN

In this context, ETSI NFV has published a detailed report [SDN-NFV] describing the various possible options of SDN federation in NFV. Figure-3-2 summarizes these possible options of integrating *SDN application*, *SDN resources* and *SDN controller* with different entities within the NFV MANO and NFV architecture. Each one has its own requirements on the NFV MANO interfaces. For example, there are five integration options for SDN controller to either;

(i) be part of OSS/BSS,
(ii) exist as an entity within NFVI,
(iii) exist as a PNF,
(iv) be instantiated as a VNF, or
(v) be integrated within the VIM.

Thus, Figure-3-2 gives different recommended options of integrating the SDN system (application, resources and controller) in the context of NFV and [SDN-NFV] provides an overview of each option and its combination. The key point is that NFV aims at leveraging the programmability feature of SDN to implement NS that may be designed according to some pre-configured VNF Forwarding Graph (VNFFG), or implement NS that may require the chaining of VNFs based on some policy/service or even based on VNF processing, for example, a security related VNF may want to change the path of traffic on the fly depending on its processing output.

3.1.2 5G NORMA Considerations and Approach

The 5G NORMA system has the complex requirement to provide inter/intra-slice management and orchestration across multiple domains. For this reason, the resources and services of each slice instance has to be managed throughout the slice lifetime in order to ensure uninterrupted services within prescribed QoE/QoS bounds. The 5G NORMA architecture thus mandates a SDM-C instance to be associated per slice instance for slice specific resource/service management. Moreover, owing to the role of the SDM-X for the management of shared/common resources between the slice instances, there is a unique functional relationship between the SDM-C and SDM-X that is dynamic and hence must be maintained and managed throughout the lifetime of the slices. In other words, the SDM-C and SDM-X instances and their lifecycle and their associated resources also need to be managed and orchestrated with a high degree of dynamism.

In addition, the SDM-X and SDM-C form the control layer of the 5G NORMA architecture, which is between the MANO layer (comprising of SDM-O, VNFM, VIM) and Data layer (comprising of PNFs, VNFs that form a slice), which allows the SDM-X/C to translate decisions of control applications into commands for the data layer elements. Moreover, each time a new slice is instantiated, a corresponding SDM-C instance has to be made available and associated with the new slice. Considering that there could be hundreds of slices in a data centre, provisioning of SDM-C/X as a physical control entity can not only have scalability issues but also lead to performance issues. It is with these considerations that the SDM-X and SDM-C are deployed as VNFs and their functions and interactions are managed by a VNFM just like other VNFs. The deployment of SDM-X and SDM-C as VNF instances not only makes the lifecycle management of these controllers efficient but it also enables the MANO layer to better manage the interactions of the SDM-X with multiple SDM-Cs. It also allows the system the flexibility of implementing the SDN applications, for example, 3rd party applications can be deployed to interact with the SDM-C/X to enhance its functional/operational scope beyond the applications that may be integrated within the SDM-X/C instances.

Figure-3-3 graphically depicts the scalability considerations behind this choice: we clearly have three levels of scalability regions: SDM-O that works at the operator level to assign resources to each slice, the SDM-C which is implemented at VNF level takes care of the network setup, while NFs (of any kind, including distributed control) are the most real time element in the chain.

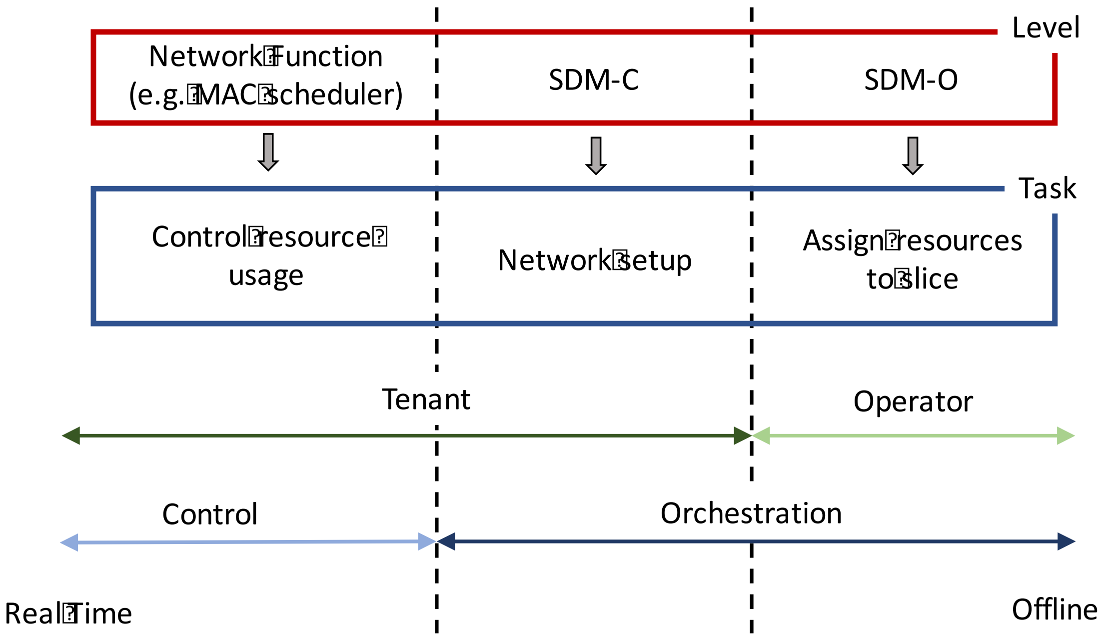


Figure-3-3: Scalability considerations for SDM-C placement

3.2 VNF Mobility

3.2.1 Replication/Migration decisions

Network Function Virtualization has changed the way network functions are deployed. It's no longer necessary for a technician to manually install a device somewhere in the network. Virtual network functions can be deployed anywhere, usually without direct human intervention outside of defining the right configuration files. Replicating and migrating network function is significantly easier using NFV, since creating new instances of a virtual machine or copying a virtual machine from one place to another is much more straightforward than transporting an actual machine from one location to another. The changes in configuration can also be automated, in the case of the VNFs.

One of the key innovations of 5G NORMA is the adaptive (de)composition and allocation of network functions. Functions can run either on the central cloud or on the edge cloud, based on service requirements and deployment needs. This means that in some situations, network functions (specifically, virtual network functions) should be moved within the network to meet all those requirements and needs. In this section, we will describe why and how a VNF could be migrated or replicated. Some strategies for performing this replication/migration are described in the next section.

Replication and migration will be necessary whenever the network cannot fulfil the service requirements of a given service. It's a re-orchestration process, triggered by the SDM-C or the SDM-X, and implemented by the SDM-O using the VNFMs and VIMs. Analogously to what has been already defined in Section 2.3.2, there are two types of events that will trigger a replication or migration:

- Inability of meeting defined QoE/QoS targets, for example
    - Inability of meeting QoS goals for a specific parameter (the most common example are time-critical functions being moved to the edge cloud)
    - Sudden changes leading to service interruption
        - Significant and fast increase in demand, for example, an accident creates a traffic jam in a segment of a highway only served by one base station
        - A large group of users attached to a base station manage by an edge cloud moves to another edge cloud, for example, a large group of soccer fans takes the train from the suburbs to the stadium area
- Resource shortages, such as
    - An overwhelmed edge cloud, requiring functions to be moved to the central cloud

There are many possible ways of modelling the replication/migration decision. In the previous deliverable [D5.1], we presented an overview of the state of the art for service migration decision. The two most common approaches are fuzzy logic and Markov Decision Processes (MDPs). The latter is used for Edge Function Mobility (section 4.3 of Part 2), which focuses on the function placement decision when a group of users change edge clouds

3.2.2 Replication/Migration strategies

After the decision for replication/migration has been made, two potential strategies for replication/migration can be gathered.

- Context migration and replication
    - This option consists of the transfer of state information and reassignment of flows from a function on one cloud to the same function in another cloud. The target function could be already instantiated or be instantiated on demand (replication of the original function). The deployment will follow the same blueprint followed by the SDM-O when the original function was first deployed. Functions that don't contain large amounts of state information and that don't tolerate long service interruptions will use this strategy.
- Live Migration for stateful functions
    - Live migration consists of instantiation of the same VNF, followed by the live transfer of memory, storage and network connectivity from the original VNF to the new VNF (e.g., similar to what is currently implemented in OpenStack Nova Live Migration). It's suitable for a function like Video Caching. If a video is

being frequently requested in an edge cloud, it could be moved closer to the users (together with the video server VNF) using live migration.

The main challenge to consider here is the replication/migration time and service downtime. Both should be minimized, especially the service downtime. However, we are still dealing with replication/migration times ranging from hundreds of milliseconds (for context migration) to dozens of seconds (for live migration) [Cerroni]. This entails that with current technology, replication or migration should only be performed when other options have been exhausted.

3.3 QoS Monitoring Granularity

3.3.1 UE mobility management granularity

This section discusses considerations on interoperation between different SDM-C Apps or VNFs under the control of SDM-C and SDM-X. Especially the question is in scope how the QoE/QoS framework is interworking with the functionalities (Apps) referring to the service performance e.g. in terms of triggering actions to preserve or enhance a predefined service quality. It has to be considered at which level (e.g. flow/UE/slice/…) the interworking is required and provided, respectively, depending on the specific use case or deployment scenario. This issue is denoted as granularity of the interworking between e.g. QoE/QoS Monitoring functionality and the Mobility (MM) Management protocol. Details of the QoE/QoS Monitoring design and MM schemes will be handled in Part 2 (see Section 4) whereas here the general principles will be described and illustrated.

In the following we assume that each slice is representing a single use case or service to be provided to the users connected to this slice: The MM selection occurs with a per-slice granularity and the selected MM scheme within slice is continuously enforced or confirmed based on the available QoE/QoS monitoring provided at same (per-slice) granularity. In case of violation of QoE/QoS threshold a re-configuration of the MM scheme may have to be instantiated – possibly with need for SDM-O support.

In general, we assume that multiple flows can be active concurrently within a session which may be forwarded via different paths in different environments and respective link qualities what may benefit from a per-flow granularity. Also in case the various flows carry different or same services with their requirements and call for flow specific modifications. A QoE/QoS monitoring on comparable level should be available to optimally fit the changing conditions.

Regarding the possibilities for selectable App granularity (in terms of parameters as e.g. terminal speed or session continuity as discussed in Section 4)we face a trade-off between effort and complexity which is related to provision of multiple MM schemes per slice on one hand and the actually expected gain for service performance and resulting customer satisfaction achieved with a more fine-grain selection.

As a function of such granularity but also specific to slice performance KPIs as defined by the SLA, the decision on interface between MM-App and QoS monitoring and the manner of interworking has to be considered. The amount of information to be exchanged (e.g. simply a flag indicating threshold violation or details as outcome of an analysis of the reasons for it) and the frequency of exchanging data (on demand or continuously) has to be specified. An essential parameter is the threshold for QoS Monitoring to trigger MM App activity. As well-known from the ping-pong effect in HO decision at cell borders here e.g. a low threshold without enough hysteresis margin would frequently invoke MM activity without real gain. So to avoid much signalling effort and risk of false decisions during scheme change or modification the threshold parameter has to be carefully decided on.

3.3.2 QoE/QoS enforcement granularity

As introduced in [D5.1], QoE/QoS enforcement functions are responsible for dynamic and self-adaptive management of the resource based on derived application specific QoE targets in order to achieve good customer experience. Considering the management granularity or aggregation level of the proposed QoE/QoS enforcement functions, there are two options as illustrated in Figure-3-4 using deployment view of 5G NORMA architecture [D3.2]:

- In the first alternative, referred to as central QoE/QoS enforcement point, the traffics of all the user or service flows served by a given 5G access point or by multiple access points implemented in the same edge cloud is handled by the central QoE/QoS enforcement point. This deployment enables the QoE/QoS enforcement functions to optimize and enforce the QoE/QoS for multiple users jointly, including the possibility of differentiation among applications run by different UEs.
- In the second alternative, referred to as distributed QoE/QoS enforcement point, one QoE/QoS enforcement point/instance handles only the traffic of one user or service flow. This deployment option may be preferred in case of high mobility UEs so that frequent reconfiguration of centralized QoE/QoS enforcement point is not needed due to UE's mobility. In addition, the deployment option also enable the possibility to integrate QoE/QoS enforcement functions with other UE or service flow specific functions to have correct more insight information to facilitate QoE/QoS enforcement. However, this option may require an information exchange between different QoE/QoS enforcement instances handling the UE or service flows that are served by the same radio resources.

In the first alternative, the centralized QoE/QoS enforcement point is able to use and correlate all the measurements taken from each individual user or service flow for congestion detection as described in [D5.1]. Once the resource conflict or demand congestion is detected, the corresponding enforcement actions (e.g. either redistribution of available resources or degrade or even terminate/block some user or service flows) can be performed jointly by taking into account all the user or service flows managed by the centralized QoE/QoS enforcement point. Therefore, QoE/QoS is managed through a logically centralized scheduling of all manged traffic and each user or service flow gets a share from the total available capacity according to its needs, maximizing the number of flows served well and at the same time maintaining fully utilized resources.

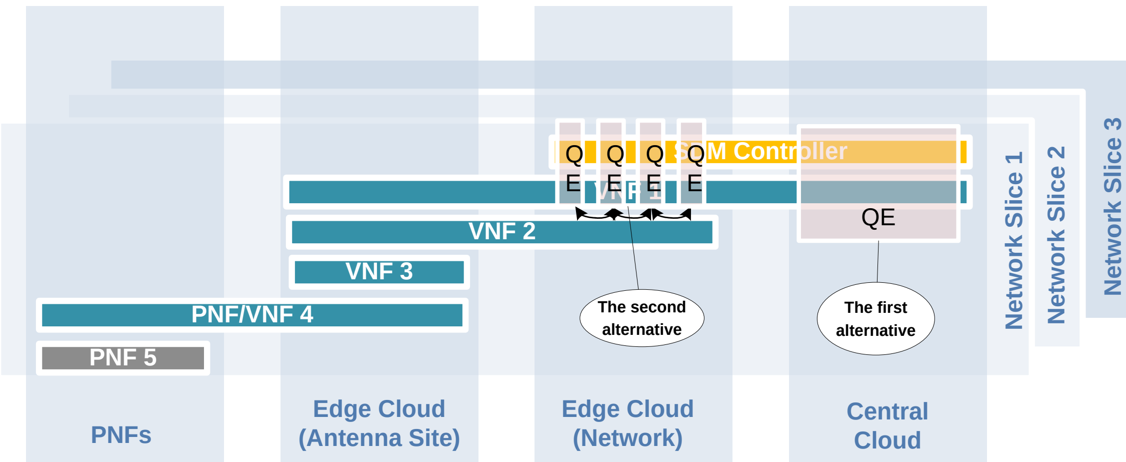


Figure-3-4: Illustration of the QoE/QoS enforcement alternatives on different granularity level

In the second alternative, each QoE/QoS enforcement point performs distributed system status (e.g., congestion) detection and executes individual actions as it has access only to user or service flow specific traffic and measurements. However, the individual enforcement instance measurements are still implicitly coupled with overall system status as their traffic are served by the same shared resource. Therefore, each instance would detect congestion caused by shared resources approximately at the same time. Additionally, each instance executes the same program upon detecting the same system status, which harmonizes their effect on the overall traffic mix. For instance, in case of congestion, the enforcement instances that handle user application or service flow with lower priority (e.g., best effort) or less throughput sensitivity (e.g., web browsing sessions with graceful degradation on resource shortage) would start acting first by gradually decreasing the scheduling rate of their own traffic. An enforcement instance with applications that are more sensitive to the change of the throughput (e.g., the media rate of the streaming video) would keep their scheduling rate intact longer at the level required by the application session targets, and coordinate with other instances (i.e., by means of SDM-X applications) that take actions on their traffic first. In the optimal case, the self-reduction of low priority traffic may be able to alleviate the load on the shared resources before the service level of important applications needs to be decreased. Therefore, the distributed enforcement instances can keep the QoE/QoS enforced through their individual actions.

However, in order to improve the effectiveness and efficiency of overall QoE/QoS management process, the second alternative may require the interface between individual enforcement instances to exchange congestion detection and resource profiling information. For example, if congestion detection information is exchanged among individual enforcement instances, the enforcement instances that control the best effort traffic can start to decrease the amount of data forwarded to the radio interface based on QoE/QoS degradation detected by an enforcement instance that handles an important application. As another example, if the enforcement instances also exchange the QoE/QoS targets and priorities of their traffic mix, the amount of traffic reduction at each instance required to resolve congestion can be even calculated explicitly and enforced in one step. Thus, different levels of distributed enforcement alternative can work as efficient and optimal as centralized alternative, but at the cost of more information exchange. So as a conclusion, 5G NORMA prefers the centralized approach.

PART 2: SOLUTIONS

1 Introduction

The second part of the deliverable provides a detailed view on several solutions that, by building on the functional architecture defined by Part I, improve the current state of the art. In order to have a consistent view on both the architectural aspects of WP5 and the devised technical solutions, we included them in the second part, avoiding the use of Annexes. As already done for D5.1, the goal is to keep the overall vision concise and compact, while the reader can refer to Part II for the technical details of the 5G NORMA system.

1.1 Objective and structure of Part II

The objective of Part II is to describe in details the several algorithms, protocols, techniques and evaluation framework that implements the functionality of the architecture defined in Part I. Some of those contributions were already described in a preliminary way in [D5.1], in this case we further extended them, providing in many cases quantitative evaluations. Other ones are new contributions that were not included in the previous version of the deliverable. Finally, we did not include in this document content that was already finalized in [D5.1].

Each contribution is thoroughly described, with a emphasis on how the key elements of the functional architecture described in Part I play a fundamental role towards the achievement of the final solutions. Each of the proposed solutions introduce novelty by either solving a problem by introducing one of the WP5 key elements or by demonstrating how enhanced functionality can be achieved with the introduction of elements such as SDM-C, SDM-X or SDM-O.

The second part of the deliverable is structured around three pillars that have been the main tasks developed in WP5:

- Section 2 describes the **Network Slices Orchestration** solutions, that tackle the problem of service aware orchestration involving the different modules of the SDM-O
- Section 3 focuses on **Network Slice QoE/QoS Control**: that is, how to apply SDM-C and SDM-X to provide the required KPIs to the different tenants and network slices. Also, architectures and performance assessments are described in this Section.
- Finally, we focus on one of the most important categories of SDM-C applications in Section 4: **Network Slice Mobility Management**. In this Section, we both emphasize the novelty of the SDM-C approach and provide further details of how this paradigm can be applied in this context.

1.2 Mapping to the functional architecture

Highlights of each specific contributions have been detailed in the introductory part of each subsection, explaining their detailed relationship with the overall functional architecture. Still, we provide here an overall view of the different solution described in the project and how they fit into the WP5 functional architecture described above.

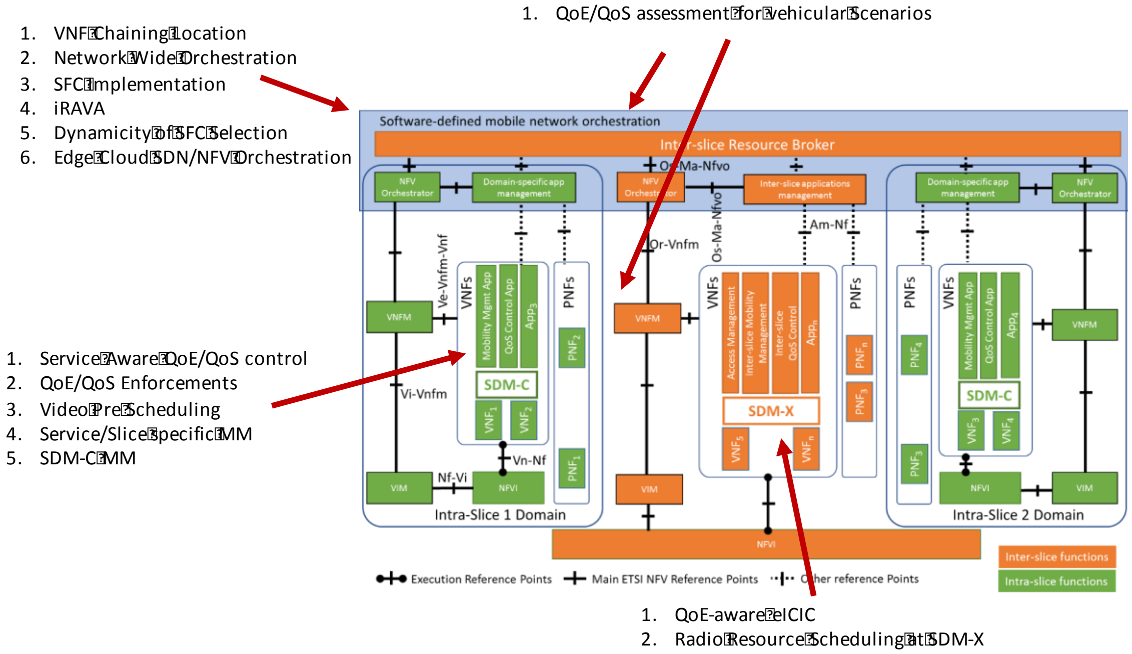


Figure-1-1: Mapping of the contributions of D5.2 to the WP5 functional architecture

The solutions described in this deliverable well span the extent of the WP5 functional architecture, considering very novel topics such as network sharing with SDM-X. We remark that several technical contributions were already presented in D5.1 and have not been included here for the sake of conciseness.

2 Network Slices Orchestration

How to properly consider the novel concept of network slicing during the orchestration process is an open issue that is currently being discussed in the major standardization 5G fora and the most prominent EU projects on 5G. In this Section, we describe some specific solutions for Network Function orchestration and Network Management in general. They all rely on the 5G NORMA enhanced controllers (more specifically SDM-O) and the MANO architecture jointly defined by WP5 and WP3. The topics addressed by these solutions cover a wide research area tackling both fundamental research problems and more practical aspects. We briefly summarize them next:

- We start with a theoretical analysis of how VNFs have to be orchestrated in Section 2.1 in which several optimization aspects are considered.
- Then, we move to more practical issues of how VNF orchestration may impact real deployment. In Section 2.2 and 2.3 we discuss how *i)* compounding VNFs into the same machine may improve the overall performance of the system and, *ii)* the impact of service aware orchestration algorithms on achieving the required KPIs associated to each slice.
- Section 2.4 discuss about RAVA, an algorithm for VNF re-orchestration due to QoS parameters. It takes a hybrid approach compared to the one described in Section 2.3.2, but it can be considered a necessary intermediate step from the current ETSI NFV MANO architecture and the 5G NORMA one.
- Standardization and migration paths and are in the scope of Sections 2.5 and 2.6. Specifically, Section 2.5 discusses about possible standards in the field of SFC, while Sections 2.6 provides a thorough argumentation on how the 5G NORMA Orchestration architecture, as described in Part I, can be implemented starting from the current architecture.

All these contributions have been disseminated as paper submissions or standards. More details can be found in the upcoming [D7.2]

2.1 VNF Chaining Location

2.1.1 Proactive Caching as a VNF Chain

Motivation and Problem Statement: Despite the fact that there has been a significant research effort placed on Network Function Virtualization (NVF) architectures over the last few years, little attention has been placed on optimizing proactive caching when considering it as a service chain. Since caching of popular content is envisioned to be one of the key technologies in emerging 5G networks to increase network efficiency and overall end user perceived quality of service we explicitly consider the interplay and subsequent optimization of caching based VNF service chains. This can be considered as an extension of the previous work reported in [D5.1] where the focus has been placed on chaining and optimizing application agnostic VNF chains by taking into account mobility. To this end, we detail a novel mathematical programming framework tailored to VNF caching chains and detail also a scale-free heuristic to provide competitive solutions for large network instances since the problem itself can be seen as a variant of the classical NP-hard multi-dimensional binpacking problem.

Within the NFV framework, an end-to-end network service (e.g., rich voice/data) is described by an VNF forwarding graph, where a number of VNFs (possibly distributed in various physical nodes in the network) need to be visited in certain predefined order. To be more precise, the sequenced VNFs of a service request form a service chaining as the service flow passes through an ingress or egress point in a virtual network device. An illustrative example of such service chain is shown in Figure-2-1, where caching is considered as one of the VNFs that constitute the overall service chain; these VNFs might be located in different nodes in the network. Our aim is to consider caching and the other possible VNFs that might be required for the service in an integrated manner in order to increase network efficiency.

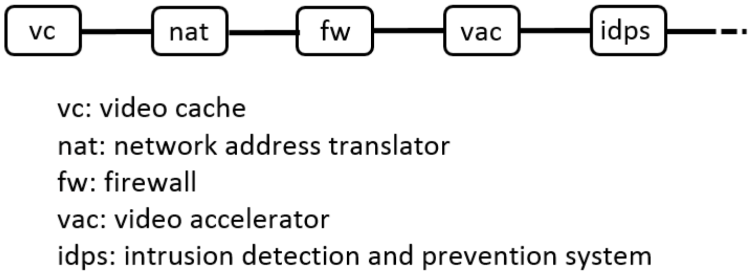


Figure-2-1: An example of caching as a VNF chain

Undoubtedly, among different VNFs, it is expected that caching would emerge as one of the potential key network elements to be supported in emerging and future wireless/mobile networks. Viral and popular video streams dominate aggregate mobile Internet traffic[3] and it is an application well suited to various different caching strategies. Most video traffic relates to over-the-top (OTT) video content providers (CP) such as for example YouTube, Vimeo and NetFlix. According to predictions from CISCO it is expected that the world's mobile data traffic will reach 30.6 monthly exabytes by 2020 and from this overall volume approximately 75% will be video.

In that respect, caching of popular content deserves paying a special attention in terms of VNF hosting location and chaining. Caching can play a key role in decongesting the backbone network of an operator especially in times of congestion episodes. Hence, caching on the edge of the network (edge computing) together with a number of other VNFs that might need to be visited for a requested cached content need to be considered jointly to optimize network performance. This is because in the most general case, a cached content must be visited before other VNFs can be applied and this service flow might originate from different possible network locations depending on the caching strategy. Hence, the service does need to reach a gateway node but can originate at a node that host the required cached content (which can be topologically close to the end user). Therefore, the location of caches in a VNF service chain, greatly affects the overall VNF chain orchestration as well as the aggregate traffic dynamics in the network, since links of higher aggregation (deeper in the network) can reduce their utilization levels. However, efficient caching in mobile networks can be deemed as a highly challenging task since the optimality of the cache locations are dependent on the movement/mobility patterns of the users. Notably, to significantly reduce access delays to highly popular content caching content close to the end user without considering the effect of mobility might lead to degradation of performance. In this case, caching popular content closer to the end user might inevitably require more frequently changes of the cache location to keep providing optimal performance. In this case, the caching location and the associated VNF chaining need to be jointly considered to avoid sub-optimal cases, especially under congestion episodes where performance can be significantly affected. To summarize, the focus and motivation of the contribution is on enhancing proactive caching policies by taking into account the whole VNF chain.

2.1.2 Related Work

An overview of the challenges emerging in virtual network function scheduling is presented in [Riera]; in this work the authors explain the application of SDN and NFV technologies with the

[3] Mobile video traffic accounts for 60 percent of total mobile data traffic according to the CISCO Global Mobile Data Traffic Forecast Update that has been released in February 2017.

emphasis placed more on backbone networks. In terms of caching there has been recently a significant amount of work. A caching scheme suitable for mobile networks that takes into account user mobility has been proposed in [Han] where the idea is to predict the mobility pattern of users and opportunistically cache content along the predicted path of users. A scheme that pro-actively cache content using transportation and focusing on video content has been presented in [Kanai]. The idea is to utilize the almost deterministic mobility of users in transportation systems such as trains to proactively cache popular content that the users might request upon their arrival. The ideas on proactive caching detailed hereafter resemble more closely the work in [Zheng] which propose a set of mobility-aware caching schemes (these research work was also part of D5.1).

However, none of previous research works make caching decisions on a view of the whole service chain. To the best of our knowledge this is the first work to consider in an explicit and integrated manner proactive caching as part of a VNF chain. In most practical cases, this simple cache moving could lead to inefficient routing of a mobile user to receive a service. Figure-2-1 gives an example of the inefficient routing problem where firewall as a VNF must also be visited and only cache is moved[4]

It is apparent that, in order to improve the mobility support of SDN-enabled networking, other NFs on a same VNF service chain must also be moved, with the decision of caching. A close related work can be found in [Riera] which aims to assign VNFs into given SDN-enabled networks. However, it does not take routing and location of VNFs into consideration.

2.1.3 Network Modelling for Proactive Caching and VNF Chaining

A mobile network is modelled as an undirected graph **G**=(**N, E**}), where **N** denotes the set of nodes in the network and **E** denotes the set of links in the network. By **F**, we denote the set of VNFs and f_i represents the specific VNF i. Each f_i, if activated, consumes/requires some physical resources (i.e., CPU cycles, DRAM memory). We uniformly describe these resource requirements as a single column matrix u_i, meanwhile, the amount of available resources of node k, which is able to host VNFs, is denoted using the single column matrix U_k.

The term "chain" in the so-called service chaining represents the different middleboxes that the service should traverse, with a specific order, across the network using software provisioning. This is the case under the proposed NFV architecture, where new services and/or network slices can be instantiated as software-only, running on commodity hardware on top of virtual machines or containers. To provide a service request $r \in$ **R** (with **R** we denote the set of requests that were accumulated arriving within a predefined fixed time slot) for a mobile user and/or tenant, a network function forwarding graph (VNF-FG) needs to access a set of corresponding VNFs that are visited in a pre-defined order (which the VNF orchestrator should preserve). Hereafter, we consider a service request r as the set r= (f_1, f_2, ..., f_i) where the sequence express the visiting order of the different network functions f_i.

For mathematical modelling simplification reasons, the corresponding relationship of a VNF and its order in a request can be represented by a binary matrix V_{ril} as follows,

$$V_{ril} = \begin{cases} 1 & \text{if the } l^{th} \text{ NF of request } r \text{ is NF}_i. \\ 0 & \text{otherwise.} \end{cases}$$

We define a candidate node set **K** (which is a subset of the set of nodes **N**) that consists of the potential candidate nodes of hosting VNFs. By **D**, we define a set of potential destinations that

[4] NF movement in this document refers to any approach that occurs the change of the function's location. (e.g., proactive caching)

mobile users might move due to their inherent mobility. At this point it worth to be mentioned that using historical data which are readily available to mobile network providers it is feasible to estimate such probabilities of end users moving from their current location to an adjacent candidate destination node d. We denote this probability of changing their serving access router as ρ_d. As eluded, we assume that ρ_d is predefined by using available historical data from operators so this assumption can be deemed as realistic due to vast available data which can provide accurate characterization of user mobility patterns. With known candidate cache locations, which can be done using for example a proactive caching technique such as for example the one presented in [4], the proposed framework aims to proactively place requested network functions (f_i) into the set of nodes **K**. To be more precise, we define by **Sr** to be the set of initiating nodes (i.e., the proactive caching locations) of a service chain r, and with **H** we denote the set of **Sr** for all requests to be considered. Given the sets **H, D**, the requirements per request r and the available network resources the proposed scheme returns the optimal proactive allocation of the VNFs that minimizes the joint cost of routing, location and chaining.

Based on the previously described network settings we define the following binary decision variables,

$$x_{ri}^{k} = \begin{cases} 1 & \text{if NF}_i \text{ is placed at } k \text{ for request } r. \\ 0 & \text{otherwise.} \end{cases}$$

$$y_{ri}^{ksd} = \begin{cases} 1 & \text{if NF}_i \text{ of request } r \text{ with head } s \text{ and} \\ & \text{destination } d \text{ is visited from } k. \\ 0 & \text{otherwise.} \end{cases}$$

The optimal VNF location and chaining for the proactive caching problem is defined as the following non-linear integer optimization problem,

$$\text{S.t.} \quad \sum_{r\in\mathbf{R}}\sum_{i\in\mathbf{F}} u_i x_{ri}^{k} \leq U_k, \forall k \in \mathbf{K}$$

$$\sum_{k\in\mathbf{K}}\sum_{i\in\mathbf{F}} V_{ril} y_{ri}^{ksd} \geq 1,\ \forall r \in \mathbf{R}, s \in \mathbf{S_r}, d \in \mathbf{D},$$
$$l = 1, \dots L$$

$$y_{ri}^{ksd} - x_{ri}^{k} \leq 0, \forall r \in \mathbf{R}, i \in \mathbf{F}, k \in \mathbf{K}, s \in \mathbf{S_r}, d \in \mathbf{D}$$
$$x_{ri}^{k} \in \{0,1\}, \quad \forall i \in \mathbf{F}, k \in \mathbf{K}$$
$$y_{ri}^{ksd} \in \{0,1\}, \quad \forall r \in \mathbf{R}, i \in \mathbf{F}, k \in \mathbf{K}, s \in \mathbf{S_r}, d \in \mathbf{D}$$

where C_i^k is the cost of placing VNF fi at node k. While P_{sk}, P_{km} and P_{kd} are the shortest path routing costs between the candidate nodes. The first set of constraint bounds the resources that can be consumed by each VNF fi in every node. The next set of constraints enforce that each VNF in a requested chain must be visited at least once. Following those we include the binding constraints that insures the availability of a VNF at a node is valid only when the VNF is hosted at the specific node. Note also that the first term of the objective function is the placement cost of hosting VNFs at a node. The rest of the terms in the objective function reflect the accumulative routing cost of each hop on the VNF-FG of a requested chain. To linearize the optimization problem, we replace the product of binary decision variables $y_{ri}^{ksd}\ y_{rj}^{msd}$ with an auxiliary variable z_{rij}^{kmsd}, which is defined as follows,

$$z_{rij}^{kmsd} = \begin{cases} 1 & \text{if request } r \text{ with head } s \text{ and destination } d \\ & \text{visits NF}_i \text{ at node } k \text{ and NF}_j \text{ at node } m. \\ 0 & \text{otherwise.} \end{cases}$$

Based on the above, the previous defined optimization problem is converted to an integer linear programming problem shown as follows,

$$\min_{x_{ri}^k, y_{ri}^{ksd}} \sum_{r\in\mathbf{R}}\sum_{k\in\mathbf{K}}\sum_{i\in\mathbf{F}} C_i^k x_{ri}^k + \sum_{r\in\mathbf{R}}\sum_{s\in\mathbf{S_r}}\sum_{d\in\mathbf{D}}\sum_{k\in\mathbf{K}}\sum_{i\in\mathbf{F}} \rho_d P_{sk} V_{ri1} y_{ri}^{ksd}$$

$$+\sum_{r\in\mathbf{R}}\sum_{s\in\mathbf{S_r}}\sum_{d\in\mathbf{D}}\sum_{k,m\in\mathbf{K}}\sum_{i,j\in\mathbf{F}}\sum_{l=1}^{L-1} \rho_d P_{km} V_{ril} V_{rj(l+1)} z_{rij}^{kmsd}$$

$$+\sum_{r\in\mathbf{R}}\sum_{s\in\mathbf{S_r}}\sum_{d\in\mathbf{D}}\sum_{k\in\mathbf{K}}\sum_{i\in\mathbf{F}} \rho_d P_{kd} V_{riL} y_{ri}^{ksd}$$

$$\text{S.t.} \sum_{r\in\mathbf{R}}\sum_{i\in\mathbf{F}} u_i x_{ri}^k \le U_k, \forall k \in \mathbf{K}$$

$$\sum_{k\in\mathbf{K}}\sum_{i\in\mathbf{F}} V_{ril} y_{ri}^{ksd} \ge 1,\ \forall r\in\mathbf{R}, s\in\mathbf{S_r}, d\in\mathbf{D},$$
$$l = 1, \ldots L$$

$$y_{ri}^{ksd} - x_{ri}^k \le 0, \forall r\in\mathbf{R}, i\in\mathbf{F}, k\in\mathbf{K}, s\in\mathbf{S_r}, d\in\mathbf{D}$$

$$z_{rij}^{kmsd} \le y_{ri}^{ksd}, \forall r\in\mathbf{R}, i\in\mathbf{F}, k\in\mathbf{K}, s\in\mathbf{S_r}, d\in\mathbf{D}$$

$$z_{rij}^{kmsd} \le y_{rj}^{msd}, \forall r\in\mathbf{R}, j\in\mathbf{F}, m\in\mathbf{K}, s\in\mathbf{S_r}, d\in\mathbf{D}$$

$$z_{rij}^{kmsd} \ge y_{ri}^{ksd} + y_{rj}^{msd} - 1, \forall r\in\mathbf{R}, i,j\in\mathbf{F}, k,m\in\mathbf{K}$$
$$s\in\mathbf{S_r}, d\in\mathbf{D}$$

$$x_{ri}^k \in \{0,1\},\quad \forall i\in\mathbf{F}, k\in\mathbf{K}$$

$$y_{ri}^{ksd} \in \{0,1\},\quad \forall r\in\mathbf{R}, i\in\mathbf{F}, k\in\mathbf{K}, s\in\mathbf{S_r}, d\in\mathbf{D}$$

$$z_{rij}^{kmsd} \in \{0,1\},\quad \forall r\in\mathbf{R}, i,j\in\mathbf{F}, k,m\in\mathbf{K},$$
$$s\in\mathbf{S_r}, d\in\mathbf{D}$$

Note in the above formulation the additional binding constraints in order to ensure that the new auxiliary variable z_{rij}^{kmsd} takes the same value with the product of variables y_{ri}^{ksd} and y_{rj}^{msd}.

2.1.4 A scale Free Heuristic Algorithms

The Proactive Chaining-Caching (PCC) problem falls within the family of NP-hard problems since it resembles a generalized bin-packing problem and as a result heuristics, becomes the only viable option of finding competitive feasible solutions for real time operation under realistic topologies and size of VNF requests. Therefore, we present three heuristic approaches for finding caching points and VNFs allocations that ponder features including user mobility, network capacity utility and request importance. Nevertheless, the presented schemes differ in the performance of obtaining lower routing cost and the ability of providing smaller pro-active service missing rate.

First, we propose Probability-prior proactive caching chaining (PPCC) which aims at minimizing the overall network traffic cost with the awareness of end user mobility. Based on user moving trend, PPCC places VNF chains between a pro-active caching point and the potential user moving destination that with highest d. The second algorithm, hereafter called Shortest Path Based Allocation (SPBA) also allocates caching as well as VNFs along the shortest path from pro-active caching points to serving access routers but without taking user mobility into consideration. The SPBA is presented as a mobility unaware baseline where allocation decision is made by assuming the current accessing node is the permanent destination. Finally, in the last algorithm, henceforth called All in Gateway (AGW), hosts all content caches and VNFs at the network gateway. With a straightforward decision, AGW shows a lower bound on the network traffic cost performance, in which no optimization techniques are applied.

Probability-prior proactive caching chaining (PPCC)

In order to handle end user mobility feature, we propose PPCC approach in which caching and VNF chains allocations are decided based on user moving trend. In particular, the main philosophy of the proposed PPCC heuristic is to create a set of candidate pro-active caching points for each possible visited access router and then weighted by the probability of visiting each access router and explore node combinations for creating the service chains. This approach is highly efficient when the user movement is predicable such as for example in the case of public transportations. The pseudo-code of the PPCC scheme is shown in Figure-2-2 below

1) For any request r, select the target node $d \in \mathbf{D}$ by highest ρ_d and find the closest starting node $s \in \mathbf{S_r}$ by minimum shortest path routing cost P_{sd};
2) On the shortest path from the selected s and d, find all candidate nodes by $\mathbf{K}$;
3) Choose the closest k from the selected s on the path to host the NF_i with the lowest visiting order sequence in request r if there are enough resources to support the function, otherwise, host the sub-lowest function, until running out of resources;
4) Repeat step 2 and 3 until all NFs of request r are hosted.

Figure-2-2: Pseudo-code of the PPCC scheme

In step 3, depending on different consideration of the features of network capacity utility and request importance, PPCC also provides two sub modes, namely, PPCC node first mode and PPCC function first mode, which are denoted as PPCC-k and PPCC-f respectively. In PPCC-f, step 1,2 and 4 are identical to PPCC-k. However, Step 3 will be as follows: "Choose the VNFi with the lowest visiting order sequence in request r to host in the closest k from the selected s on the path if there are enough resources to support the function, otherwise, host in the subclosest node, until the last node". In short, the main principle of PPCC-k is making use of the network capacity by risking VNF visiting order. While PPCC-f ensures the serving quality for a set of requests by over using some network resources.

Shortest Path Based Allocation (SPBA)

Similar to PPCC, SPBA moves towards the same objective of minimizing the network traffic routing cost. The distinction between it and PPCC is that SPBA calculates the allocation solution without the requirement of knowing the end user mobility trend. Accordingly, SPBA creates a set of candidate pro-active caching points for the original access router and then explores node combinations for creating the service chains. The pseudo-code of the SPB3 scheme is shown in Figure-2-3 below.

1) For any request r, select node o and find the closest starting node $s \in \mathbf{S_r}$ by minimum shortest path routing cost P_{so};
2) On the shortest path from the selected s and o, find all candidate nodes by $\mathbf{K}$;
3) Choose the closest k from the selected s on the path to host the NF_i with the lowest visiting order sequence in request r if there are enough resources to support the function, otherwise, host the sub-lowest function, until running out of resources;
4) Repeat step 2 and 3 until all NFs of request r are hosted.

Figure-2-3: Pseudo-code of the SPBA scheme

Finally, as a baseline scenario we assume the so-called 'all-in gateway' (AGW) scheme which places all the requesting VNFs and content caches at the network gateway. As a result, all benefits of using proactive caching techniques are lost. Moreover, with a mass of VNF entities running on the network gateway, the network resources of the gateway become the bottleneck.

2.1.5 Evaluation

In this section, we provide a wide set of numerical investigations to evaluate the performance of proactive chaining-caching problem under various network scenarios. The applied random networks are composed by a range of 10 to 20 candidate VNF hosting nodes and each candidate node has a degree ranged from 2 to 5. Besides, the number of starting points and destination points are set from 1 to 5. We assume that, the number of accumulated arriving requests in a time slot is from 5 to 20, and the number of different VNFs is randomly selected from 1 to 5.

The moving probability to each destination node is randomly generated between 0 and 1, notice that, the summation of the moving probability to each destination of a mobile user does not exceed 1. With the aim to make VNF placement consider routing mostly, the VNF placement cost is set as 0. While, the shortest path routing cost can be any linear function of the traffic flows on the link, i.e., a delay, reliability, congestion, or energy metric. Without loss of generality, we choose the Open Shortest Path First (OSPF) or Enhanced Interior Gateway Routing Protocol (EIGRP) like routing metric in the simulation. To maintain the link diversity, we normalize the routing metric in the range from 1 to 100. In terms of physical resources of candidate VNF hosting node, we assume that each candidate node has 2 GByte memory capacity and 16 virtual CPU cores. While each VNF consumes memory in a range from 10 to 50 MByte and use 0.5 to 1 cores. The results are obtained by averaging 100 Monte Carlo simulations.

The proposed scheme is compared with two baseline schemes. In the first one, which provide a lower bound on the performance, content caching and VNFs are hosted at the network gateway, namely, AGW. The second scheme allocates caching as well as VNFs along the shortest path from the gateway node to the serving access router without considering mobility, and is as detailed in the previous section is entitled as the Shortest Path Based Allocation (SPBA) algorithm.

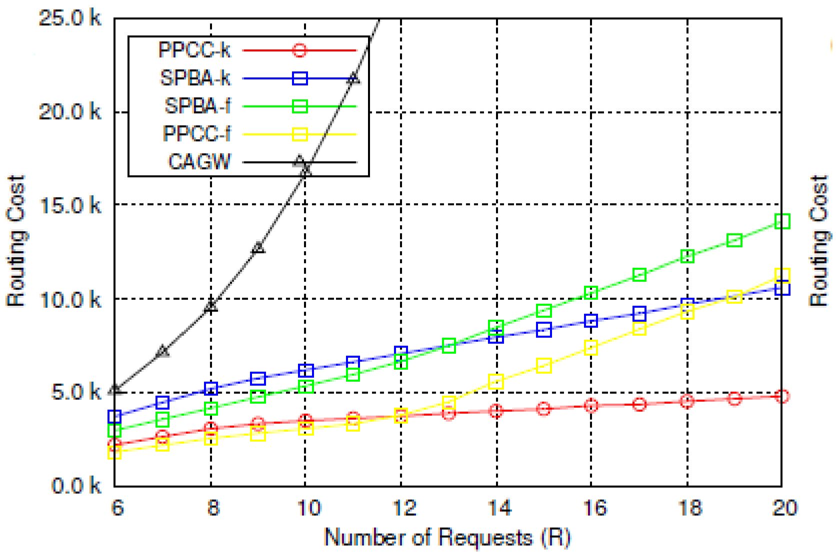


Figure-2-4: Routing performance of the proposed schemes with different number of nodes in the network. (assuming that K=20)

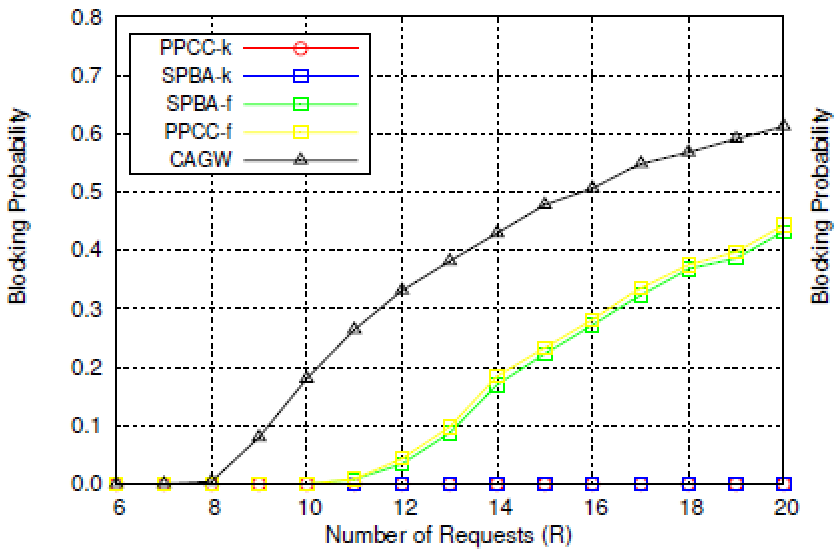


Figure-2-5: Blocking performance of the proposed scheme with increased number of service requests in the network. (K=20)

Figure-2-4 and Figure-2-5 provide a glimpse on the performance aspects of the different algorithms detailed. Figure-2-4 depicts the routing performance of the different proposed schemes with different number of nodes in the network, whilst Figure-2-5 shows how the probability of having a request blocked (due to resource unavailability) grows with the number of service requests for the different schemes. As expected the upper bound on the blocking probability performance will be the one from the capacitated version of the AGW scheme. Also note that for the other the k-mode performs better than the f-mode in terms of blocking. This should be expected since the f-mode excessively place the VNFs among the cache destination path for ensuring the routing performance of a selective set of requests. In general and with respect to mobility, the proposed PPCC scheme could reach over 75% gains compared to the other techniques

2.1.6 Summary

In this section, the rational of VNF location and chaining for proactive caching has been presented together with some key observations on this problem and the general principle of optimizing cache specific VNF service chains. Based on those preliminaries an optimization framework using integer linear mathematical programming has been detailed that integrates VNF chaining for proactive caching. In addition, since the problem resembles the multi-dimensional bin-packing problem, which is NP-hard, a scale-free heuristic algorithm has been presented that can be applied in large network instances amenable for real time implementations. Finally, the attainable performance of the proposed proactive caching service chains schemes was investigated under different network settings.

2.2 Network-wide Orchestration

It is often said [WOLF] that success of the IN architecture will largely depend on the success of network-wide service management. This concept of network-wide orchestration is associated with the replacement of the individual device configuration by a more powerful network services management mechanism able to provide network-wide services definition, configuration, deployment and monitoring. Using network-wide orchestration services are not deployed, configured and managed in a node-by-node fashion as it is originally done in legacy systems, but using higher-level abstractions and automated procedures to deploy and configure each single component of the whole network service at once.

The main advantage of this network-wide orchestration is that it gives a single point of integration, providing a centralised representation of the distributed network no matter the number of resources involved or where they could be physically placed. This provides great opportunities for accessing KPI measurements and automation, opening up possibilities for the deployment of advanced services across the entire network domains. In this way, the inherent complexity of deploying and managing complex and feature-rich services can be simplified by automating the underlying configuration and monitoring tasks from the orchestration module. For example, a complex distributed network service composed of multiple VNFs, PNFs, network links connecting different clouds and a number of KPIs to be monitored could be automatically deployed and managed from the orchestrator and treated as a single entity (a Network Service) in the network.

In 5G NORMA network-wide orchestration is performed at two different levels:

- Inter-slice orchestration, dealing with the orchestration of resources to conform the different network slices in the network.
- Intra-slice orchestration, referring the orchestration of resources into the network slices

In the following subsections, we describe in more detail these two different levels.

2.2.1 Inter-slice orchestration

Inter-slice orchestration is performed by the 5G NORMA specific SDM-O component (see Section 2.2.1). As a whole, inter-slice orchestration is commonly understood to provide the necessary mechanisms for sharing different NFs among the multiple slices in the network; however, in 5G NORMA, this sharing of resources is just limited to those resources which are not possible to split in individual pieces that could be assigned to the different slices in an isolated way, i.e., normally those common resources in the RAN which are controlled by the SDM-X component. The rest of the components, uFigure-2-6p to the MANO layer in the 5G NORMA architecture, are susceptible to be part of individual slices.

Let's recall here how slicing is managed in 5G NORMA. As we see in Figure-2-6 below, the whole InP architecture (NFVI-0) is sliced according to quotas assigned to the different tenants, in such way that certain subsets of this whole infrastructure (NFVI-1…NFVI-n) are assigned to the different slices (i.e., a complete ETSI NFV MANO stack is assigned to each slice, assigning resources in the NFVI-0 area to the different tenants according their SLA).

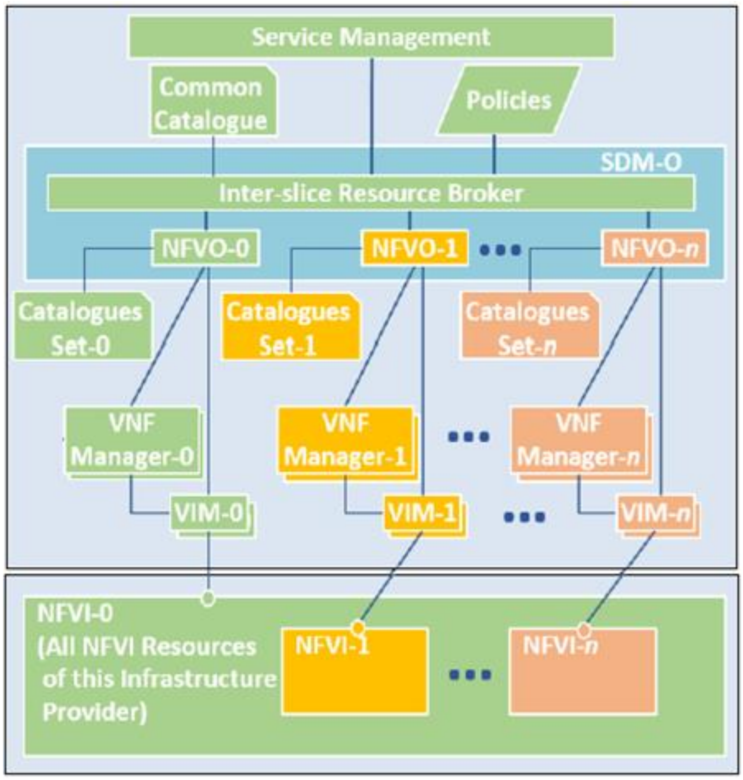


Figure-2-6: Simplified 5G NORMA MANO architecture

So, the functionality of the SDM-O is basically limited to create and maintain the different slices according the tenants' requirements. Each slice will be created according specific quotas that will be stablished from the beginning in the SLAs signed by tenants and InP, and those quotas won't change until a new SLA is signed again. This means that inter-slice orchestration is not expected to be a very dynamic process in which resources should be quickly moved from one slice to another. The only dynamic orchestration process that we consider is perhaps the reconfiguration of certain parameters in the RAN shared resources or in some specific shared PNFs.

Instead of dynamism, we consider it is much more important to provide the tenants their own *isolated* slices with a well-defined set of resources and behaviour, and with the assurance that those resources will not be assigned to other tenants using the infrastructure; we consider it wouldn't be acceptable for a tenant that some infrastructure resources assigned to him by means of an SLA could be temporally assigned to a different tenant just because that second tenant could be experiencing a lack of resources. The view of the network for each tenant is its own slice (or set of slices); each tenant is paying for the resources assigned to its slices, so initially, there is no justification to dynamically move resources from one slice to another (even if one tenant has a lack of resources while another has resources to spare). The only exception to this could be a tenant owning different slices; in this case that tenant could request to share resources among those slices belonging to him (this could be specified in the SLA). As a whole, although this resource reservation policy based on quotas could reduce potential multiplexing benefits, we consider for the tenants is more beneficial to have a fixed, well defined and stable framework assigned to them.

So, although the functionality of the SDM-O is *just* limited to instantiate and maintains the different slices according the tenant requests, this is not a minor task; it comprises the following:

1. Slice instantiation, receiving from the OSS/BSS blocks a package (or set of packages) containing the software components and information elements to create each new slice; this package should contain:
    - The software packages of the different functional blocks composing the slice. This comprises:
        - VNFs in the slice
        - ETSI MANO components in the slice (NFVO, VNFM, VIM and corresponding catalogues).
    - Slice Descriptor file(s). This could be provided using a general purpose information-exchange language (e.g., XML, JSON, YAML…). It should be a kind of a programmatic definition of the SLA signed by the InP and the tenant requesting the deployment of this slice. Among others, it should declare:
        - The different building blocks forming the slice,
        - The configuration for each one,
        - Interconnection among them (different topologies and NFs forwarding graphs to implement the services).
        - Monitoring parameters,
        - Behavioural policies (e.g., scaling, sharing of resources…),
        - QoE/QoS service requirements,

This file should also declare the configuration parameters for the network slice shared elements (e.g., the MAC scheduling parameters in the RAN). Also, the configuration parameters for the

PNFs in the slice if any and configuration of the different ETSI MANO components in the slice[5].

This descriptor file should also contain the Network Service Descriptors for those services deployed on the slice. Those descriptors will be just propagated to the corresponding NFVO once it is instantiated for the slice, in order to implement the corresponding intra-slice orchestration mechanisms once the slice is fully deployed.

The communication between the OSS/BSS blocks and the SDM-O to implement this would be performed using the '5GN-Os-Ma-Sdmo' reference point (see figure 2-12 in section 2.2.1).

2. ETSI MANO components lifecycle management[6]; this includes:
    - Instantiation; i.e., instantiation of the whole ETSI MANO stack components for the slice (NFVO, VIM, VNFM and so on).
    - Slice instance update (e.g., to update certain configuration parameters in the VIM deployed in the slice).
    - Slice instance query (e.g. retrieving usage information about the deployed VNFM).
    - Slice instance termination.

Note that we don't consider scaling operations as part of this life-cycle management, since as a general rule, scaling will be performed as an update operation after a new SLA is signed between the InP and the tenant.

3. Receive and process control commands from the SDM-C/X control modules requesting re-orchestration for specific slices (see sections 2.1.1 and 2.1.2). The SDM-O should be able to properly process those requests and apply the re-orchestration measures to the corresponding slice. Although re-orchestration doesn't normally imply re-assignment of resources among slices, the IS-RB in the SDM-O should be able to process and propagate the requests towards the corresponding NFVO.
4. Forwarding of relevant events, performance measurement results and accounting and usage records towards the OSS/BSS blocks.
5. Policy management and/or enforcement for the Slice (authorization, accounting and access control, resource reservation/placement/allocation, etc.).

As a summary, by means of the inter-slice orchestration mechanism described here, the infrastructure providers can combine and jointly manage large-scale resources to simultaneously serve multiple tenants assigning different quotas to them. This is mainly performed by the SDM-O component, which determines the MANO components, NFs and resources (both computational and networking-related) that must be included in a network slice according the agreement between InP and tenants shaped in an SLA. The SDM-O also processes re-orchestration requests from the SDM-C/X control blocks in order to make possible, among others, QoE/QoS service aware management.

The SDM-O provides the '5GN-Os-Ma_Sdmo' reference point to communicate with external entities, and to provide a single access point for orchestrating the whole infrastructure. This reference point could be used to implement high-level interfaces such as GUIs, automatization engines, performance monitors or other, that could be used to ease the monitoring and control of the different slices deployed on the network.

[5] Recall that in 5G NORMA a complete ETSI MANO stack is deployed for each slice.

[6] VNFs life-cycle management is performed as part of the intra-slice orchestration process.

2.2.2 Intra-slice orchestration

As mentioned before, the SDM-O deploys a specific NFVO component for each slice in order to implement the specific intra-slice orchestration tasks. This NFVO block is the same as the one defined in the ETSI MANO framework [MANO], and communicates with the external OSS/BSS systems using the 'Os-Ma-Nfvo' reference point through the slice-specific Application Management block and the Inter-Slice Resource Broker component (see Figure 2-12 in Section 2.2.1).

So, 5G NORMA delegates in the ETSI MANO NFVO component for the intra-slice network orchestration tasks. As the ETSI NFV MANO framework defines, the NFVO is in charge of the network orchestration and management of NFV resources (infrastructure and software) [ETSI_GS_NFV], but in this case, applied to each single slice. Basically, the NFVO operates, manages and automates the NFVI associated to its own slice, helping to deploy, manage and configure the different NFV service topologies on that NFV Infrastructure, having control and visibility of all VNFs running inside the NFVI quota assigned to that slice.

Since services are defined per slice, the service orchestration is resolved at this intra-slice level; i.e., the intra-slice orchestration mechanism is the responsible to transform the slice specific SLA parameters (received from the IS-RB for each slice) into the corresponding network service. But in this case, the orchestration process is not as static as the inter-slice orchestration process described before; on the contrary, here we need quick and dynamic adaptation of the service to different load situations or to fulfil the agreed QoE/QoS requirements. For this, besides the regular life-cycle management and control mechanisms, the application of actions such as scaling the different VNFs, re-route traffic among them or updating the VNF-FG in a rapid and adaptive manner is expected to be performed. So, main functions performed at this orchestration level are focused to adapt the service to the current system and load situations; this can be performed in the following ways:

- Scaling up/down/in/out individual NFs;
- Restructuring a NS graph;
- Modifying the placement of functions
- Rerouting traffic to or between different instances of such functions,

The trigger to perform these re-orchestration actions comes from the 5G NORMA control blocks (SDM-C and SDM-X), and is propagated by the IS-RB to the appropriate NFVO in the corresponding slice.

Low level resources orchestration (i.e., connectivity, compute, and storage resources) across multiple network functions is performed at this level also. For this case, the NFVO delegates on the VNFM and VIM as it is defined in the ETSI NFV MANO framework.

The NFVO is accessed from the Domain Specific Application Management for each slice through the 'Os-Ma-Nfvo' reference point. This specific Application Management is available for each slice through the IS-RB in the SDM-O, so each tenant can access to manage their slices from their corresponding OSS/BSS systems (using the '5GN-Os-Ma-Sdmo' reference point for that).

The NFVO available operations are those already defined for the 'Os-Ma-Nfvo' reference point; that is:

- NS Descriptor and VNF packages management.
- NS instances lifecycle management (instantiation, termination, scaling, query and update).
- VNFs lifecycle management.
- Policy management and/or enforcement for Network Service instances, VNF instances and NFVI resources.

- Querying relevant Network Service instance and VNF instance information

Forwarding of relevant events, accounting and usage records and performance measurement results.

Integration of PNF

One of the major challenges regarding intra-slice orchestration is the integration of virtual network functions (VNF) together with physical network functions (PNF). In real deployments, it is common that NFV-based network functions need to co-exist with legacy non NFV-based NFs (this can include PNFs, and also, logical NFs that are not NFV-based). This integration is also assumed to be performed on a network wide basis, so integration crosses the boundaries between NFV-based and non-NFV based functions.

To integrate PNFs the ETSI NFV MANO specification already includes a specific descriptor called A Physical Network Function Descriptor (PNFD), which describes the connectivity, interfaces and KPIs requirements of Virtual Links attached to Physical Network Functions. This descriptor is used when it is necessary to incorporate physical devices as part of a Network Service. However, the ETSI NFV MANO specification does not explain how or where this PNFD is on-boarded, because it is assumed that this is out of scope regarding NFV. In 5G NORMA we are not considering this in detail either, although we consider it is a potential area for further research.

2.3 SFC Implementation Options and Management Aspects

A common way for implementing the Service Function Chain - SFC (further also referred to as Network Function Chain - NFC) is to have a dedicated virtual machine (VM) for each running chained network function. Such **classical SFC** design offers high flexibility in chaining the elements that constitute the network function. On the other hand, this implementation approach results in higher latency due to the chaining overhead between VMs. As for many 5G applications the latency is extremely critical the 5G NORMA considers and evaluates an alternative option for SFC implementation in order to increase the efficiency of network function chaining. The novel SFC approach considered in 5G NORMA is based on the implementation of entire SFC in a single VM, i.e. **compound SFC** implementation. The compound SFC aims at optimization of placement and colocation/combination of SFC building blocks in order to minimize the latency introduced by the SFC implementation. The compound SFC is thus not contradicting the idea of flexible decomposition of network functions, but it aims at optimizing the placement and implementation of such decomposed NF building blocks. We evaluate the compound SFC implementation especially in terms of latency between network functions and the impact of limited computing resources on the maximal executable load. In the following we give the description of the compound SFC approach, its performance evaluation compared with classical SFC approach, as well as associated control and management aspects within 5G NORMA architecture.

2.3.1 Compound SFC implementation and evaluation setup

The novel approach that is evaluated within 5G NORMA, i.e. **compound SFC** combines a SFC inside one virtualized environment (e.g. VM or container). By this means, there is the potential of reducing the latency introduced due to communication between VNFs. However, the requirements of the individual NFs/SFs need to be taken into account when composing the compound SFC. These requirements have to be translated into resource restrictions of the VMs.

Essentially, the evaluation of the compound SFC approach needs to answer two questions:

1. Can the chaining overhead (expressed by latency when routing from one SF to another SF) be reduced by the compound SFC design and to what extend?

2. Does the combined implementation of SF introduce limitations for the performance by different SF competing for same resources (like CPU cache)?

The first question aims at evaluating a potential reduction of the virtualization overhead of the classical SFC design by using the novel approach of compound SFC. The second question focusses on investigating the restrictions of the compound SFC approach in terms of resource contention by different SFs that are chained together.

In order to evaluate and compare the classical and the compound SFC approaches, both scenarios (classical and compound SFC approach) are implemented in a measurement lab setup. Both scenarios are tested with different chain lengths of up to 16 NFs.

The classical SFC scenario is used as a reference for VM-based SFC with one VM per NF. The implementation relies on Kernel-based Virtual Machines (KVM) and interconnects VMs using Open vSwitch (OVS) in the hypervisor. Both OVS and KVM are considered as de-facto standard solutions. The NFs implement the standard OS socket interface for communication with neighbouring elements in the SFC. Figure-2-7(a) illustrates the setup.

The compound SFC can be implemented using modular packet processing frameworks such as Click [Kohler], FastClick [Barbette], or Snabb [Snabb]. These frameworks can be used to establish a forwarding path across multiple modules using proprietary interfaces not compatible with the OS socket interface. This makes the packet processing modules independent from VMs or containers and allows the chaining of multiple NFs inside a virtual machine. The measurement setup described here is based on Snabb [Kohler] which focuses on efficient interfaces and fast packet processing. Several NFs run within a single VM. These VMs are chained together via Snabb as illustrated in Figure-2-7(b)

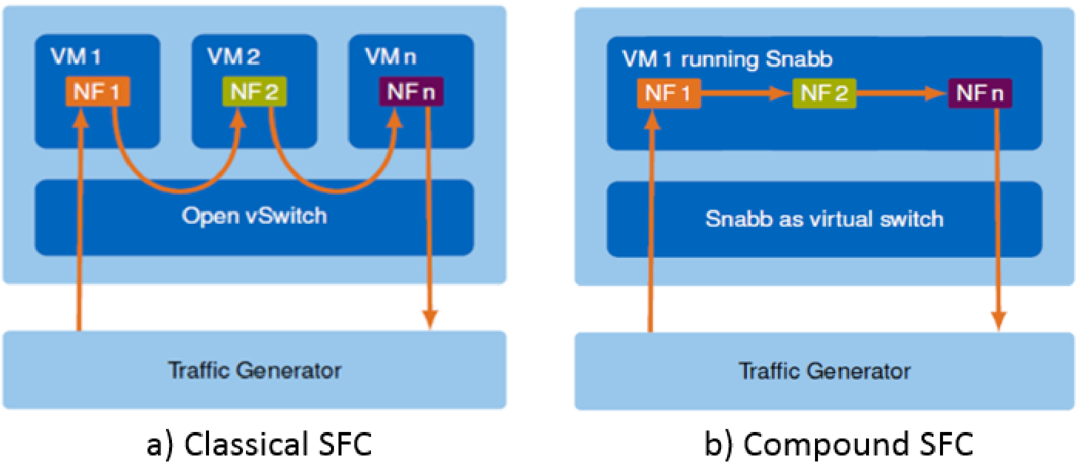


Figure-2-7: Classical SFC implementation using OVS, b) Compound SFC implementation using Snabb

The metric used for measuring the required processing time is the number of CPU cycles consumed per packet (cycles/pkt). This measure is generic and allows comparability with other hardware configurations, e.g. the same CPUs at different frequencies. The latency (measured in microseconds) introduced during packet processing is another important metric in the tests. Compared to the mere processing time (measured in cycles/pkt) it also includes time packets spend waiting in buffers. The latency metric is applicable to the measurement system as a whole. It depends on the processing time (measured in cycles/packet) and on factors, such as buffer size and batch size and strategies.

The machine hosting the device under test was equipped with the following hardware: Intel(R) Xeon(R) CPU E31230 (3.20GHz clock speed), 16 GB RAM, Intel 10 Gbit X540-T2 NIC. The device under test runs Debian Linux (Kernel 3.16) and OVS version 2.3.0 (for classical SFC implementation) or Snabb 2016.11 (for compound SFC implementation). The traffic generator runs MoonGen [Emmerich15], a software-based load generator. The traffic generator applies constant bitrate traffic at a fixed frame length of 64 Bytes.

Furthermore, the experiments include a variety of NFs ranging from simple forwarding functions, real NFs (e.g. IwAFTR Carrier-Grade NAT), to synthetic NFs that mimic the resource consumption of real NFs while having the advantage of tunable parameters (e.g. L3 cache memory consumption).

2.3.2 Evaluation results

The performance analysis aim at answering the two aforementioned evaluation questions and providing an insight on the performance of compound SFC in terms of latency as well as impacts of resource limitations.

Evaluations of compound SFC in terms of latency

The first set of measurements was conducted to compare the chaining overhead present in the classical SFC and compound SFC. All measurements were run on a single CPU core to ensure that the test results are comparable. In the case of classical SFC, the different VMs each implementing a single NF are all running on the same CPU core. The compound SFC is implemented in a single VM, on a single CPU core and contains multiple NFs. Figure-2-8shows the results of the performance comparison of compound and classical (conventional) SFC measured in CPU cycles per packet as a function of the chain length.

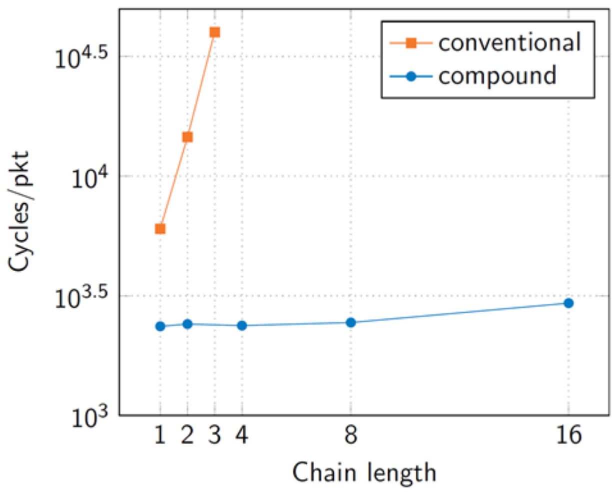


Figure-2-8: Performance comparison between classical (conventional) SFC and compound SFC in terms of cycles per packet with respect to the number of NFs in the chain. (chain length 1 equals 2 NFs)

In both, the classical and compound SFC cases, for one NF already a considerable number of cycles is necessary for a packet to enter and leave the NF. This includes the processing of the NIC driver and the virtual switch performance that is involved in both cases.

In the compound implementation, a linear correlation of performance and chain length can be observed. The calculation shows that the communication overhead between two Snabb NFs requires only 35 cycles per packet. In other words, each additional NF in a compound SFC solution adds a constant overhead of 35 cycles per packet. The cycles can be converted into time by applying the 3.20 GHz CPU clock: 35 cycles equal 0,01 µsec. In the classical SFC implementation, an exponential growth of the consumed processing time can be observed with increasing chain length.

As the compound SFC implementation based on Snabb implies running the entire chain on a single CPU core, for comparison reasons the classical SFC was implemented in both ways by pinning the entire chain to a single CPU core as well as having the NFs distributed over multiple

CPU cores. For optimal performance, OVS was allocated to a dedicated core and the chained VMs are distributed among other cores of the processor (up to three NFs in a four core CPU). The results of this evaluation of the classical SFC are presented in Figure-2-4. Although the performance of the classical SFC approach has improved in the multicore implementation the compound SFC approach still shows significantly better performance.

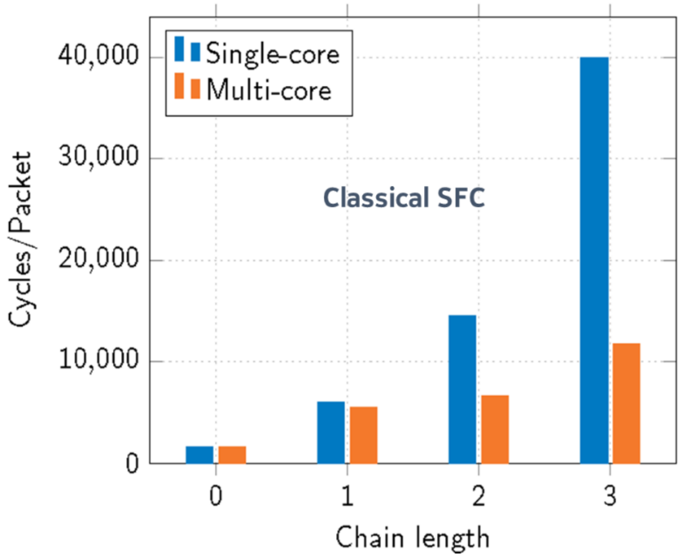


Figure-2-9: Performance evaluation of single and multicore implementations of classical SFC approach

In addition to the measurement of processing time, the overall latency was also measured based on precise hardware time stamping. Apart from the processing overhead for chaining NFCs, the latency is more significantly impacted by buffering. Packets face waiting times in buffers on the NIC, within the batches that are used to transfer packets between the chain elements, and at VM interfaces.

Table 2-1 shows the results of experiments measuring the latency of the whole system where different numbers of NFs have been chained together in a classical (single and multicore implementation) and compound SFC. OVS comes with a dynamic batch size algorithm that allows for lower latency for a small number of NFs. In Snabb the batch size is fixed, which results in an unchanged latency for 1 – 4 NFs.

Table 2-1: Latency measurements with different chain lengths.

# NFs	1	2	3	4
Latency of OVS in µsec (under low load, 100 Mbit/sec)				
all NF on one core	39.7	67.5	195.5	833.4
Dedicated cores	39.7	74.6	151.4	491.2
Latency for Snabb in µsec				
Snabb	95.7	80.9	96.0	95.9
w/o power saving	16.6	59.8	63.2	60.6

Latency can be reduced in Snabb on the cost of energy efficiency: In busy mode, Snabb consumes the computing resources completely by busy waiting for new packets (polling) for shortest latency. Due to highly efficient Snabb chaining forwarding (0.01µsec) the latency of the overall Snabb chain is nearly independent of the number of NFs. The latency mainly depends on the workload of the NF, the batch size and the use of power saving modes.

In contrast, in an OVS-based chaining the latency depends also on the number of NFs significantly. The forwarding overhead increases exponentially in particular when NFs are hosted on the same core. Also in case of dedicated cores for the OVS and NFs the overhead for the first additional chain element is considerably higher compared to the compound SFC case.

As investigated by Emmerich et al. [Emmerich14] the performance of OVS can be increased up to the factor of 6 by DPDK. Taking this finding from Emmerich et al. [Emmerich14] and the results illustrated in Table 2-1 it can be concluded that the Snabb overhead in processing is still smaller even compared to a DPDK accelerated OVS.

Evaluation of impacts of resource limitations

In case several NFs run in a Snabb environment to constitute a compound SFC they need to share the resources of a single CPU core they are running on. For the SFC performance in the compound SFC implementation critical is the available cache size on the single CPU core where the SFC is running.

Computing and memory resources differ among the NFs. To evaluate the concepts of compound SFCs, a synthetic NF was constructed based on Snabb that is configurable with respect to the resources it consumes. It emulates in this way the performance characteristic of real NF. Configurable parameters are the number of CPU cycles per packet (CPU load), the size of a data set to be looked up for packet processing and the number of accesses on the data set per packet (Cache load). The NF accesses the working set randomly to accommodate for worst-case behaviour.

Figure-2-10: Impact of cache size to NF performance shows the cycles per packet from the measurements of forwarding performance of Snabb with the synthetic NF (simple forwarder) with a synthetic cache load (100, 200, and 400 accesses per packet) and a varying working set size (ranging from 4KB up to 8GB). When the working set size exceeds the cache size of the L1, L2 and L3 cache this results in a significant decrease of performance (by increasing the number of CPU cycles needed for packet processing). While in the classical SFC approach the NFs on different cores share the same L3 cache but have own L1 and L2 cache (Intel processor) in a compound SFC approach implemented by Snabb also the L1 and L2 cache is shared among NFs. In this experiment, the L1 cache size is 32KB, L2 cache size is 256KB and L3 cache size is 8MB. As illustrated in Figure-2-5 L1 and L2 cache misses result in about each time doubling the number of cycles per packet when data on the next level cache are accessed.

Nevertheless, the biggest decrease in performance is caused by L3 cache misses. The risk of performance degradation due to L3 cache misses is present also in classical SFC as the NFs share L3 cache.

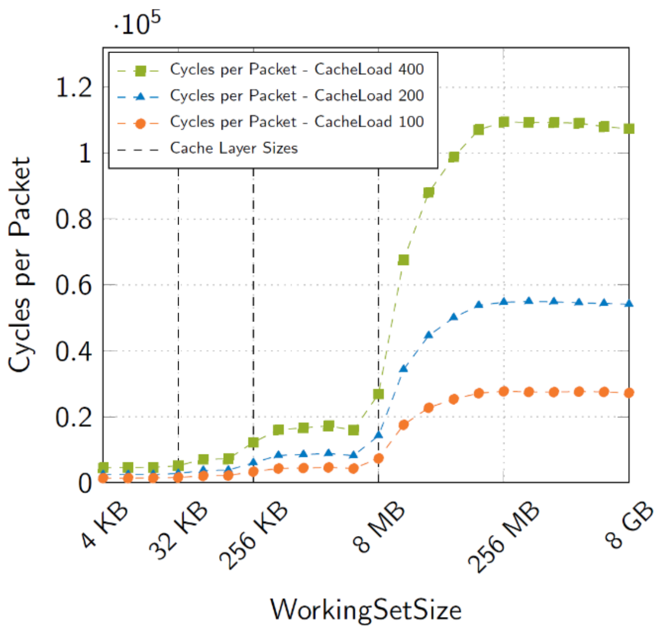


Figure-2-10: Impact of cache size to NF performance

Due to its good performance in terms of communication overhead and latency the compound SFC framework can be applicable to low latency 5G services discussed in 5G NORMA. A compound SFC approach can be also well suited for 5G microservices that process different tasks on the same work load as a higher number of NFs might not decrease the performance dramatically. Furthermore, compound SFC provides a framework for services that can be reconfigured or re-programmed flexibly to adapt to varying traffic patterns in telecommunication networks. As such flexibility is one of the imperatives of 5G networks, the compound SFC approach might be suitable for implementing agile 5G services. However, the drawback of compound SFC is that it provides less isolation of individual SFs as isolation only exists for the compound element. However, this is less important for functions that are provided by one vendor. This is the case when network functions are decomposed into micro services. Further details on evaluation of compound SFC framework can be found in [Hahn].

2.3.3 MANO and Control Aspects of Compound SFC

Compound SFC can be seen as an additional implementation option to be taken into consideration when reconfiguring the network functions by SDM-C. Especially in the case where low latency is required the SDM-C might aim at utilizing the compound SFC approach for implementing the network functions.

Different compound SFCs can be configured and run on the same VM. The image of such a VM needs to contain all NFs of one or more configurable SFCs. In other words, all the building blocks of potentially configurable SFC need to be available on the VM. The SDM-C needs to have the information about available NFs on the VM as well as possible chain templates that can be configured using available NFs. Depending on the service requirements and current traffic demands, the SDM-C can dynamically re-configure the VM and implement different SFCs consisting of different NFs. In such a way, the agreed QoS can be maintained by re-configuring the SFCs on already existing VMs without a need for re-orchestration by SDM-O, e.g. by adding new VMs for hosting missing NFs needed for implementing the new SFC. This improves the responsiveness of the system to the changing traffic condition, as less delay is introduced by handling the traffic changes entirely on SDM-C level compared to the case where the SDM-O is involved. Furthermore, this implies an optimization in resource consumption, as resources available on running machines are more efficiently utilized and re-used. Scaling out by starting new virtual machines on the SDM-O level is thus minimized.

2.4 Intelli-RAVA

2.4.1 Introduction

In [D5.1] an algorithm was presented that empowered the SDM-O to make optimized lifecycle management and orchestration decisions for individual VNFs of a network slice, based on the respective VNFs resource utilization and its forecast. This algorithm is proposed to be part of the Inter-Slice Resource Broker inside the SDM-O. We can identify three main unique and novel features of the proposed algorithm as follows:

1. The algorithm takes a correlated view of the resources (e.g., CPU, memory, network, storage) consumed by the VNF, and based on this a correlation score is derived, which is referred to as a Reference Resource Affinity Score (RRAS).
2. The algorithm makes a forecast on the VNFs' resource requirements.
3. The algorithm is VNF agnostic, i.e., it does not rely on information on the type of VNF that is being monitored/processed and the RRAS score gives insight into a VNF's functional profile.

In view of the above two characteristics, the algorithm was referred to as Resource Aware VNF Agnostic (RAVA) method for VNF lifecycle management. The proof-of-concept of RAVA method was described in [D5.1] with results derived from an OpenStack-based testbed. The results proved the potential of the respective concept, which was to enhance the Quality-of-Decision (QoD) of the SDM-O. The process overview for the RAVA algorithm is shown in Figure-2-11, which has been described in detail in [D5.1].

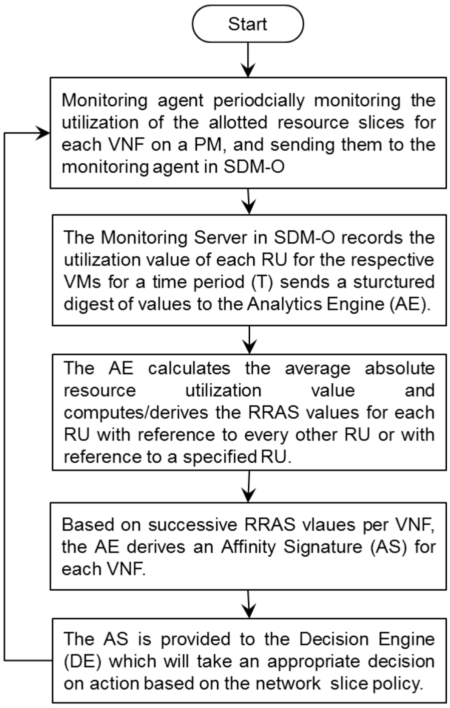


Figure-2-11: RAVA process overview

The RAVA algorithm proof-of-concept as described and analyzed in [D5.1] was based on a Pearson correlation model where the Pearson co-efficient (*r*) is then derived over these samples with reference to a Reference Resource Unit (RRU) and the derived value of *r* is the RRAS. Although an effective novel method however, the proposed model was observed to have the following drawbacks:

1. The Pearson correlation model although gives a good indication of the strength of correlation (or affinity) between two variables, however it can be misleading as it may indicate strong correlation between RUs that may be under low utilization. Therefore, a false event may be triggered at low utilization values of correlated RUs making the SDM-O to make a lifecycle decision on action. This is counter to the main objective of achieving higher QoD.

2. The static assignment of a RRU makes the RAVA algorithm restrictive and inflexible; causing the SDM-O to potentially miss out on RUs that may have strong correlation (or affinity) with RUs other than the RRU.

3. Considering that the number of VNFs in a datacenter may be in 10s of 1000s, the entire process shown in Figure 1 can incur a high load in terms of the monitoring load/data as the algorithm is unable to discern between wanted and unwanted data. This runs counterproductive to the advantages of the RAVA algorithm.

In view of the above limitations, we extend our concept by adopting the use of Machine Learning (ML) based method to make the RAVA algorithm more intelligent and thus efficient and reliable. We will refer to this sophisticated variant as Intelli-RAVA (iRAVA). In the next section, we will provide details of an analytical model that employs ML method that we have developed. It should be noted that the RAVA algorithm is part of the Inter-Slice Resource Broker inside the SDM-O.

2.4.2 System Model Concept and Description

In this section, we provide details of the analytical model for the iRAVA that we have developed. The main objective of this model is to provide a base-model from which a suitable algorithm can later be derived that can then be implemented inside the Inter-Slice Resource Broker within the SDM-O. The detailed assumptions and description is provided in the following section.

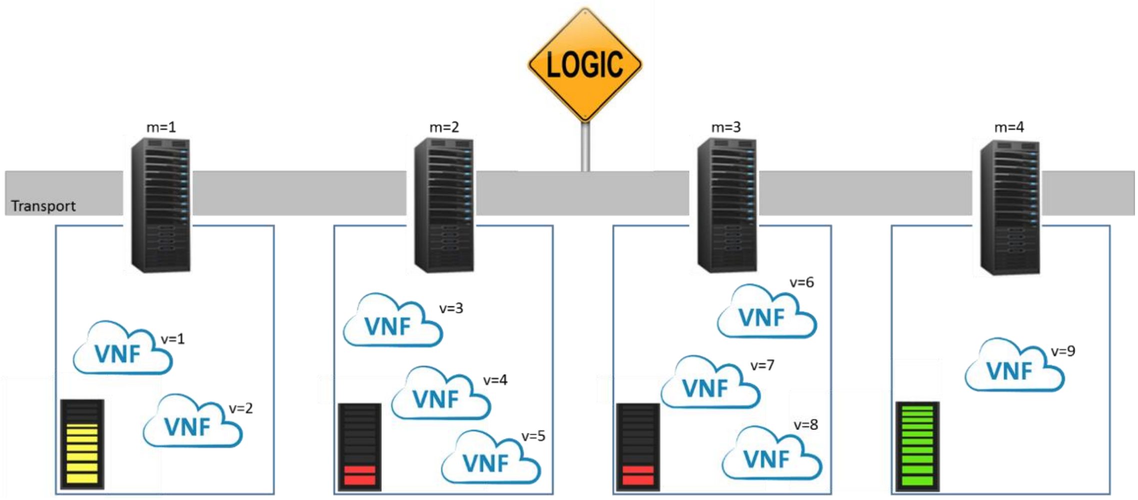


Figure-2-12: iRAVA Model Description

Let us assume a network with multiple physical machines, denoted as $m \in M$. Several Virtual Network Functions (VNFs), denoted as $v \in V$ can be easily deployed. We rely on the assumption of full-supported physical machines, where each machine can easily support multiple VNFs, leading to $|V| > |M|$.

An overview of the model is depicted in Figure-2-12. In this example, we assume $|M| = 4, |V| = 9$. Any single VNF is characterized by three different values, such as storage s, computational level μ, and network capacity η. Please note that in this first analysis we are not considering network delay requirements. However, they can be easily introduced and used in our generic model.

Each physical machine m is characterized by a maximum capacity level in terms of storage S_m, computational resources W_m, and network datarate X_m.

We introduced now the concept of *network function migration* as the action moving a VNF from one physical machine (which is running out of resources) to a different one (with resource availability). This process can be easily performed with trivial algorithms, e.g., alert messages issued when the overall physical machine capacity is below a certain level (as shown with the red bar in the second physical machine in Figure-2-12). An easy-to-use mechanism can randomly pick a VNF up from the affected physical machine and promptly move it to another physical machine, e.g., physical machine 4 in Figure-2-12. While this mechanism can readily prevent resource congestions and VNF service degradation, a migration process might take time to be carried out causing additional delay in the service delivering.

Therefore, an intelligent iRAVA mechanisms is needed to find an optimal VNF/Physical machine associations set which minimizes the probability to run further VNF migrations while, at the same time, guaranteeing the VNF quality of service. We denote this associations set as a binary value $x_{m,v}$, which is 1 whether VNF v is installed in physical machine m, 0 otherwise. Then, we formulate the following optimization problem:

Problem `VNF ProPlacement`:

$$\begin{aligned}\text{maximize} \quad & \sum_m \log \sum_v \left(f_{\text{CORR}}(s_v, \mu_v, \eta_v) x_{m,v}\right) \\ \text{subject to} \quad & \sum_v s_v x_{m,v} \leq S_m, \quad \forall m \in \mathcal{M} \\ & \sum_v \mu_v x_{m,v} \leq W_m, \quad \forall m \in \mathcal{M} \\ & \sum_v \eta_v x_{m,v} \leq X_m, \quad \forall m \in \mathcal{M} \\ & \sum_m x_{m,v} \leq 1, \quad \forall v \in \mathcal{V};\end{aligned}$$

where f_{CORR} is the correlation function between required computational, storage and network resources. The problem is a Mixed-Integer Convex Programming, as f_{CORR} can be considered convex within the space of the solutions. Please note that the *log* function allows to guarantee fairness among different physical machines. In other words, the maximization of the sum of the logs will automatically enforce the same level of utilization of the physical machines, preventing additional VNF migrations in the short-term. The problem can be seen as a generalization of a *bin packing problem*, where the utility function is a convex function. A plenty of solutions have been proposed in the literature to tackle this problem providing near-optimal solutions.

Additionally, f_{CORR} plays a key-role in the overall process. In particular, we apply the machine-learning concept to "learn" the VNF behaviors and predict the resource demand trend. This helps to proactively apply VNF migrations if the VNF load is expected (within certain confidence levels) to grow and exacerbate the physical machine resource availability. Conversely, inaccuracy in the forecasting process might lead the system to additional migrations to recover from physical machine congestions.

2.5 Dynamicity of SFC Selection

This section addresses slice specific set-up of concatenated network functions (VNFs) to provide a network service which is orchestrated following 5G NORMA concept by SDM-O. Here we refer to the SFC approach as in focus of IETF Working Group on Service Function Chaining (SFC): Service Functions (SFs) within cellular networks up to now are mainly so-called (S)Gi-LAN functions for security and privacy, service quality enforcement, and charging support as e.g. packet filtering and Deep Packet Inspection at firewalls, load-balancing and transactional proxies as, e.g., spam filters, TCP optimizers, or general performance enhancement proxies (PEP). Implementation of such types of services will significantly alter with next generation technologies like introduction of virtualization, network overlays, and overarching orchestration. Each complete service represented by all required functionalities in an abstracted way and the right order of application is denoted as SFC. The SFC instantiation is called Service Function Path (SFP).

Service Classification within an SFC enabled domain allows for subsequent SFC encapsulation – alternatively an SFC proxy is included – before the SFF (SF Forwarder) connects different SFs together building up an SFP. Details are specified in the SFC architecture document [RFC 7665].

From an SFC point of view the dynamic instantiation and re-configuration of a chained service function is discussed in the case of specific slice demands with impact on e.g. location and other characteristics environment of the function implementation site (see [D5.1], sect. 5.8 on 'Constrained SFC sets').

With respect to 5G NORMA architecture and SDN/NFV model [Gu] proposes an extended architecture in SFC including applications to tenants, SDN controller, network function virtualized manager (NFVM) and service function node. Auto-deployed self-service is provided by orchestration of SDN controller and NFV manager. Besides, fundamental configurations and realizations of SFC are introduced with requirements raised. Benefitting from Network function virtualization (NFV) and cloud technologies, SFC in virtual networks can bring convenient and elastic network to customers with central management to operators.

A service function chain is directing UP traffic through series of service functions in Data Centers or across Data Centers. Due to virtualized network, SFC can be centrally controlled with servicing traffic on same network or across the different networks. Open issue is whether also c-plane traffic as e.g. inter NF signalling can be described in SFC model.

With other words an SFC App could be constructed to represent the concatenation of VNFs and PNFs to be executed per message exchanges as specified in the MM scheme and laid down in a respective MSC. Such a control of p/vNFs via SDM-C is following the SDM-O pre-configured SFCs or alternatively realizes dynamicity (due to changing path delay figures affected e.g. by varying local network load or propagation conditions) either on c-plane level by SDM-O/SDM-C action or on u-plane level on a per packet basis and header information assessment.

In the following some issues of SFC dynamicity are addressed in detail

Dynamic instantiation and re-configuration of a chained service function discussion in case of specific slice demands with impact on e.g. location and other characteristics environment of function implementation

The envisaged situation here is the case of a specific end-to-end service concatenated of sub-functions or processes which are executed in a virtual machine instantiated at a specific cloud, i.e. computing and storage resources accessible in combination with corresponding transport capacity used either for user data packet (payload) or control messages transfer – whatever is more efficient in the specific case. E.g. deep packet inspection requires packet transport to the VNF location or ‘outsourcing’ of the inspection algorithms to the forwarding node where the packets have to pass anyway. The specific path (SFP) of the packets is either known in the SDM Controller (resp. in the corresponding SFCApp as one of the Apps denoted e.g. in Fig. 2 13: SDM-C SDM-X interfaces) or included in the SFC header (NSH) of each packet. In case certain policy or service driven restrictions for nodes to circumvent (e.g. due to missing security requirements or being congested and adding delay to the service) the path has to be re-constructed i.e. re-calculated and the decision enforced in the respective node. Criteria for choosing the hierarchical or the distributed approach may be effort for the overall process and potential latency resulting from the process.

Framework considerations

Compared to sect. 2.2 on VNF Chaining Location here no algorithms are designed or discussed here but the framework of services which can be modelled by those approaches shall be described roughly. While originally SFC has been applied to the 3GPP defined flexible mobile service steering for (S)Gi-LAN services [3GPP TR 23.718] predominantly we want to extend the service to any core network functions providing services as VNFs for Session (Mobility) management, QoS control, Security, Charging/Policy Control (all together with corresponding enforcement on u-plane level) as well as Optimization in general. Such services differ from the prior ones also in that they generally cannot be executed in a serial manner but in parallel – as e.g. mobility impacts the QoS experienced and also the way it has to be considered in resource allocation etc. Also, to apply at the end charging and accounting to the provided service will not be straight forward as Byte or service duration counting but has to consider the heterogeneity and dynamic adaptation of service parameters to both the environment and the contractual framework (SLA) between customer, vertical/service provider, and network (infrastructure) operator.

Comparison of c-plane Architecture vs. u-plane (packet header) approach

As mentioned before the both approaches in mind here differ by c-plane or u-plane centricity and degree of hierarchy/distribution of the decision, and may also be differently applicable to SDM-C architecture of 5G NORMA when it comes to implementation. Such consideration has to be regarded in addition to performance issues already mentioned before. To finally come to an assessment of either one or the other method or model further issues have to be investigated which may comprise the following next steps already planned and identified but not yet fully examined in the limited project time frame. The items to be analysed are recognised as:

- Estimation of expected performance difference of dynamic vs. pre-configured SFCs/SFPs construction (V/PNFs) for exemplary services.
- Proposal of provisioning of (slice characterizing) parameters as quick-and-easy to detect header information which can be accessed and consumed by all relevant functions within a SFC.
- Description of detailed exemplary methods for dynamic SFC forwarding paths construction.
- Assessment of the potential of NSH metadata to enable dynamic SFC setting (slice construction and re-configuration).

An extension to NSH metadata formats has been proposed defining header metadata on slice and service specific context in terms of additional Network Service Header (NSH) Type Length Variables (TLVs) for specific service performance requests as e.g. low latency/high reliability consideration [BHS]. The idea is to set-up rules for SFC/SFP construction properly considering slice and service driven preferences.

NSH TLVs in SFC carrying useful or required context information on service/slice specifics may be configured by a function chain as e.g. service descriptions or the QoS/DSCP (QoS-Class Identifier) as proposed in [NKMH].

However, within a simple flag detailed special characteristics (demands) for high reliability of the service (e.g. to be reflected by network function selection e.g., at multiple locations for redundancy) or extreme low latency (SFP between neighboured locations only) cannot be included. Therefore these (slice characterizing) parameters shall be made available as quick-and-easy to detect header information which in terms of proposed new TLVs can be accessed and consumed by all relevant functions within a SFC.

Planned activity is an investigation on slice/service specific applicability of SFP adaptation due to context change with an exemplary protocol solution comparison for selected use cases (UHR/ULL) as outcome.

In addition, reference to LISP for SFC a recent proposal [Erm] defines extensions to LISP control plane protocol to enable support for Network Service Header (NSH) based Service Function Chaining (SFC). Locator/ID Separation Protocol (LISP) defines c-plane for driving dynamic network overlays, and can be used with various encapsulations such as VXLAN-GPE (Generic Protocol Extension for VXLAN – which defines an extension to the LISP and VXLAN encapsulations with multi-protocol support, enabling encapsulation of any inner payload, including e.g. NSH). The Virtual eXtensible Local Area Network in [RFC7348] defines a format for encapsulating Ethernet frames in an outer UDP/IP transport..

2.6 Edge Cloud SDN/NFV Orchestration

2.6.1 Edge Cloud infrastructure optimization

For some of its tenant applications, 5G NORMA architecture requires an Edge Cloud infrastructure to be in place. This could be the case, for instance, to meet the communications latency requirements of specific applications, or to keep the bandwidth requirements confined to the network edge when considering applications that are intensive in data exchange with the user terminals or with the VNFs/PNFs located at the base stations.

However, as of today, Edge Cloud deployments are not yet a reality, the cause being the economic impact of their deployment. For example, when deploying Edge Cloud infrastructure at locations aggregating a number of mobile stations, using typical data center architectures in these edge locations may be overkill in terms of the infrastructure overhead. These edge locations, because of their highly distributed nature, have to be very optimized in terms of infrastructure. Any infrastructure inefficiency in these edge locations gets multiplied by the distribution factor (e.g. x1000 factor or higher, depending on the footprint and the level of distribution targeted by the infrastructure operator).

Typical data center architectures follow the one depicted in Figure-2-13.

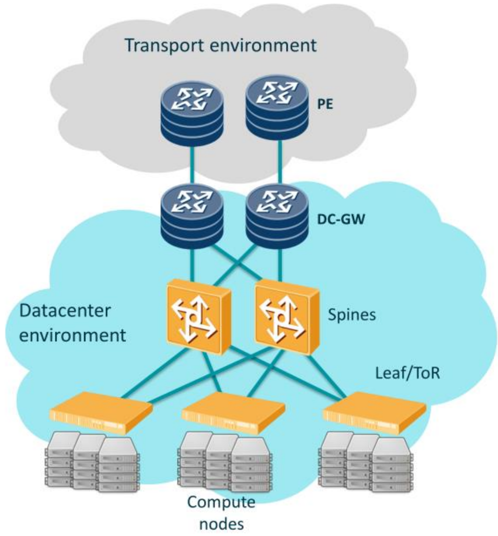


Figure-2-13: Typical data center architecture

Data center architectures in IT environments typically employ a leaf (Top-of-Rack or ToR) and spine switching fabric that interconnects the servers of the data center. For external connections, another layer of hardware based equipment, commonly called the Data Center Gateway (DC-GW), is deployed in a redundant configuration, which in turn connects to the network operator equipment, typically an MPLS Provider Edge (PE) node. This model reflects the business relationship between the data center operator and the network operator and results in two pieces of equipment (DC-GW and PE) faced back-to-back to provide a clean administrative demarcation point.

This type of architecture is not suitable for all kind of distributed deployments at the edge of the network because of the required hardware infrastructure overhead, limiting it to very specific cases, justified only if the number of edge VNFs in a distributed location, and correspondingly the required compute power, is very high.

The need for an administrative demarcation point is alleviated when the owner of the NFVi and the provider of the external connectivity is the same entity (the infrastructure provider), and moreover, it is justified to reduce the infrastructure overhead. As a matter of fact, part of the VNFs on-boarded in an Edge Cloud location will be providing connectivity services to other VNFs of the same infrastructure provider deployed in that location and interacting with other portions of the network of the infrastructure provider not (yet) virtualized. The data center applications of the infrastructure provider of an Edge Cloud are no longer over-the-top, but virtual parts of its network itself.

In order for a current network infrastructure provider to evolve to an Edge Cloud provider, the infrastructure deployed in an Edge Cloud location can leverage on the existing WAN equipment (typically the mentioned MPLS PE router) in a current location to provide the networking connectivity requirements of the network services instantiated over the Edge Cloud NFVI deployed in that location. For that purpose, the WAN equipment can consolidate the role of the DC-GW, and even the role of the leaf and spine fabric for very minimal deployments requiring just a few compute nodes.

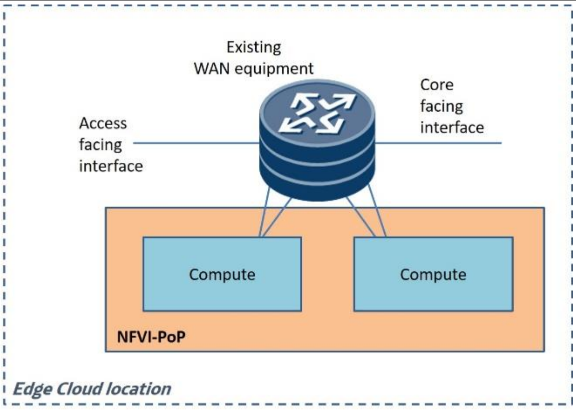


Figure-2-14: WAN equipment providing connectivity services to an Edge Cloud NFVI-PoP

In this kind of setup, the native NFVI networking resources of the location are restricted to those based on the computes, such as the vSwitch or the SR-IOV/PCI-Passthrough capabilities, and at most the leaf and spine fabric, in case there is one present. The connectivity services of these native NFVI networking resources would be under the control of the NFV MANO by means of SDN according to some of the possible options described in ETSI NFV-EVE 005 ("Report on SDN Usage in NFV Architectural Framework") and would be devoted exclusively to the network services instantiated over the NFVI.

That is not the case of the existing WAN equipment used for the Intra PoP NFVI connectivity. The existing WAN equipment will be providing other legacy services in addition to the connectivity services provided to the NFVI network services. Therefore, the dynamic configuration of the existing WAN equipment driven by the MANO on behalf of the network services deployed over the NFVI has to be achieved through a Network SDN orchestrator, that is not part of the MANO stack, but part of the Network SDN hierarchy of the operator. That Network SDN orchestrator is in charge of arbitrating between the direct requests from the OSS for the support of legacy applications/services and the requests from an ETSI NFV MANO stack as required by network services deployed over the NFVI.

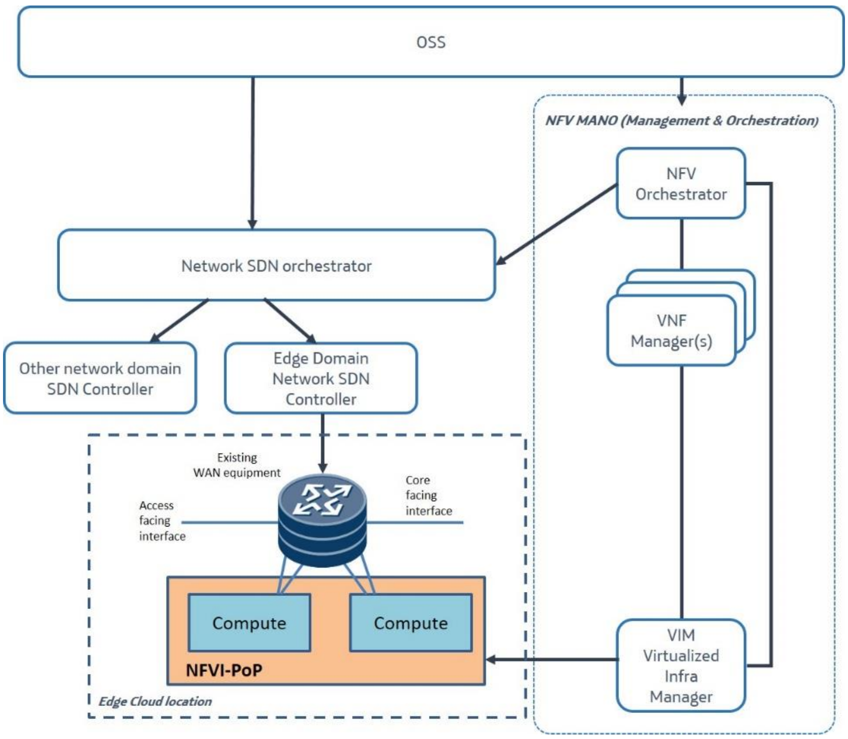


Figure-2-15: MANO and SDN Network

ETSI NFV do consider the interaction of an NFVO with a WAN infrastructure manager (WIM) in order to account for the network services spanning over multiple sites, as shown in the Figure-2-16 adapted from Figure 5.2 in ETSI NFV-MAN 001 (“NFV Management and Orchestration”).

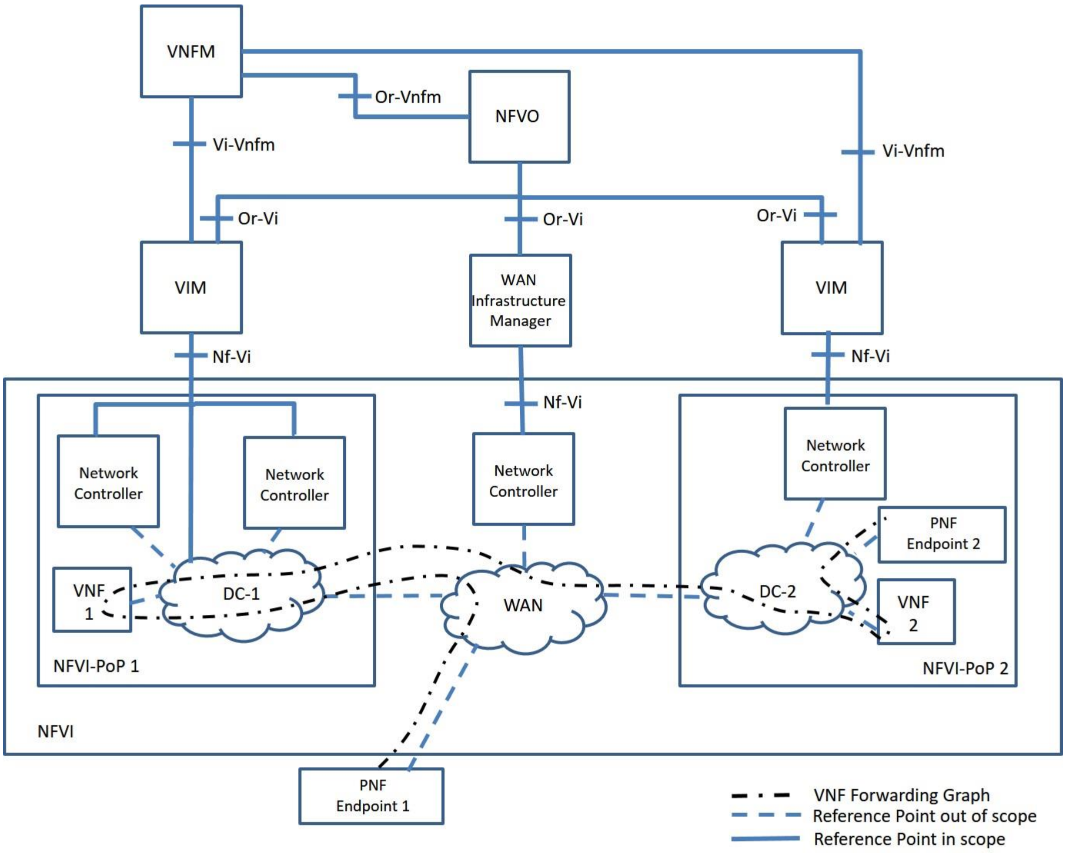


Figure-2-16: Network Controller example (from ETSI NFV-MAN 001)

According to this figure, the requests from an NFVO to WAN equipment could be through an Or-Vi interface to the WAN infrastructure manager. In the mentioned evolution of the fixed line operator to SDN-enabled networks, the role of the WIM could be embedded in the WAN Network SDN orchestrator as an interworking function to receive the connectivity requests coming from a MANO stack. In that case one of the interfaces exposed by the WAN Network SDN orchestrator would be the Or-Vi. The requests received by the WIM would be progressed downstream though the SDN hierarchy of the network operator to reach the ultimate SDN controller in charge of the appropriate equipment and using the Southbound Interface supported (typically a NETCONF/YANG interface).

Mapping this reuse of existing WAN infrastructure and the interaction with an existing WAN Network SDN controller to the 5G NORMA architecture yields an architecture as the one depicted in Figure-2-17.

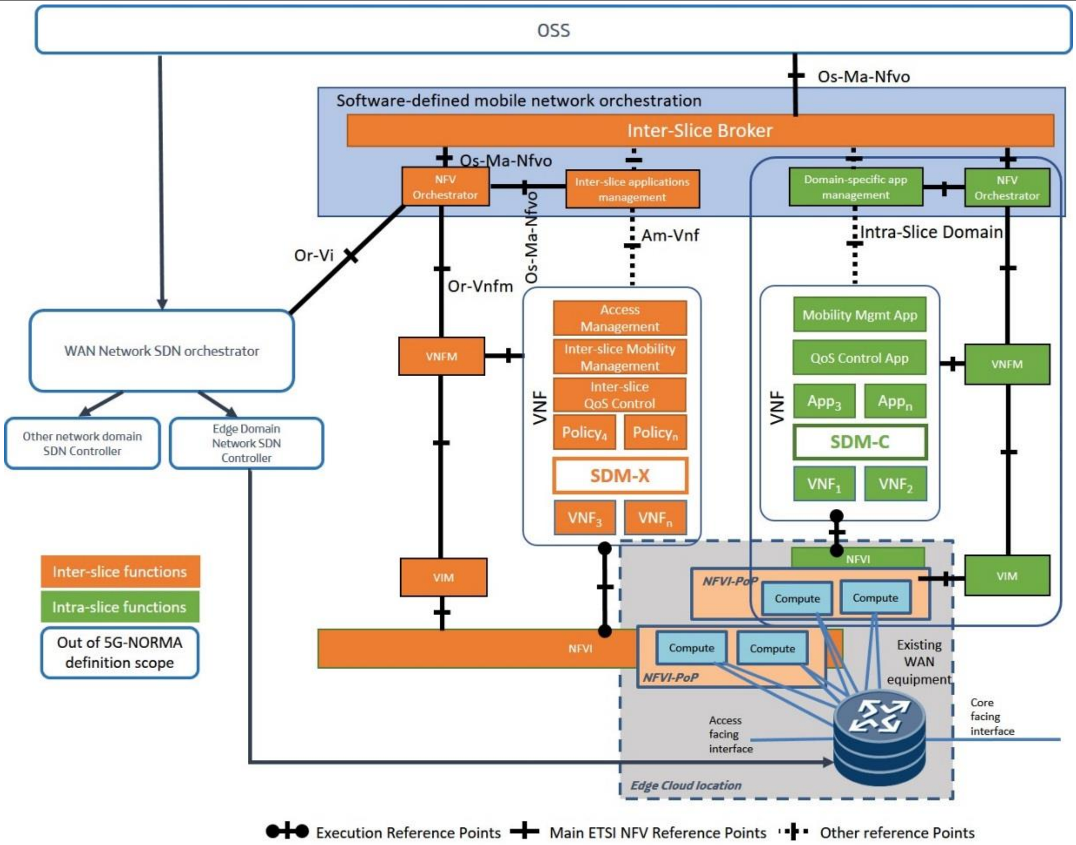


Figure-2-17: Interaction of 5G NORMA architecture with WAN SDN

The interaction with the WAN Network SDN orchestrator in the 5G NORMA architecture is proposed to take place from the inter-slice NFVO. That way the tenants do not need another separate business relationship with the WAN network provider, and the interactions with the WAN are part of the contract with the infrastructure provider, which could be just a network operator that has evolved to become a Cloud Edge provider, by connecting compute resources to existing WAN infrastructure.

However, this use of the Or-Vi interface towards a WIM is not further elaborated so far in the normative work of ETSI NFV. An analysis on the different multi-site use cases requiring an interaction with a WAN infrastructure manager (WIM) is being made on the draft of the “Report on Management and Connectivity for Multi-Site Services” (ETSI GR NFV-IFA 022, current version 0.5.1 from April 2017). 11 use cases have been identified so far. For each use case, an analysis will be carried out so that a set of recommendations can be made regarding possible updates to existing MANO functional block roles and reference points, such as the mentioned Or-Vi interface.

The use of existing WAN infrastructure for the local connectivity of an NFVI-PoP of an Edge Cloud location can be regarded as a special multi-site use case where a NFVI-PoP site connects with itself making use of the connectivity services provided by a WAN infrastructure manager.

The following section provides a description of a new use case that can be proposed to be included in NFV-IFA 022 as “Reuse of WAN infrastructure resources for Intra NFVi PoP connectivity”.

2.6.2 Reuse of WAN infrastructure resources for intra NFVi PoP connectivity: Use Case analysis

Analysis of the resource of WAN infrastructure resources use case according to template of the use cases section of current NFV-IFA 022.

Use case description

This use case is discussed in the context of a general Network Service orchestration. As shown in the overall model, it focuses on one NFVi-PoP located in one site that makes use of shared WAN infrastructure (e.g. IP/MPLS router) for some of the connectivity services required among the VNFs that are part of the Network Service.

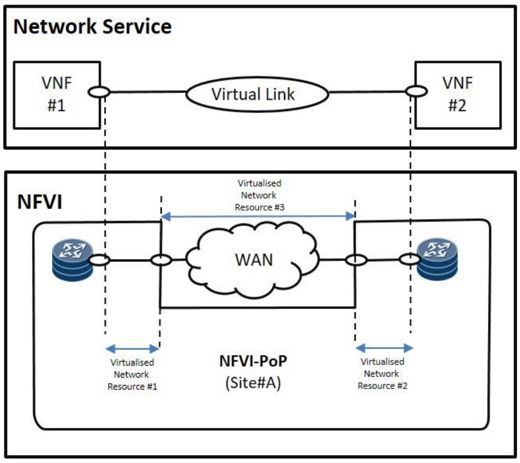


Figure-2-18: Connectivity overview for enabling Network Service

A network service consisting of two VNFs is instantiated as shown in Figure-2-18. Each VNF is installed in the same site but are connected across the WAN infrastructure equipment present in the site.

The virtualised network resources connecting VNF#1 and VNF#2 with the WAN infrastructure equipment are referred as virtualised network resource #1 and virtualised network resource #2, respectively. The virtualised network resource implemented across the WAN infrastructure is referred as virtualised network resource #3. As a result, the unified Virtual Link is created by combining the virtualised network resource#1, #2, and #3.

Base operational flows for deploying a network service connecting the two VNFs are examined. Both VNFs are deployed in the same site, Site#A, and network connectivity is configured between the VNFs in this site through the WAN infrastructure. The VNF deployments at the site and the network connectivity between the two VNFs should be coordinated in such a way as to deliver a unified service. The VNFs at the site will be connected across the WAN infrastructure (although very likely traversing no WAN link, just being forwarded by the WAN equipment). The connectivity of the two VNFs over the WAN can be performed:

- Through a gateway function at the WAN equipment that translate/map between the virtual networks attaching the VNFs to the WAN equipment (attachment virtual networks, corresponding to virtualised network resource #1 and virtualised network resource #2) and the WAN virtual network used to forward the traffic across the WAN equipment (WAN virtual network, corresponding to virtualised network resource #3)
- As an overlay network using tunnelling protocols. Examples of tunnelling protocols typically used in data centres include VXLAN and NVGRE. Tunnelling protocols offer the ability to stack/aggregate different customer private networks across a provider network

Two base operational flows, BF#1.1 and BF#1.2, corresponding to the two connectivity approaches, are described below.

Figure-2-19provides a more detailed view of the use case. The architectural model is derived from Figure 5.2 in [NFVMAN001]. It shows a single-site model managed by a single Service Provider and making use of WAN equipment shared with non-NFV-aware applications. The figure also shows the related architectural components (e.g. WIM, Network Controller, NFVO, etc.) and reference points, which are further referred in the present use case.

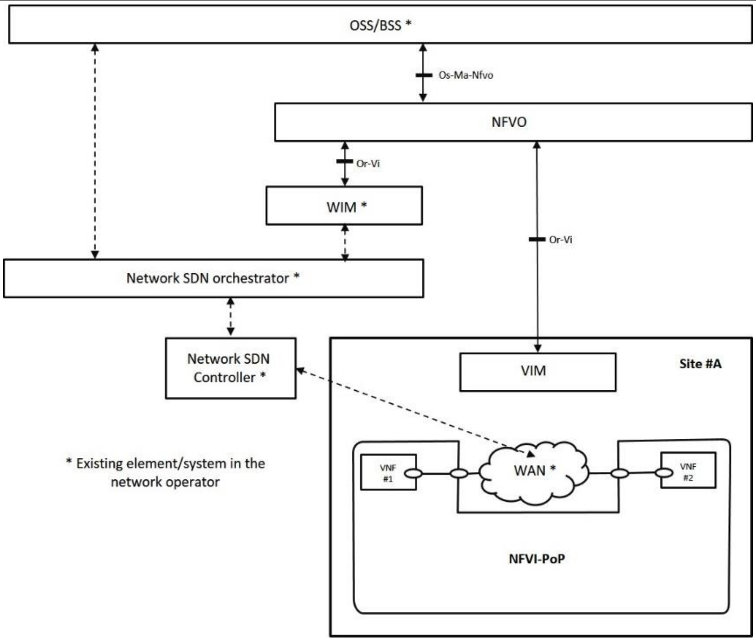


Figure-2-19: High-level view of the Reuse of WAN infrastructure

Trigger

Table 2-2: Baseline flow trigger for Intra-PoP Network Service reusing existing WAN infrastructure.

Trigger	Description
Baseline flow #1	The OSS requests the NFVO to instantiate a Network Service with VNF#1 and VNF#2 in Site#A, with these VNFs connected by a virtual link.

Actors and roles

Table 2-3: Reuse of WAN infrastructure actors and roles.

#	Actor	Description
1	OSS/BSS	OSS is in charge of triggering the instantiation of a network service between 2 VNFs in a site that have to be connected making use of a WAN equipment shared with other non-NFV-aware applications, also driven from the OSS/BSS domain
2	NFVO	NFVO is in charge of mapping the OSS request for the network service to requests to the involved managers, in this case the VIM for the location NFVI-PoP and the WIM responsible of the WAN equipment at the location
3	VIM	VIM is in charge of establishing the virtualised network resources on the NFVi. That includes the configuration of the attachment virtual networks in the computes and in the location switching fabric, if available and required for the Network Service. The use of an NFVi switching fabric by this use case only makes sense if the NFVi-PoP (under the control of one VIM) is partitioned in two separate sites connected by a WAN infrastructure. That scenario no longer matches this use case (that considers only one site) but can be considered as an extension of this use case.
4	WIM	In this use case, WIM is in charge of receiving the requests from the NFVO to establish the virtualised network resources on the WAN infrastructure. WIM could be a module inside the Network SDN orchestrator acting as a Northbound plugin for it to receive such requests, or otherwise be a standalone function and use the Northbound API of the Network SDN orchestrator (not standardized in ETSI) translating between the Or-Vi (or an extension for WAN control) and the mentioned NBI.
5	Network SDN orchestrator	Network SDN orchestrator is in charge of arbitrating the connectivity requests from the different Northbound clients. This includes the NFVO via the WIM and other non-NFV-aware OSS applications.
6	Network Controller	Network Controller is the SDN controller hosting in its Southbound interface the interactions with the WAN equipment infrastructure. It can be one element or a complete SDN hierarchy according to the infrastructure needs (e.g. with technology specific domains, geographical domains or a combination of both)

Pre-conditions

Table 2-4: Reuse of WAN infrastructure pre-conditions.

#	Pre-condition
1	The infrastructure of the NFVI-PoP at Site#A and the WAN infrastructure are physically connected.
2	The NFVO knows about the endpoints connected to a specific WAN infrastructure and the WIM in charge of that WAN infrastructure.
3	WAN infrastructure of the provider is SDN-controlled through an SDN orchestrator and a hierarchy of SDN controllers that can be invoked through an ETSI NFV compliant WIM module.

Post-conditions

Table 2-5: Reuse of WAN infrastructure pre-conditions.

#	Post-condition
1	The network service connecting VNF#1 and VNF#2 deployed at NFVI PoP of Site#A is instantiated. The virtual link connecting the two VNFs is supported across the WAN infrastructure equipment.
2	The Network SDN orchestrator is aware of the WAN connectivity established through the WAN infrastructure and can take it into account to arbitrate subsequent requests, either from the NFV Network Services or from other OSS legacy applications

Figure-2-20 shows the mapping of service instance model to infrastructure for this use case. For BF#1.1, the Virtual Link is directly mapped to the underlying network. On the other hand, for BF#1.2, an overlay network is created over the underlying network and the Virtual Links are mapped onto the overlay network. For the case of BF#1.2, the WAN can be shared with other Virtual Links.

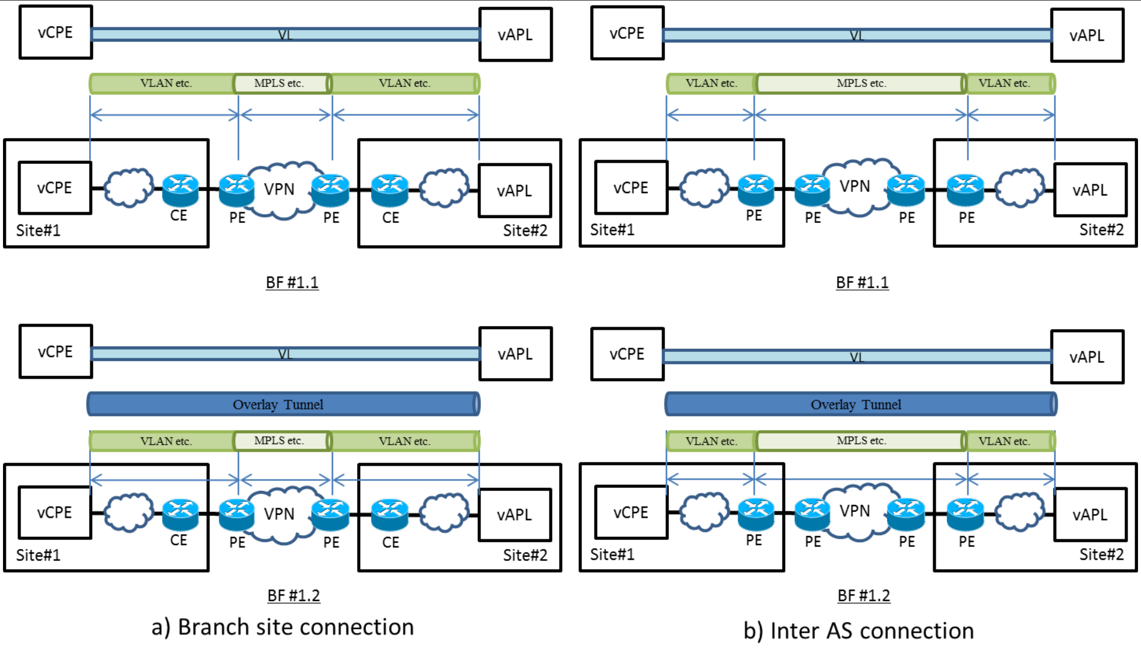


Figure-2-20: Mapping of service instance Model to infrastructure

Figure-2-21 presents the details of the instance information model. Some attributes to be discussed are introduced.

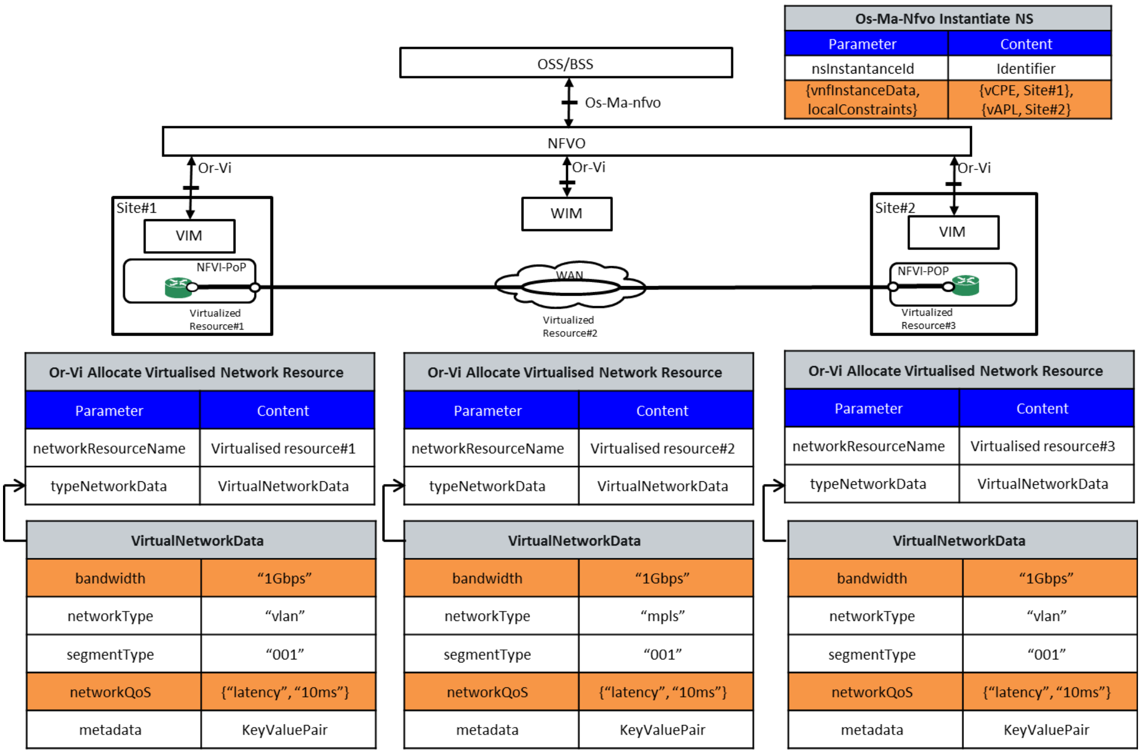


Figure-2-21: Reuse of WAN infrastructure instance information model

Operational Flows

Table 2-6 describes the base flow for the approach of translating/mapping in between in-site NFVI-PoP and WAN virtual networks

Table 2-6: Reuse of WAN infrastructure for Intra NFVI-PoP connectivity base flow #1.1.

#	Flow	Description
1	OSS/BSS -> NFVO	Requests to instantiate a Network Service in Site#A. Optionally OSS/BSS can specify other local constraints, such as the computes where its constituent VNFs should be allocated. *Interface - Os-Ma-nfvo*
2	NFVO	Starts an instantiation process for Network Service VNFs with the VNFM(s). The NFVO determines that the instantiation involves a specific WAN infrastructure and the corresponding WIM. The NFVO checks the capability (e.g. MPLS and QoS support) and capacity which are provided by the NFVI-PoP at site#A and the WAN. Then the NFVO decides where to instantiate the VNFs and decides to setup network connectivity between them across the WAN infrastructure translating/mapping in between in-site NFVI-PoP and WAN virtual networks.
3	NFVO ->WIM	Requests to allocate virtualised resource#3 between NFVI-PoP attachment virtual networks (virtualised resource #1 and #2) with a designated bandwidth. Editor's Note: Or-Vi reference point for WIM should be analysed if it should be leveraged or updated. *Interface – Or-Vi*
4	WIM -> Network Controller	Requests to create network connectivity between connecting ports in the WAN infrastructure with the designated bandwidth between virtualised resource #1 and #2. The request traverses the Network SDN orchestrator, for authorization and so that it remains updated, and can traverse a hierarchy of SDN controllers till it reaches the controller in charge of the equipment(s) hosting the connecting ports. *Interface – e.g. NBI for Network controllers*
5	Network Controller	Creates the network connectivity in the WAN infrastructure with the designated bandwidth. In the general case, there are multiple options where the end points for the VNFs are installed in the NFVI PoP, as discussed in ETSI GS NFV-INF 005 [NFVINF005] (e.g. vSwitch, NIC, ToR, vRouter, etc). However, this use case mainly applies to scenarios where the end point resides either in the NIC or in a vSwitch, because the WAN infrastructure is playing the role of the switching fabric in this use case.
6	Network Controller -> WIM	Returns the response to the network creation request. In this context, the information for connecting to the WAN (e.g. IP address, VXLAN ID, and MPLS-VPN RD) are returned.
7	WIM -> NFVO	Returns the response to the virtualised resource allocation request between connecting ports to the WAN at the NFVI-PoP at Site#A. In this context, the resource identifier, which is used for identifying the virtualised resource at the WIM, and information for connecting to the WAN (e.g. IP address and VXLAN ID, and MPLS-VPN RD) are returned. *Interface - Or-Vi*
8	NFVO -> VIM at Site#A	Requests to allocate the virtualised resource#1 connecting to the WAN. The NFVO sends information for connecting to the network connectivity over the WAN which are obtained in step 7. *Interface – Or-Vi*
9	VIM at Site#A	Allocates the virtualised resource for connecting to the WAN at Site#1.
10	VIM at Site#A -> NFVO	Returns the response for allocating the virtualised resource #1 for connecting to the WAN. The VIM returns resource identifier which is used for identifying virtualized resource at the VIM. *Interface - Or-Vi*
11	NFVO -> VIM at Site#A	Requests to allocate the virtualised resource#2 connecting to the WAN. The NFVO sends information for connecting to the network connectivity over the WAN which are obtained in step 7. *Interface – Or-Vi*
12	VIM at Site#A	Allocates the virtualised resource #2 connecting to WAN.
13	VIM at Site#A -> NFVO	Returns the response to the request for allocating the virtualised resource #2 for connecting to the WAN. The VIM returns resource identifier which is used for identifying virtualized resource at the VIM.

		Interface - Or-Vi
14	NFVO	Completes the instantiation process for VNFs with the VNFM(s).
15	NFVO -> OSS/BSS	Returns the results of NS instantiation request.

If overlay technology is used, after step 13 the setup of the overlay tunnel would be requested by the NFVO to the VIM at Site #A which would allocate the corresponding separate virtualised resource for the overlay tunnel.

Other considerations

This use case has been described as a mono site. However, it could be applied also to a scenario where an NFVI-PoP extends over several sites connected by the WAN infrastructure. The VIM controlling such an NFVI-PoP would be deployed remotely to the sites being managed, which would be also in line with the optimization of the infrastructure deployed in distributed locations.

3 Network Slice QoE/QoS Control

As defined in Part I, Section 2.1.2, different services need different QoE/QoS levels that may involve different metrics to be monitored and, hence, interpreted in a different way. In Part I we described how the generic framework works and how it interacts with the other elements of the architecture: SDM-C and SDM-X for the control within a network slice and SDM-O and the MANO stack for the orchestration among different network slices. QoE/QoS information is essential for the correct behaviour of network control through SDM-C or SDM-X applications: in this section, we also explain in full details how the SDM-C and SDM-X approaches can be used to perform innovative network procedures ore enhance existing one with new features made available by the 5G NORMA innovative centralized approach. Therefore, the type and granularity of control messages flowing through both southbound and northbound interfaces are discussed briefly discussed here. Summarizing, the solutions described here are:

- We start with a general discussion on how to Implement and enforce the QoE/QoS parameters by using the WP5 enhanced controller. More specifically, in Section 3.1 we describe the role of the QoE/QoS in one of the 5G NORMA demonstrators (i.e., Demo 2) and how the defined procedures will be implemented there.
- Section 3.2 describes how QoE/QoS levels are enforced through the enforcement points, as explained in Part I, Section 3.3.2. Simulative results explain how the overall performance of the network can be improved by using the proposed mechanisms.
- Sections 3.3, 3.4, 3.5 describe three exemplary SDM-C application. The first one is related to the core network only and envisions the application of reinforcement learning techniques for the routing of flows in the network. Then, two solutions for RAN network functions (MAC Scheduling and ICIC) that benefit from the centralized view of the SDM-C to perform joint core access optimization.
- As described in Part I, Section 2.2.3, Network Functions are shared through the SDM-X controller. Most of the network functions that are going to be shared by using the 5G NORMA architecture will be RAN NFs. Although more details on shared RAN NFs can be found in [D4.2], in Section 3.6 we describe an exemplary SDM-X application that controls a MAC Scheduler NF shared among different network slices.
- Finally, in Section 3.7 we assess the QoE/QoS of a future network service such as vehicular networking. Useful insights on resource control and network orchestration on a large-scale scenario are described here.

Most of the solutions described in this section have been published in or submitted to international journal of conferences, or disseminated in different ways (i.e., the 5G NORMA demonstrators).

3.1 Service Aware QoE/QoS Control

Service Aware QoE/QoS Control in 5G NORMA is performed using the QoE/QoS framework defined in Deliverables D5.1 and D3.2 [D5.1] [D3.2] and previously exemplified in section 2.1.2 in this document (Intra-slice management and control – see figure 2.4). Obviously, the basic idea is to provide the mechanisms to control QoS and/or QoE depending on certain service parameters which are specified for each slice and tenant depending on their specific service deployed on the network, causing a re-orchestration request when the specified QoE/QoS levels are not meet. That re-orchestration will typically consist on scaling operations, but also, they could include the migration of VNFs between different network nodes (computing nodes and/or PoPs), and also, by redefining certain VNFs forwarding graphs (e.g., including or removing certain VNFs in forwarding graph already deployed to improve the QoE/QoS parameters).

A specific example of this is the work being performed in the context of the 5G NORMA Demo number 2 in the WP6, which is described in the Intermediate Report IR6.1 [IR6.1]. This consists on the deployment of two different slices for two supposed different verticals running different services:

a) A LL slice, focused on real-time physical measurements triggered by the reading of QR labels.
b) A MBB slice, focused on adding contextual captions to streaming media according to the user profile and surrounding context.

This Demo #2 shows how different network slices with different KPIs in the SLA could be orchestrated and executed on the same infrastructure.

For the 1st slice a so-called “Factory of the Future” service is deployed; with this service the final users are assisted by an augmented reality application providing real-time measurements in a hypothetical large area factory. It is assumed that different devices are spread in such large area, and real-time measurements on those devices could be triggered by reading certain QR labels distributed in different places across the factory. In order to support real time information, the network slice should be orchestrated in such a way that the core network functions are located close to the end user, i.e., into the edge network cloud.

In this case, the re-orchestration is performed by migrating a VNF (the SP-GW) from the Central Cloud to the Edge Cloud (i.e., close to the final user). To get this, the monitoring function is expected to gather information from the infrastructure monitoring modules; the QoE/QoS Mapping functions should assess whether the related KPIs are fulfilled or not, and based on that, they should trigger the SDM-C in order to request the re-orchestration when it is necessary. When necessary, the Core Network functions (and the associated application servers) are migrated from the central to the edge cloud according to the network condition. The overall demo plot and setup is shown in Figure-3-1 below.

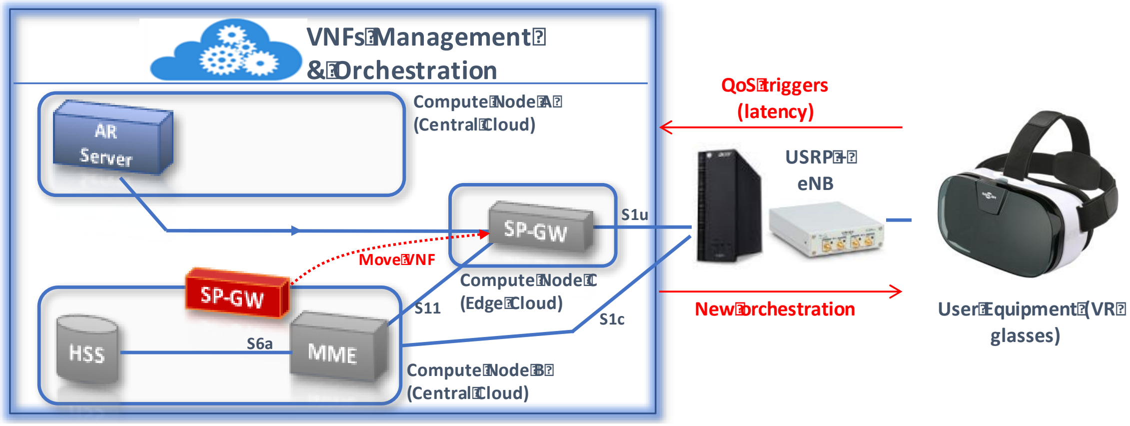


Figure-3-1: LL Demo Concept

On the other hand, the 2nd slice consist on a MBB service to add context-based captions on a video streaming system depending on the user profile (age, mother language, preferences…) and certain environmental conditions (location, video content…). These parameters (user profile and environment conditions) are used here as QoE influence factors.

Figure-3-2 below shows the main blocks we are considering for the demo to develop this concept.

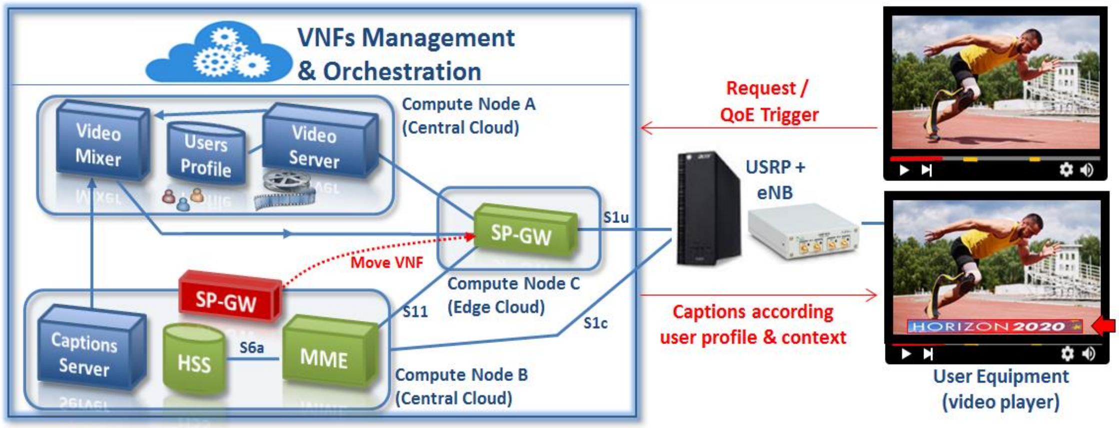


Figure-3-2: MBB Demo Concept

The UE consists on a device able to reproduce video (laptop screen, smart phone, tablet…). The big blue rectangle on the left represents the cloud infrastructure with the VNFs Management and Orchestration components; it contains all the VNFs necessary to provide the service. The green blocks (HSS, MME and SP-GW) together with the eNodeB and Universal Software Radio Peripheral (USRP) box in the middle are the main blocks of the LTE SAE architecture[7]. The blue blocks are the specific functions for the captions service itself; they are the Video Server, the Users Profile Database, a Video Mixer and the Captions Server Function (CSF). The Video Server Function (VSF) is the host dedicated to deliver the videos with the capacity to play and store multiple video streams. The users profile database stores the user information that is relevant for this service (age, preferences and language). The CSF is a repository with the different captions the system could generate; they could be simple text strings, images audios or even other videos. Finally, the Video Mixer Function (VMF) is used for dynamically perform the overlaying of the live video feed with the selected captions; its output is delivered to the end user via the Serving Gateway embedded into the SP-GW function.

In this case re-orchestration is performed, not only moving certain functions from the core to the edge cloud, but also, by updating the VNF-FG of a service that is already deployed and running (i.e., a service providing video streaming without captions). In a simplified way, the initial VNF-FG would be similar to Figure-3-3.

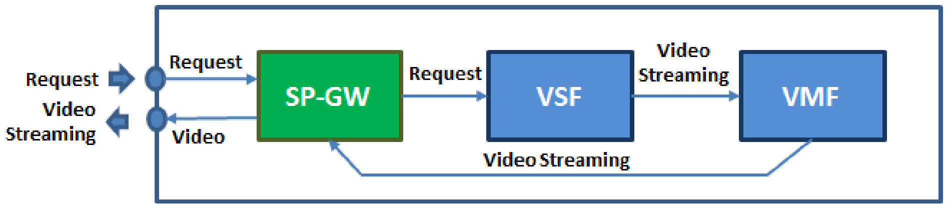


Figure-3-3: VNF-FG Before re-orchestration

However, once the re-orchestration is performed to add the requested captions the VNF-FG is updated to include the new CSF block, becoming similar to Figure-3-4.

[7] S-GW and PDN Gateways are built-up together into the single SP-GW VNF.

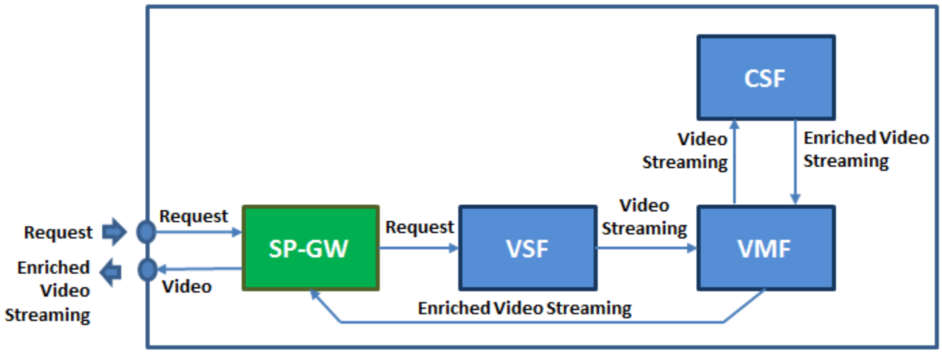


Figure-3-4: VNF-FG After re-orchestration

Beyond these examples from the WP6, the following Figure-3-5 shows in a more general way a simplified sequence diagram which illustrates how the user re-orchestration request would be processed in a Service Aware QoE/QoS Control scenario, including the main blocks in the 5G NORMA QoE/QoS framework.

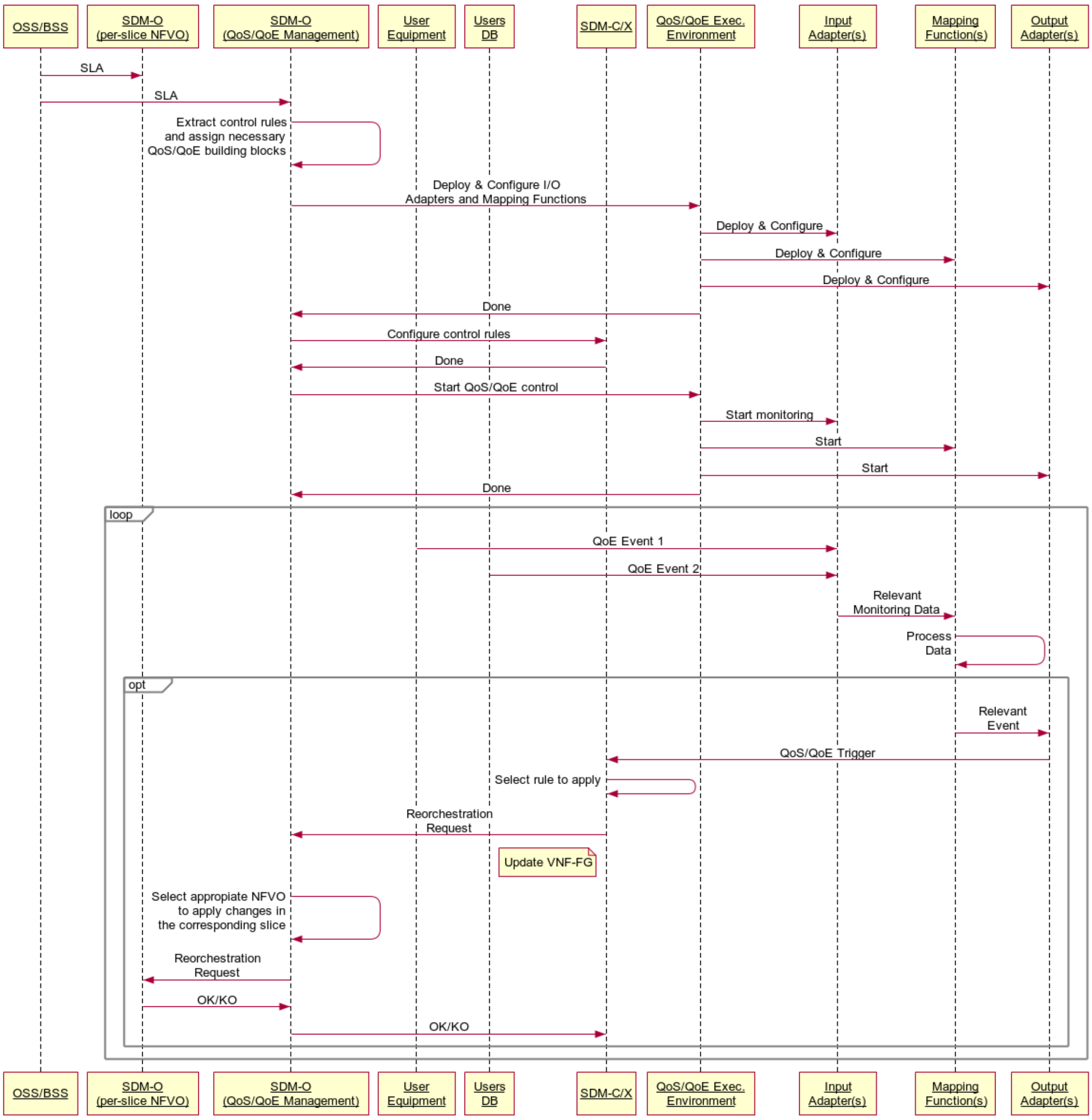


Figure-3-5: MBB Slice. Simplified Sequence Diagram

As we see, the diagram shows a hypothetical case were the UE and a User's DB are used as QoE influence factor sources; in general, the monitoring will be implemented at different processing points in the network, collecting measurements related to the behaviour of the network or the service, but for this case the relevant information is supposed to be collected from the Users DB and the UE. That information will be monitored by a (or a set of) Input Adapter(s), which are feeding the deployed QoE/QoS Mapping functions, which in turn are sending significant events towards the SDM-C/X components through the corresponding Output Adapter(s).

An important point here is that, if the parameters to be adjusted are slice-specific, then a specific Output Adapter connecting with the corresponding SDM-C will should be triggered; otherwise, if the relevant parameters are shared (e.g., certain RAN scheduling parameters), then a specific Output Adapter connecting the SDM-X controller would be used. This behaviour (parameters under control, Input/Output adapters to be deployed, connection with the SDM-C or SDM-X, rules to apply on each component…) is expected to be defined in the SLA for each tenant and slice, and should be provisioned from the OSS/BSS system through the SDM-O.

The QoE/QoS trigger could be generated in very different ways depending on the service requirements. For example, for the WP6 Demo #2 described before, some captions could be generated just after an explicit request from the final user to improve his user experience, or also, could be automatically generated depending on other QoE influence factors, such as the user profile stored in certain profile database (e.g., the user could be a person with a hearing impairment), some environmental parameters (e.g., ambient noise), or also, using real-time tracking signals to generate contextual captions associated to certain advertising campaign (e.g. when the user enters in certain geo-fence). Obviously, the monitoring sources would be different for each case, so the InP should provide the tenants the possibility to configure the different monitoring sources in the network, and also, the ease of including service-specific monitoring parameters to provide enough flexibility as well.

As we see, the 5G NORMA SDM-C is a central piece in the Service-Aware QoE/QoS control.

3.2 QoE/QoS Enforcements

The basic principle and concept of QoE/QoS enforcement and monitoring mechanism was studied in the early phase of 5G NORMA and introduced in [D5.1] to support fully dynamic, context aware QoE/QoS management. The work was continued to define the specification for deploying and implementing the proposed QoE/QoS enforcement solutions in 5G NORMA architecture as well as the verification of the proposed implementation and deployment options.

3.2.1 QoE/QoS Service Flow management

The proposed QoE/QoS enforcement functions has the capability of collecting real-time insights of the end user applications flows and QoE/QoS requirements and enforcing the targets dynamically. It is also responsible for providing the indications on the service parameters dynamically to the other functions such as radio related functions so that the QoE/QoS requirements can be taken into account by those functions. However, the interaction between QoE/QoS enforcement point/functions to the other functions especially the radio functions requires the definition of the corresponding interfaces, information elements, procedures and roles, which is the main focus of this section.

In LTE, the granularity of traffic and service differentiation is based on data bearer granularity with pre-configured QoS parameters such as priority, guaranteed bit rate. Therefore, all the traffic aggregated into the same bearer cannot be differentiated in QoS handling. 5G service flow (SF) and sub-service flow (sSF) was introduced in [D4.1] on QoE/QoS control, which provides the finer granularity or in-bearer/flow differentiation of QoE/QoS handling. Reusing 5G SF and sSF concept, the QoE/QoS SF and sSF management procedures are studied to facilitate the proposed QoE/QoS enforcement solutions.

During SF establishment, the QoE/QoS enforcement point obtains the QoE management policies. The policies define the default service parameters to be applied to the SF and the policies for additional QoS/QoE differentiation within the SF. The QoE/QoS enforcement point monitors the user data packets to detect flows and application sessions that require dedicated service according to the policy. In the sSF management context, the QoE/QoS enforcement point is able to automatically define the QoE/QoS parameters as proposed in [D5.1] on QoE/QoS target definition and based on that the service parameters for each sSF can be defined during sSF establishment or sSF modification.

A valid sSF establishment/update logic executed by the QoE/QoS enforcement point based on monitored user data traffic and the policies is shown in Figure-3-1:

- Unknown/unidentified traffic: no sSF establishment is needed (default service).
- Identified but deliberately unmanaged traffic (e.g., traffic that falls under the best effort category): in case unknown and unmanaged traffic needs to be differentiated according to the policy, an sSF that handles all unmanaged traffic can be established. Or if such sSF already exists, map new traffic into the existing sSF. Alternatively, the distinction may be enforced internally by the QoE/QoS eforcement point without the need to establish sSF. In this case, unmanaged traffic is not mapped to any sSF, but handled as the default service by the lower layer. In case no differentiation is needed between unknown and unmanaged traffic, no special handling in QoE/QoS enforcement point for the unmanaged traffic is needed either.
- Managed traffic: establish a dedicated sSF in case the traffic requires specific service according to the policies. The service parameters of the sSF are derived from the QoS/QoE requirements of the corresponding traffic. Sessions with similar QoS/QoE requirements may be grouped into the same sSF to reduce the number of sSFs and sSF management overhead. In that case, the service parameters of the sSF are derived from the composite QoS/QoE requirement of all sessions/flows mapped to the same sSF.

  For managed traffic, the QoE/QoS enforcement point also detects when the sSF service parameters need to be changed (e.g., due to change in the QoS/QoE requirements of the application sessions) and thus initiates an sSF modification.
- The QoE/QoS enforcement point terminates an sSF in case the corresponding traffic is terminated. There may be multiple reasons for termination, such as the user has closed the corresponding application, there was a handover, or the UE disappeared (ungraceful termination, detectable via reasonable timeout mechanism).

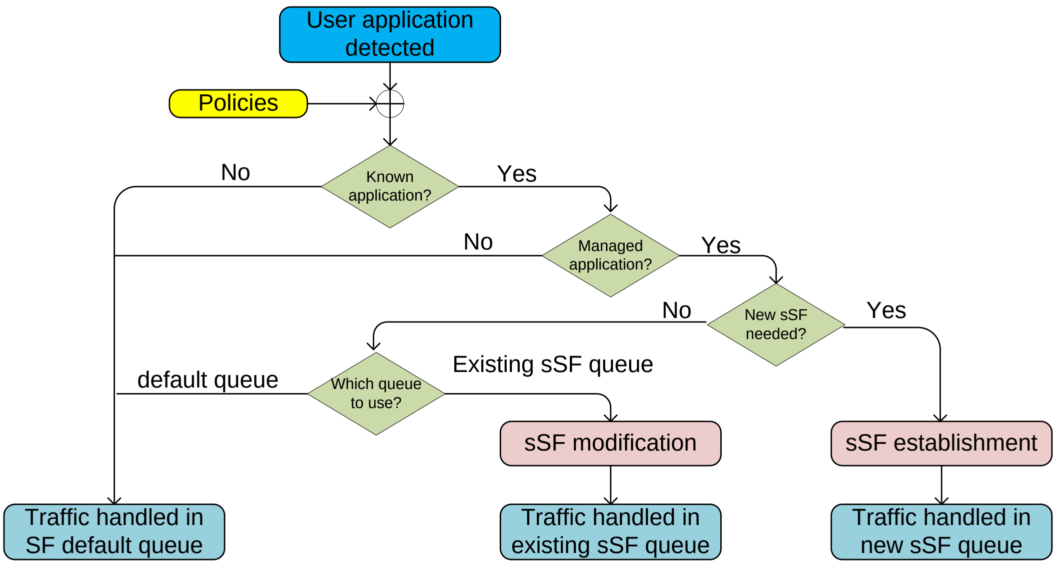


Figure-3-6: sSF management logic

There are two alternatives to implement sSF management procedures:

- using the control plane signalling. This option allows more flexible way to define and communicate QoE/QoS parameters without banding with presence of user plane data. It is also possible to have proper acknowledgement and failure identification and recovery mechanism, therefore is more reliable approach.

- using in-band user plane signalling. This option doesn't require extra control plane procedures for sSF management, thus has the benefit of less overhead. It also enables fast adaptation of sSF management based on the change of service requirement. However, it is more sensitive to user plane packet losses or delays.

Therefore, the coordinated approach of control plane signalling and user plane packet marking is considered to achieve more dynamic, on demand and real-time sSF management. Herein, the establishment, modification and termination of sSF is done via control plane signalling, in which the sSF identifier (sSF ID) and the associated service parameters are exchanged between enforcement points of different network elements including UE if applicable. The service parameters are defined by QoE/QoS enforcement point and describe the data layer treatment that the data packets should receive on an abstraction level understood by the VNF of data layer (e.g., scheduler parameters, weights, etc.).

Upon establishment of sSF, the in-band per-packet marking mechanism is used to identify by VNFs of data layer the sSF that each data packet belongs to. The design of in-band packet marking should be efficient in terms of overhead, i.e., it should not convey redundant information such as QoE/QoS information that applies to all packets within the same sSF and communicated during sSF establishment or modification. On the other hand, it should allow the indication of additional information that applies only to that specific packet. Finally, the marking should also be closely aligned with the actions on the sSF management related control plane interface in order to orchestrate the establishment/termination of new sSFs on the C-plane and their marking on the U-plane.

When QoE/QoS enforcement point decides to establish a new sSF, it can autonomously allocate a new sSF ID and request control plane to initiate sSF establishment procedure. On the other hand, user data packets belonging to the new sSF may already be available for transmission. These packets should not be held back until the sSF establishment signalling is completed, especially if the data flow require low latency. Instead, the QoE/QoS enforcement point should tag/mark the packets with the newly allocated SSF ID and forward them to the next function in the service chain. Since the sSF establishment procedure might not be finalized yet, hence the VNF in the following functions of the service chain may not have specific information on the treatment of these packets. Those packets may be mapped to the default data layer buffer and handled in the default way. In order to give the possibility of differentiating the first few packets of newly identified sSF mapped to the default radio buffer and other packets in the same default buffer, a simple service parameter field (e.g. a few bits on urgency indication) may be introduced in the packet marking to enable the exceptional handling of the data transmission via packet marking. Once the sSF establishment procedure is completed, the packets that are marked with the new sSF ID may be moved from the default data layer buffer to the buffer assigned to the new sSF and served there according to the specific service parameters defined by the enforcement point for the new sSF.

3.2.2 Deployment of QoE/QoS Enforcement Point and Verification

5G NORMA architecture enables flexible placement of NFs so that QoE/QoS enforcement functions/point as VNF may have different deployment options as illustrated in Figure-3-2:

- deployed at edge cloud only: this option makes the QoE/QoS enforcement functions closer to the radio related functions and thus can access to and collect radio specific information with less overhead. It is able to efficiently manage the QoE/QoS in cooperation with the radio functions as well as manage traffic served locally without being routed through the central cloud.
- deployed at central cloud only: this option has an e2e view including not only the radio status but also transport network, mobile backhaul services and resources (including physical and virtual ones) etc.. Thus, it is able to efficiently manage the e2e QoE/QoS including the situation in case of congestion in transport network.

- dual deployment at both edge and central cloud: this option is motivated by the different role of enforcement points in edge and central cloud. For instance, the edge cloud enforcement points may mainly enforce the QoE/QoS from radio resource point of view and central cloud enforcement points look at more from transport resource perspective in addition to radio resource.

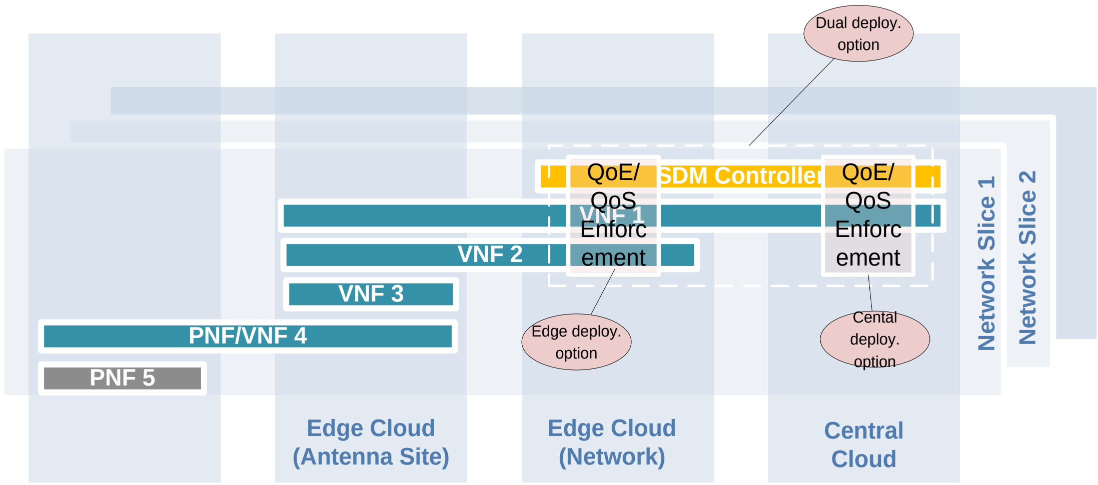


Figure-3-7: deployment options of QoE/QoS enforment point

The dual deployment is preferable whenever possible in order to achieve optimal performance. In this deployment, the aggregation level of the handled traffic in each enforcement point may not be the same. For instance, the network wide policy enforcement (such as enforcing fairness or balance traffic according to any criteria among different radio access technologies) may be handled in the enforcement point deployed in central cloud. The same kind of fairness or balance policy may be enforced by the enforcement point deployed in edge cloud, but only among a cluster of 5G APs that are managed by the edge cloud.

However, deployments of edge cloud only enforcement point or central cloud only enforcement point are also valid options. For instance, the former may be deployed by network design such as very high capacity transport networks is available and only the radio access network may be a bottleneck. While the latter may be deployed when computing processes in edge cloud become insufficient. In both case, the efficient operation can be reached with single deployment option but may have the cost of extra analytics especially in central cloud option.

The proposed QoE/QoS enforcement functions as well as the deployment options are evaluated by simulation. The traffic model used in the simulation include two popular applications: YouTube and web browsing as these represent different QsE/QoS demand and traffic profiles. YouTube application as a multimedia download requires a bandwidth derived from the individual and momentary media rate of each session. Web browsing application as an interactive data download requires a download time target that is translated to the amount of bit rate based on the progress of the ongoing session and the amount of data that is expected to be transferred still (backlog). In addition to the YouTube and web browsing applications, bulk data download (representing non-interactive background traffic) was also added to the traffic mix as the third application, simulated as large file downloads.

The following performance metric are used in the simulation to evaluate QoE/QoS enforcement deployment and operation alternatives:

- **Ratio of successful video downloads:** defined as the number of successful video downloads relative to the total number of video downloads. In our simulation, YouTube users experiencing pre-buffering above one second or more than two stallings abort their ongoing video download, which qualified as an unsuccessful session. Videos without user abort were downloaded fully and counted as successful ones.

- **Normalized HTTP download time:** defined as the download time of a given data amount (e.g. 1 MB).
- **FTP throughput:** defined as average FTP throughput measured at each user side (i.e. per connection FTP throughput) and the aggregated FTP throughput of all connections (i.e. total FTP throughput)

Simulation results of QoE/QoS enforcement points in edge cloud

First, the deployment alternative of QoE/QoS enforcement point in the edge cloud is simulated. In this simulation, the different granularity level of QoE/QoS enforcement functions as described in Section 3.3, Part 1 is evaluated.

The successful rate of video download with and without proposed enforcement functions are shown in Figure-3-8 for the entire traffic mix range. In case of low network load, good YouTube experience in term of video download successful rate can be delivered in both with and without the proposed enforcement function as there is no resource competition among the applications in low load range. The performance gain of the proposed scheme becomes significant at higher load. Without proposed QoE/QoS enforcement, YouTube sessions start to degrade immediately as soon as the average user bit rate drops around the media rate and cause a sudden decrease in the satisfaction ratio. The proposed enforcement scheme can adaptively computes and enforces the bit rate/bandwidth target for each YouTube video: Therefore it is able to maintain good YouTube experience and prevent abortion even if the average per user bit rate calculated by taking into account all the users drops below the YouTube media rate.

The performance of centralized enforcement point and distributed enforcement point is also compared in the simulation. As shown in Figure-3-8 a) and b), the distributed enforcement points can achieve almost as good YouTube experience as centralized option due to the reason that the enforcement point handling YouTube application will not start to decrease their allocation whereas enforcement instances with background traffic would reduce the amount of traffic they put into the network. Therefore, the bulk traffic is first reduced, solving the congestion on the radio resources and making it possible that the YouTube sessions still achieve the targeted bit rate they need. However, the simulation of distributed enforcement option is implemented in the way that each individual enforcement point monitors the traffic of its corresponding user and makes enforcement actions independently without synchronizing its decision or collecting input from other enforcement instances monitoring traffic. There is a slight performance degradation in distributed option in case of very high network load.

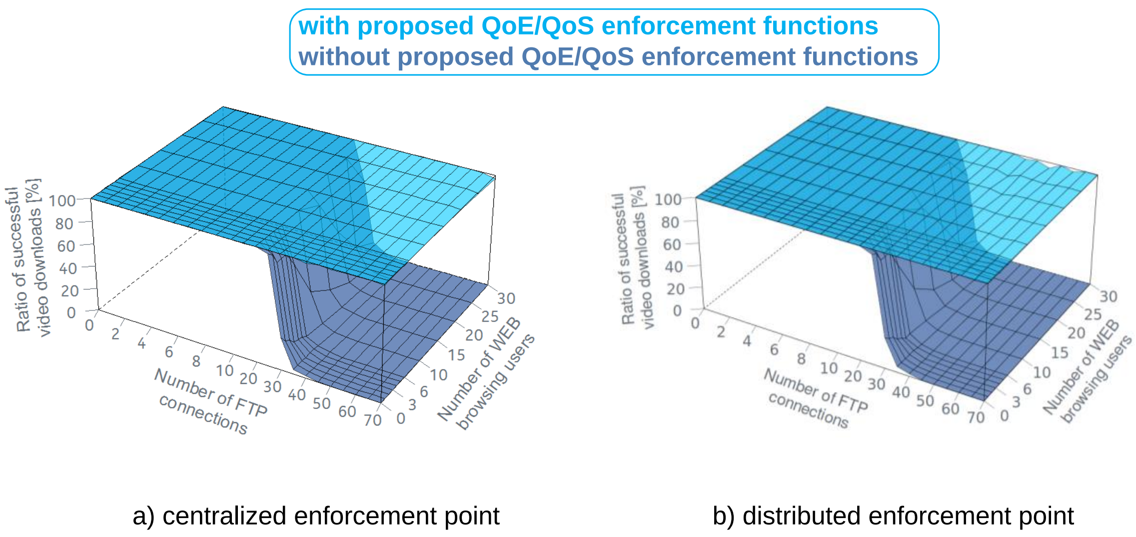
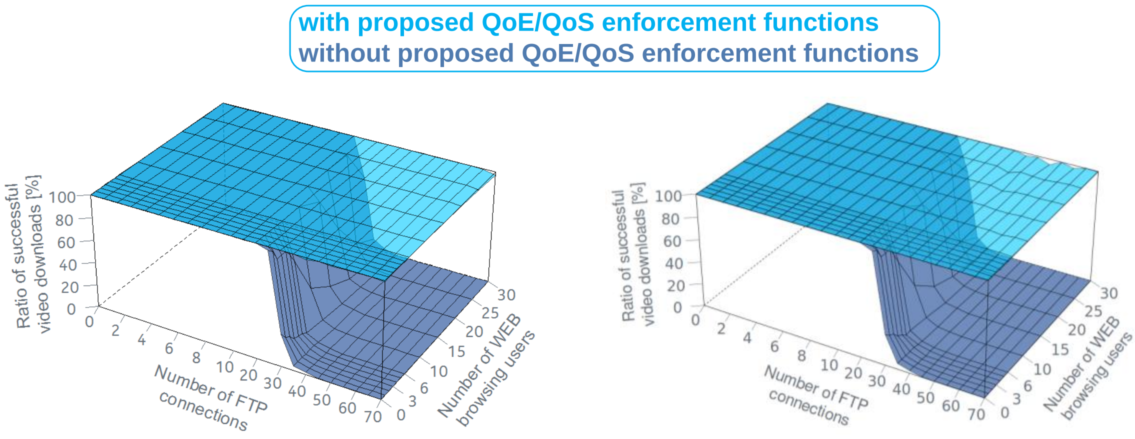


Figure-3-8: video download successful rate when enforcement point deployed in edge

cloud

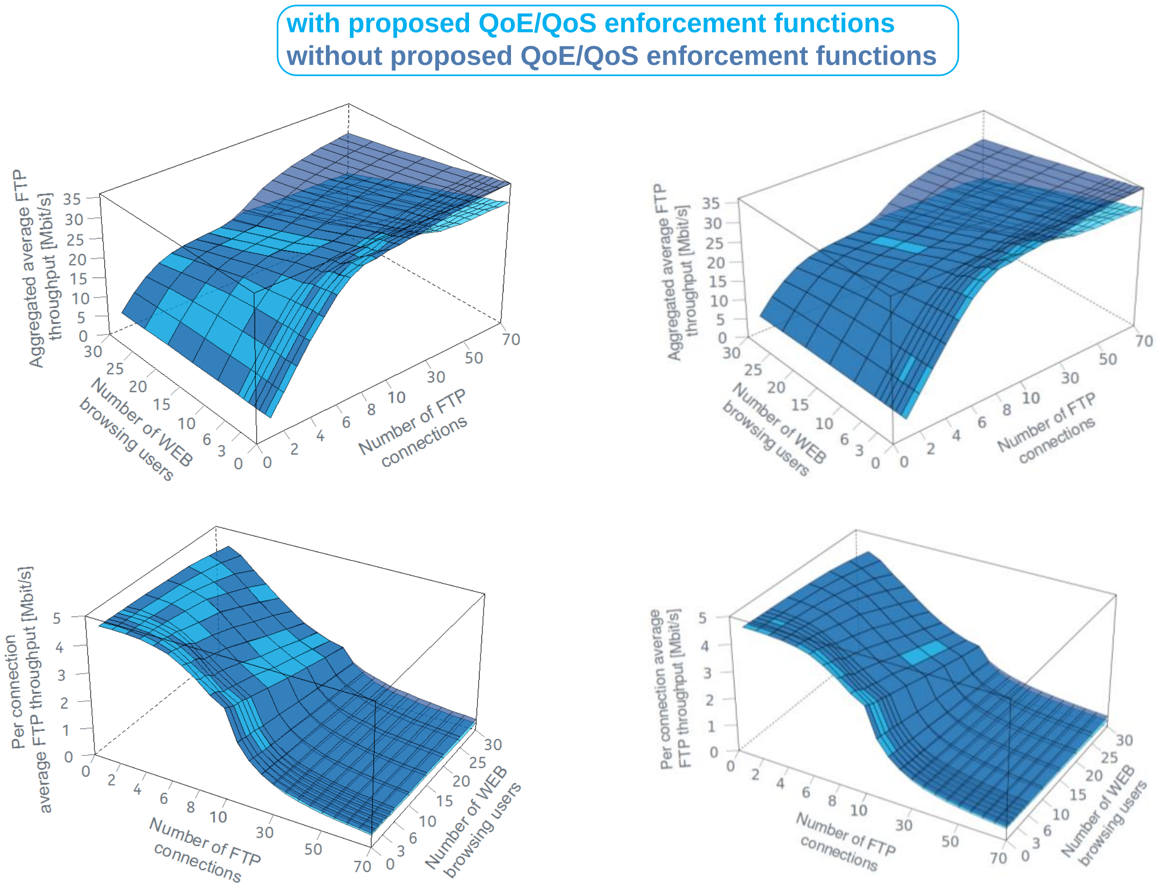
The results of HTTP download time for web-browsing applications are shown in Figure-3-9 to compare the performance with and without the proposed QoE/QoS enforcement functions as well as centralized and distributed enforcement points. It is shown that the web page downloading time without the proposed QoE/QoS enforcement functions increases sharply when traffic load is getting higher and higher. However, the proposed enforcement scheme can keep the downloading time small even in case of high traffic load.



a) centralized enforcement point b) distributed enforcement point

Figure-3-9: normalized webpage download time when enforcement point deployed in edge cloud

The cost of good QoE achievement on YouTube and web-browsing applications is also studied in the simulation in term of the degradation on FTP throughput as the proposed scheme tries to decrease the FTP data download first in case of congestion. The total FTP throughput with and without proposed scheme are shown in Figure-3-10. The results show the total FTP throughput is degraded with the proposed enforcement scheme due to enforcement of YouTube and web-browsing applications targets. However, the results also shown the degradation on per-connection FTP throughput is not significant. As FTP kind of bulk data download have no exact QoE target and good user experience only requires progressive smooth download. This kind of per-connection FTP throughput degradation should not impact QoE of FTP download application.



a) centralized enforcement point

b) distributed enforcement point

Figure-3-10: FTP throughput when enforcement point deployed in edge cloud

Simulation results of QoE/QoS enforcement points in central cloud

When enforcement points are deployed in central cloud, the end to end resources includes both radio and transport resources can be taken into account in the enforcement actions. However, there is the challenge for enforcement point to manage and enforce the QoE/QoS target in this case due to the delay between the enforcement point and managed resources especially radio resource. Therefore, the simulation is performed for different transport capacity versus radio capacity, which transits the congestion point from radio access network to the transport network.

The YouTube download success ratio is shown in Figure-3-11. The simulation results show that the proposed enforcement scheme can improve the YouTube experience even with relative high transport delay. However, with the increase of transport delay, the improvement on YouTube successful ratio becomes smaller. This is partially caused by delayed radio congestion status and partially caused by TCP performance degradation over a high delay link. The latter makes the pre-buffering time of YouTube application longer and eventually causes the termination of the YouTube session in the simulation if pre-buffering time is larger than 1 second. This simulation results also indicate the need of dual deployment of enforcement points in both edge and central cloud, especially when transport network is the bottleneck.

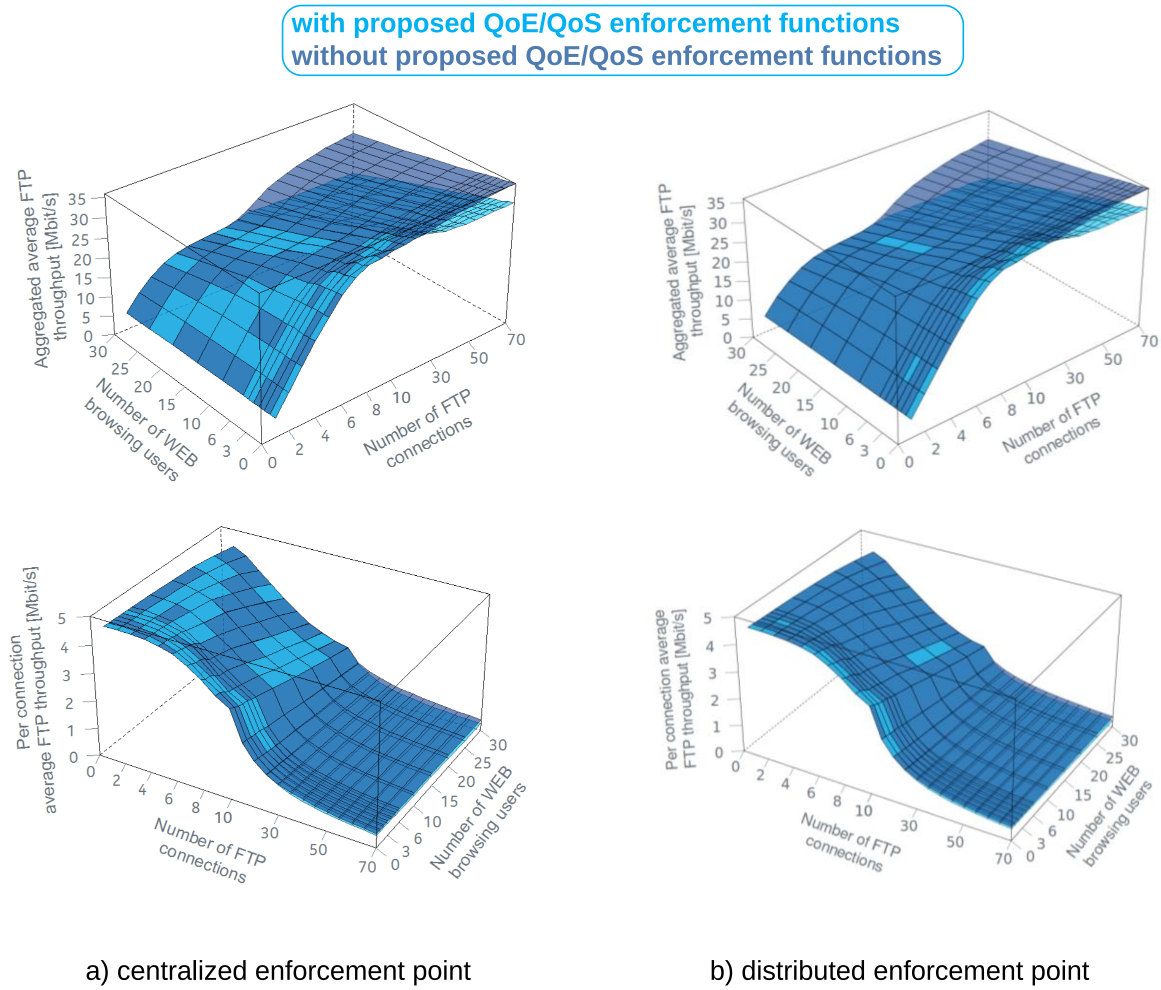


Figure-3-11: video download success ratio when enforcement points deployed in central cloud

The web page download times are shown in Figure-3-12. The proposed enforcement scheme can enforce good download times with all transport link configurations corresponding to different transport delay. This shows that the enforcement functions in central cloud has the capability to override the class based transport QoS scheme and enforce the application specific QoE targets efficiently.

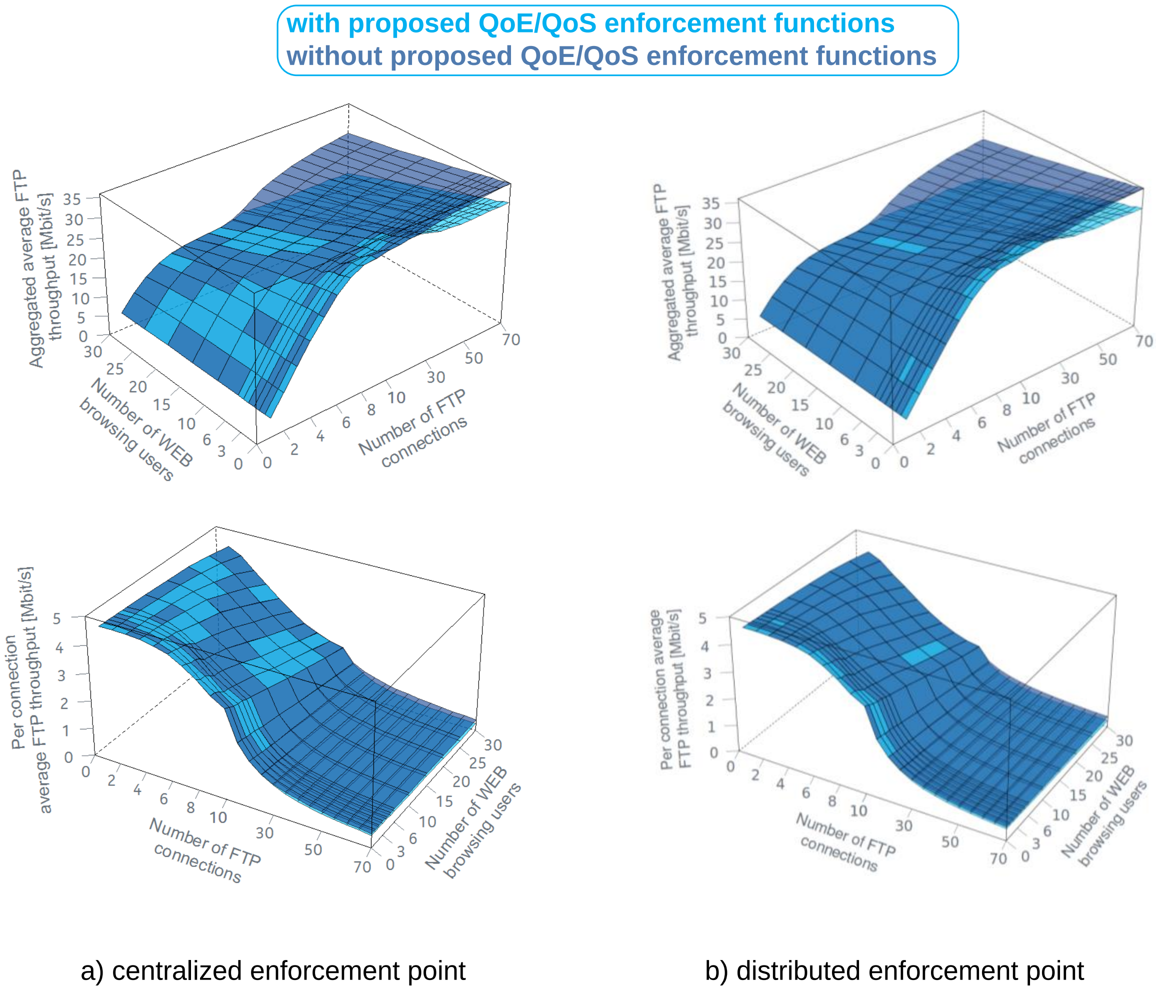


Figure-3-12: normalized webpage download time when enforcement point deployed in central cloud

3.3 QoE based routing

The architecture proposed in this document plans to control end-to-end QoE throughout its network. In this section, the focus is on extending SDN routing control with QoE considerations. The SDM-C will have a modified control of the data forwarding, aiming at improving QoE.

An application using the SDM-C northbound interface will dynamically adjust the route for a flow based on the users' QoE feedback. The controller will enforce this route by commanding the forwarding elements at its disposal.

Ideally, any proposed solution should be adaptable and reactive, gradually modifying its configuration towards improving QoE. The approach taken here is to use reinforcement learning (Q-learning).

These are the main steps when using Q-learning for routing control:

- Nodes have a Q-table, each entry indicating the estimated QoE of the link to each of their neighbours
- The end-user sends a QoE feedback that travels back through the routing path
- Nodes use this feedback to update their Q-table accordingly.

The SDM-C must provide some numerical value for the user QoE feedback (Mean Opinion Score, for example). The architecture proposed in this document has a QoE/QoS monitoring & mapping system that could provide this value.

Proposed Algorithm

In this section, a description of the proposed algorithm for QoE-based routing in the 5G NORMA architecture is presented.

- This is the formula used by a node ***x*** to update its Q-table, after receiving the feedback from a node ***y*** ahead on the flow:

$$QoE_{xy} = QoE_{xy}^{t-1} + \alpha \times ((\beta \times (\max QoE_{y*})) - QoE_{xy}^{t-1})$$

- $\mathrm{QoE_{xy}}$ is the estimated QoE value in node *x's* Q-table when directing the flow through node *y*
- $\mathrm{QoE_{xy}^{t-1}}$ means the previous calculated QoE value
- $\max \mathrm{QoE_{y*}}$ means the best estimated QoE among the values on node *y's* Q-table
- ***α*** and ***β*** represent learning rate and discount factor, respectively.
  - Learning rate determines to what extent the new information will override the old information
    - ***α = 0*** : disregard any new information
    - ***α = 1*** : consider only the most recent information.
  - Discount factor determines how important future rewards are for the system.
    - ***β = 0*** : only consider the current rewards
    - ***β = 1*** : means look for long-term rewards

- Using the formula below, node ***x*** calculates the probability of neighbor ***y*** being selected as the next hop.

$$p^{xy} = \frac{e^{\frac{QoE_{xy}}{T_e}}}{\sum e^{\frac{QoE_{x*}}{T_e}}}$$

- Probability of choosing link ***xy*** is the exponential of the current calculated QoE between node ***x*** and node ***y*** QoE_{xy} divided by a temperature T_e, divided by the sum of exponential of the current calculated QoE with all the neighbors of node ***x***

- The temperature controls the trade-off between exploration and exploitation
  - Exploration consists of trying many different links. High temperature leads to exploration.
  - Exploitation consists of continually using the links with good QoE. Low temperature is conductive to exploitation.

- The system starts by exploring a lot, eventually exploiting the good links discovered. So, the temperature value is set to decay with time, starting high, then gradually decreasing

Simulations

In order to evaluate the routing scheme proposed here, simulations were conducted in Matlab. These simulations consist of four parts: a random graph generation, network parameters generation, simulation loop, and QoE assessment.

Random Graph Generation

Random graphs were generated using the CONTEST Matlab tool box [1]. First, an Erdos-Renyi random graph with 10 nodes and 15 edges was created. Another procedure to randomly add mores edges. A check was made to make sure all nodes had at least 2 edges connected to each one. Finally, a source and target node were chosen based on the node pair the widest distance between them. An example can be found in Figure-3-13.

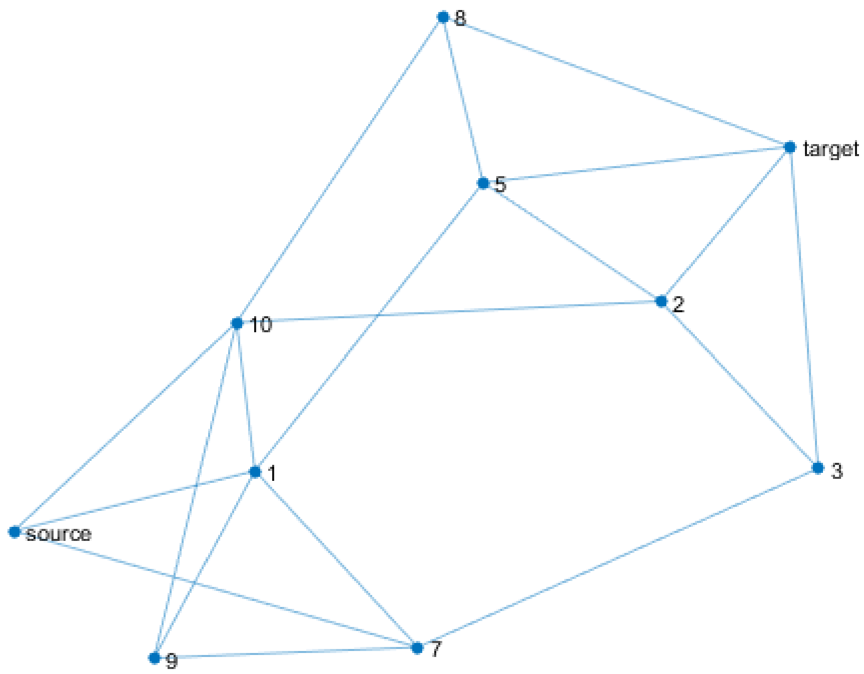


Figure-3-13: Random graph generated for simulations

Network Attributes

Since it was necessary to evaluate the QoE objectively, it was necessary to pick a service type and find a formula for calculating the QoE for that service. The type of service chosen was file transfer. This formula can be used for calculating the QoE for file transfers [2] [3]

$$QoE_{filetransfer} = 2.1 \times log_{10}\,[0.3 \times bw \times (1 - Pe)]$$

bw = bandwidth
Pe = packet error rate [0..1]
Every edge in the graph has these two attributes (bandwidth and packet error rate), which vary by a small variation randomly regularly during the simulations.

The value given for the QoE was always modified during the simulations to be between 0 and 5, to imitate a MOS that a user might give.

Simulation Loop

The simulation ran for 50000 simulation steps. At regular intervals, the QoE was estimated (more about that below), small variations on the network attributes were added to the edges, and the temperature variable was reduce by a small percentage. These were the frequencies for each:

- QoE assessment: every 200 steps
- Attribute variation: every 100 steps
- Temperature reduction: every 1000 steps

For the packet error rate, the variation was 2% with a 50% chance of going up. For the bandwidth, the variation was 5% with a 50% chance of going up.

QoE assessment

Every QoE assessment step, three routing scheme were used to determine the best route from source node to target node.

- The already detailed Q-routing
- A modified version of the shortest path algorithm, that tried to find the shortest path with the highest bandwidth (referred from now on as MSP)
- A breadth-first procedure that treats all edge weights as 1.

For the calculation of the QoE using the above-mentioned formula, the accumulated packet error rate and the minimum bandwidth on the path were used. The goal here was to use the proposed routing scheme, a routing scheme that optimizes one network attribute, and one routing scheme that completely ignored the attributes.
At the end of the simulation loop, the average QoE for each routing scheme was calculated.

Results
The performance of the Q-routing scheme will depend on the specific graph, since the routing scheme depends on fine-tuned parameters (initial temperature $\boldsymbol{T_e}$, temperature reduction $\boldsymbol{RT_e}$, learning rate $\boldsymbol{\alpha}$ and discount factor $\boldsymbol{\beta}$). Using the example graph given in Figure 40, these are the optimal values for the parameters:

- $\boldsymbol{T_e} = 122.5$
- $\boldsymbol{RT_e} = 0.0505$
- $\boldsymbol{\alpha} = 0.626$
- $\boldsymbol{\beta} = 0.99$

The average estimated QoE was for each routing scheme:

- Q-Routing: 4.0783
- MSP: 4.2711
- Breadth-first: 3.4438

Q-Routing was about 5% below the modified shortest path. Considering attributes that affect QoE (Q-routing and modified shortest path) gives better estimates than breadth-first. The discrepancy between Q-Routing and MSP are related to bandwidth having a bigger influence than packet error rate, Q-Routing taking a bit longer to react to changes and potentially implementation issues. In any case, the difference is not big (5%), so it should be imperceptible to the end-user.

Figure-3-14 shows for each Q-Routing assessment step the estimated QoE value. It's possible to see that the Q-routing scheme doesn't take long to react to changes in the network attributes.

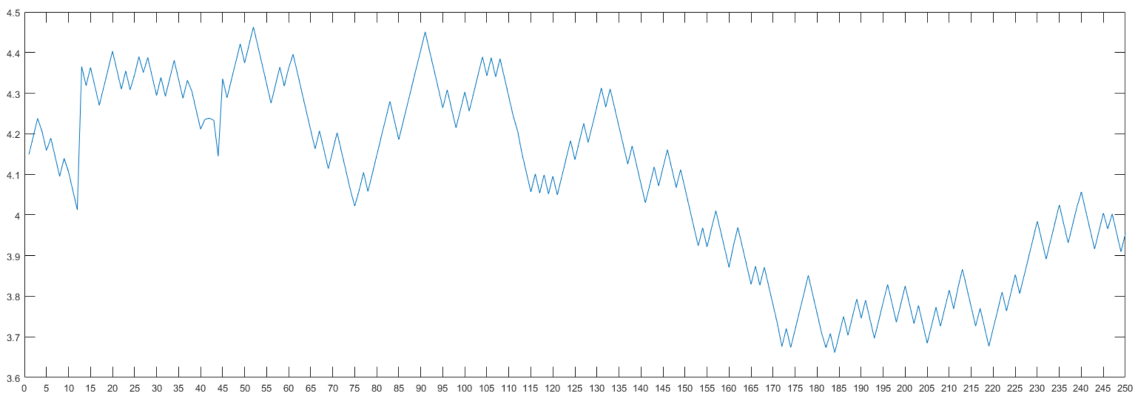


Figure-3-14: Estimated QoE for each Q-routing assessment step

3.4 Video Pre-Scheduling SDM-C application

3.4.1 Research objective

It is expected that streaming applications will continue stressing the network through the usage of 4k content, etc. Therefore, the optimization and adaptation of streaming strategies to wireless networks is still a challenging task.

The main goal of this research work is to investigate how the SDN paradigm can bring improvements to achieve QoS requirements to video streaming context. Our study focuses on finding suitable design of a video-aware scheduling for IP–based multimedia streams at the application layer atop SDN architecture, identified here as SDM-C. We consider a wireless shared channel scenario, where several streaming users share the common bandwidth and transmission power at the same time. The targeted streaming protocol is HTTP adaptive streaming know also under the name as Dynamic Adaptive Streaming over HTTP. All the video flows will be served by the layer 2 scheduler as a best effort flows. One of the targets of the video pre-scheduler is to enhance RAN resource allocation and take advantage of the SDN paradigm.

3.4.2 Mobile Broadband Slice and video pre-scheduling SDM-C application

Following 5G NORMA architecture, the MBB slice is composed of a set of VNFs deployed in the central and the EDGE cloud as the following:

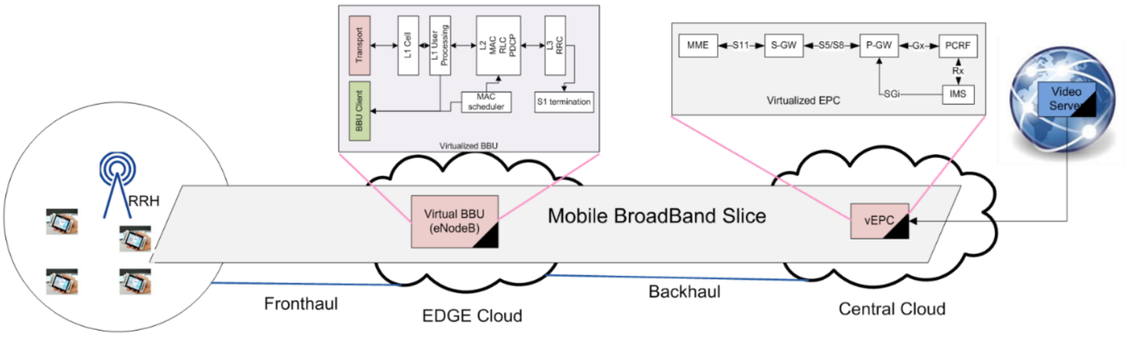


Figure-3-15: An example of MBB network slice instance

The video client could be Silverlight (Microsoft), Apple Live Streaming (Apple), or other clients. The client interacts with the video server by sending HTTP GET and HTTP SEND as depicted in Figure-3-16.

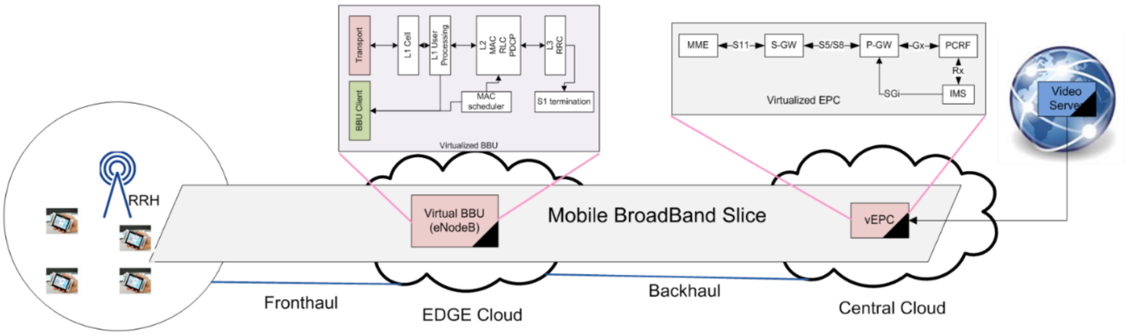


Figure-3-16: HTTP based protocol for video delivery

In this interaction, the video quality is impacted mainly by the available throughput between the client and the server. Each video segment requested by the client, will be downloaded in a certain time dependent on the throughput. If the downloading time exceeds some threshold, the client will decrease the video quality and requesting a video segment with a lower representation.

So, the client having better channels will have a better quality than others. Our proposal is to control the amount of video data received by each client by giving more data to the client suffering from a bad channel. A client having a full playback buffer will not be impacted by the reception or not of a video segment.

So, we propose to add in the Service Function Chain of the video flow a video pre-scheduler VNF running atop of SDM-C as proposed in Figure-3-17.

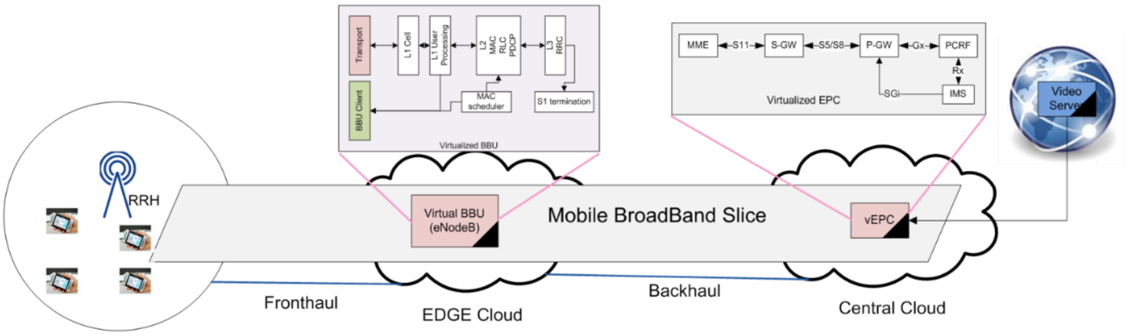


Figure-3-17: Video Pre-scheduling and SDM-C

The problem of designing the video-pre-scheduling application becomes a problem of managing the queues between the Core and the RAN. For that, we focused here:

- Develop a CRUD application able to Create/Read/Update and Delete queues in the ovswitch dynamically from the SDM-C northbound. This queuing model will allow us to control the queues from the application layer and accordingly schedule flows.
- Take advantage of SDN controller and OpenFlow protocol to map different flows in the created queues.
- A basic scheduling scheme is implemented to demonstrate the effectiveness of the proposed model.

3.4.3 Implementation of the video Pre-scheduling SDM-C application: the platform

In this section, the proposed solution is presented. Firstly, the architecture of the platform is detailed. Secondly an overview of the controller's northbound API is introduced. Thirdly, a queueing model as well as the mechanisms of managing QoS and queues via OVSDB pro-tocol is given. Finally, the scheduling approach is theoretically investigated and the result-ing scheduling algorithm is provided.

Today, HTTP based protocol such as MPEG-DASH , Apple HTTP Live Streaming, or Microsoft Smooth Streaming, are the most deployed to deliver video contents. They offer the possibility to the client to adapt to the available bandwidth by boosting up its video to the highest possible resolution. In fact, video content is encoded into different formats with distinct

bit rate and resolution and spitted into subsequent pieces of chunks (each of which of dura-tion of 2-10 seconds). Thus, a set of video chunks with different capabilities are available to the client who will select the most appropriate one according to its channel rate. Since video streaming is typically carried out by stationary users who can sometimes receive highly unfair service by the radio network, this results in some users receiving very poor video quality due to the lower rate allocated to them by the network.

We propose a scheme to leverage this shortcoming by selectively sending more content to sessions when they have better link quality while providing sufficient rate guarantees to keep their buffers from under-flowing and offering a stable video quality.

Based on the many options regarding controllers it has been decided to use the OpenDaylight (ODL) controller [60], because it provides the most basic features of an SDN controller such as providing topology information and network statistics. Furthermore, the OpenDaylight controller offers the Restful API that allows our developed application to easily communicate with the OpenVswitch via OpenFlow and OVSDB protocols.

Platform architecture

The design of our video-pre-scheduler platform can be divided into two parts. The first one consists of how to be able to manage queues in the ovswitch from application level. The second part concerns the design of the scheduling algorithm.

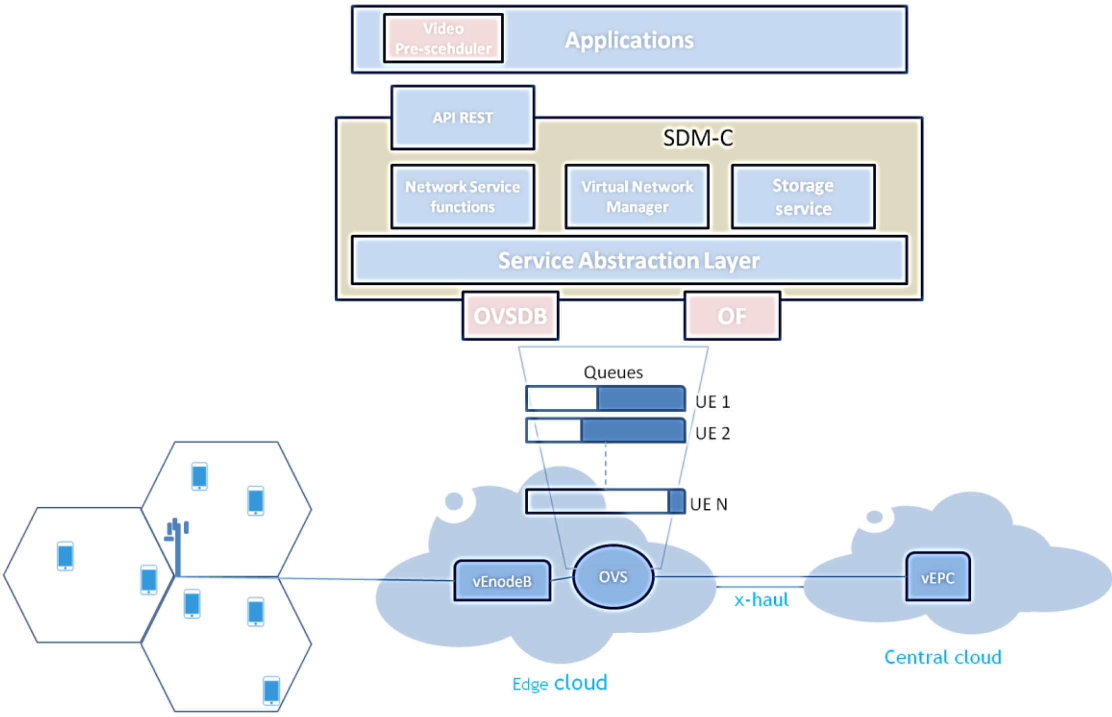


Figure-3-18: System Architecture

The designed application provides a CRUD (Create, Read, Update, Delete) API, exposed to SDM-C. This application allows external entities to create queues and manage Open-Vswitch. Whenever these REST requests are issued, our application assembles a new queue-related request and dispatches it to the appropriate Openvswitch. Once the queues are creat-ed, a pre-scheduling application could be activated and take profit of the link variation.

Figure 51 depict the overall architecture of our solution. The proposed solution can split into two parts; one that handles the queuing model, depicted in Figure 52, and the other defines the scheduling strategy.

The main components of the system are described as follows:

SDM-C: The architecture of our solution is based on the SDM-C paradigm. The Open-Flow protocol has support for centralized monitoring of switches for different statistics that can be useful for our proposed scheme. Secondly, the controller can add/modify forwarding rules at switches; therefore, it provides a centralized point to decide routing of flows which is received as output from the pre-scheduler application to prevent queue buildups.

Ovswitch queues: Using the northbound API exposed by the SDM-C (ODL in our implementation), queues in the ovswitch are created and managed from the application layer.

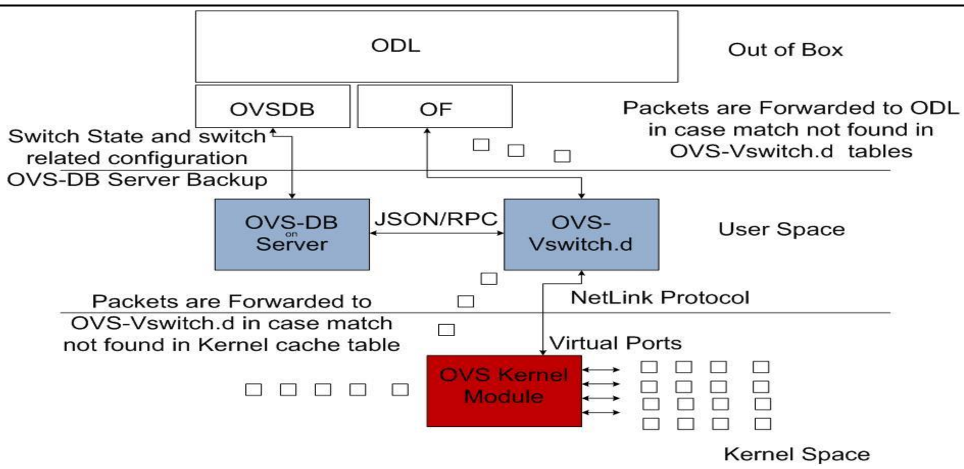


Figure-3-19: OVS and SDM-C interfaces

OpenVswitch has 3 modules: OVS-DB server, OVS-Vswitch.d and OVS Kernel Module.

OpenVswitch is typically used inside hypervisors for packet switching between vir-tual ma-chines.

OVS-Kernel Module and OVS-Switch.d communicate via NetLink Protocol, OVS-DB Server and OVS-Vswitch.d communicate via JSON/RPC.

OVSDB module in the SDM-C is responsible for backing up the status of OVS-DB Server time to time and also it can configure the OVSDB-Server from ODL. The configurations are related to creating virtual ports, bridges, tunnels, etc.

OVS-Vswitch.d is managed by OpenFlow protocol plugin in the ODL via OF pro-tocol. Main configurations are related to mapping virtual ports with openflow ports and packet forwarding logics. The status of OVS-Vswitch.d is backed up from time to time in the OVS-DB server module in the user space via JSON/RPC protocol.

OVS-Kernel module is responsible for packet forwarding (Layer 2 look up) based on the simple cached table (simple tables to get rid of performance issues).

If entry is not found in the kernel cache table it sends the packets to OVS-Vswitch.d module in the user space for decision and stores the decision in the kernel cache ta-ble for further forward-ing of the packet related to the same flow. Also if the entry is not configured in OVS-Vswitch.d it will be further forwarded to ODL.

Intel DPDK is a concrete solution to accelerate the performance by treating packets in the user space, for this we require to use Intel PCIe cards to be configured to by-pass the packets to us-erspace.

Flow Classification module: The flow classifier will classify the flow based on the header of the flow.

Pre-Scheduler application: An important component of our system is the pre-scheduling unit. Our aim is to design a pre-scheduler able to shape and allocate the streams in order to increase the performance of the system. Given a certain resource budget, e.g. the number of bytes in the ovswitch queues that are ready to be trans-mitted, the task of the pre-scheduler is to determine an allocation for each active flow that best utilizes this budget. This scheme is flexible and uses network re-sources efficiently.

Deep Packet Inspection integration capability

We have integrated the Deep Packet Inspection (DPI) enabled OVS that captures required in-formation for the SDM-C to prioritize certain traffics. During the operation, all the incoming packets will be cloned in the kernel space for DPI and will be sent to the user space DPI engine for analysis. The DPI engine has the ability to extract information that are encapsulated in those packets and are required for decision making. According-to our implementation, the DPI engine updates those flow tables in the user space for packet scheduling via respecting queues. The Plugin for DPI meta data abstraction receives list of information regarding those flows in the network e.g. source and destination address of each flow, etc, upon receiving those flows the SDM-C request the content servers for updates regarding their buffer status. The content aware service scheduler in the northbound of the SDM-C takes a scheduling decision using buffer status in the content servers, size of queues in the OVS, statistics regarding each flow in the OVS, and the information from the DPI engine. In our architecture, the flow scheduling decision will be uniquely taken in the user space of the open space and will be transmitted to kernel cache table until the change in the decision by the DPI engine

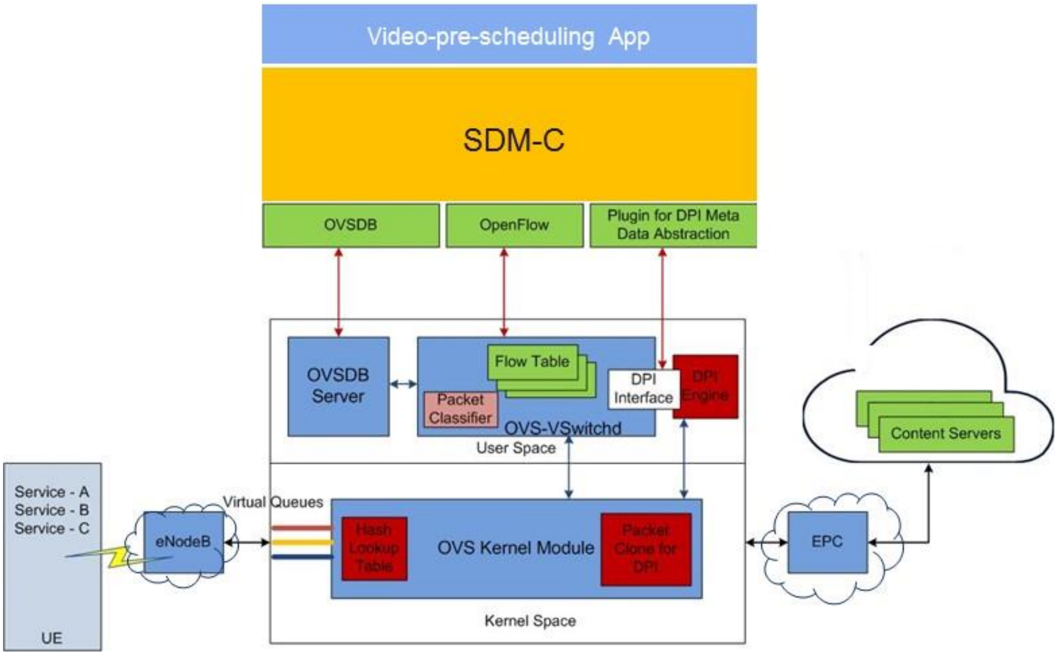


Figure-3-20: DPI integration in OVS and interface to SDM-C

3.4.4 Link and buffer aware scheduling algorithm

The streaming server forwards the packets directly into the ovswitch buffers, where packets are kept until they are transmitted to the eNodeB VNF. The latter implements a MAC scheduler taking care of scheduling user over the shared radio resources of the cell. It is important to notice that in our scheme, all the video sessions are considered as best effort traffic from a MAC scheduling perspective.

The final QoE of individual video users depend on their position in the cell, their mobility and the cell load.

The draining of the queues located in the ovswitch is controlled by a pre-scheduler deciding the amount of data should be received by the users. In general, the performance of the streaming system significantly depends on many parameters such as the queues management, the scheduling algorithm, the resource allocation strategy, the available, the number of users, etc.

Our proposed pre-scheduling algorithm takes into consideration the variations in the wireless link quality. Our scheme selectively sends more content from the queue in the ovswitch to user sessions at time when they are operating at higher radio efficiency while it gives them sufficient rate guarantees to prevent a playback buffer under-flow. This offers crucial improvement in the effective throughput of the wireless network. The proposed algorithm is described in [D5.1].
The algorithm is implemented following the diagram depicted in the Figure below. Each playback buffer has two status: steady and full. The full state indicates that no more data is needed to be sent to the UE. The state steady indicates that the network should consider to schedule the UE and send him additional data. The severity of missing data in the playback is analyzed in the second branch through checking the panic mode.

Two set of users are categorized in each scheduling period. Pool 1 hosts the UE which can still accept to not be served during the current scheduling period. However, pool 2 hosts the list of UE which are mandatory to be served.

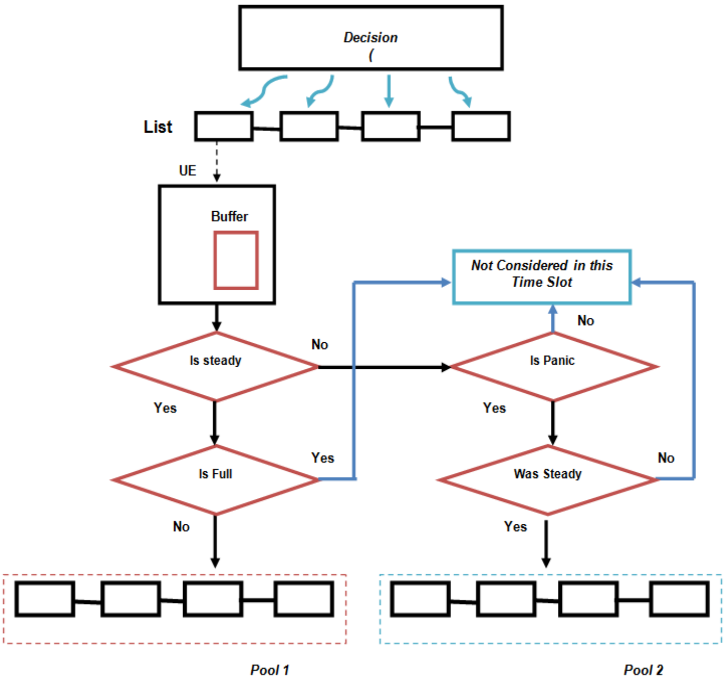


Figure-3-21: UE pre-scheduling decision diagram

3.5 QoE-aware eICIC

3.5.1 Introduction

The basic concept of QoE-aware eICIC mechanism was presented in [D5.1]. The proposal is to augment a game-theory-based optimization method for eICIC by integrating a direct service-aware measurement of QoE in the computed utility. Indeed, driving the global inter-cell interference optimization by QoE allows limiting the interference experienced by the mobile users in cell edge while improving the QoE over the network. Exploiting the QoE intelligence, the QoE-driven eICIC mechanism is in charge of deriving the optimal radio settings Almost Blank Subframe (ABS) and Cell Individual Offset (CIO), responsible of the inter-cell interference coordination, for all macro and pico cells of HetNet. ABS fix the silent (or transmission) period of macro cell base stations deployed and CIO triggers the users switch in pico cells. The work was continued to perform simulations for measuring the performance of the proposed function for 5G NORMA in [D5.2] and, to specify the deployment and the implementation of the proposed solutions in 5G NORMA architecture in [D3.3].

According to the new architectural concept of 5G NORMA, the SDMC paradigm utilizing an SDM-C application and the SDM-C controller, the QoE-aware eICIC function has been designed as a North Bound Interface (NBI) Application running at the top of SDM-C/SDM-X. The role of SDM-C/SDM-X is to control dedicated and shared Network Functions (NFs) respectively. In other words, SDM-C manages resources within a network slice and SDM-X manages a slice of shared network resources.

Different RAN slicing scenarios or slice multiplexing that corresponds to different ways of resource sharing (hardware and spectrum) between the slices is considered. The resource can be either completely isolated or either shared. As pointed out in [D4.1], three main options “related” to the OSI protocol stack (see Figure 4-4 of [D3.2]) can be applied: standalone slice (own hardware and spectrum), slice with shared resource (shared hardware and spectrum) or with own spectrum (isolated hardware and shared spectrum).

Depending on multiplexing scenario of the deployed slice, ABS and CIO is used by the local MAC schedulers of macro and pico cells hosting a standalone slice or a slice with shared radio resource. As a consequence, the QoE-aware eICIC function shall operate in:

- An optimization mode compliant with Intra Slice control corresponding to the RAN slice scenario, standalone slice and slice with own spectrum, where the dedicated *MAC* NF are SDM-C-controlled or,
- An optimization mode compliant with Inter Slice control corresponding to the RAN slice scenario, slice with shared resource where the common *MAC* NF are SDM-X-controlled.

The integration of QoE-aware eICIC at the NBI of SDM-C architecture in 5G NORMA architecture takes into account the two-above optimization mode.

The simulations and performance analysis are presented in the report in the scenario of standalone slice. In this scenario, the QoE-aware eICIC controls the inter-cell interference within an eMBB slice with HTTP adaptive streaming (HAS) video services as target application. The proposal is compared with a state-of-the-art approach maximizing an aggregated radio throughput-based utility to coordinate inter-cell interference in HetNets. Numerical simulations will be performed using a Matlab-based 3GPP LTE radio-compliant simulator extended with the QoE utility and with HAS users requesting heterogeneous video services. They show the HetNet capacity improvement in terms of both classical network (e.g. median user radio throughput) and user Key Performance Indicators (KPIs) (e.g. median QoE),

3.5.2 HetNet Inter-Cell Interference Coordination driven by Quality of Experience

The QoE-aware eICIC function is a two-tier model comprising an optimizer and a centralized coordinator/control modules [Trab14], [Trab16]. It is in charge to derive jointly the optimal radio settings ABS and CIO that are used by the local eNodeB schedulers of HetNets for fixing transmission and muting period in pico or macro cells and for user attachment to pico cells. ABS and CIO have a key role in the inter-cell interference coordination.

The function operates in three main steps illustrated in Figure Figure-3-10:

- **Collection step**: The centralized control entity receives QoE abstraction reports of new services requested by HetNet users that are derived/sent by QoE/QoS mapping module of QoE/QoS Assessment system [sec. 4.6.2.1 D3.2]. The central entity collects also the new service repartition (per zone, per cluster or per cell) once a modification occurs among the services requested by users (service repartition change or new service(s)). It collects also the updated radio capabilities or user distribution in the zone controlled by the control entity, from all eNBs Physical or Virtual Mobile Edge Infrastructure (eg. via X2 interface for physical structure), periodically or when a change occurs. SDM-C/SDM-X takes in charge this control function by collecting the metrics to resend it to the optimizer.
- **Optimization step:** The optimization entity derives the optimal ABS and CIO using a BR iterative algorithm, that is a game theory-based practical solution, that maximizes a QoE-based utility. The QoE abstractions, the service/radio states and the deployment configuration of the mobile edge infrastructure of the controlled zone are involved in the maximal utility derivation. The BR algorithm structure is made of 3 parts : a) Selection of a cell and store initial state S and utility U - by sampling states among the admissible (ABS and CIO) pairs - b) Virtual user scheduling (or emulation of user scheduling) in the cell according to a given LTE L2 scheduling policy and QoE utility computation - c) Selection of optimal sample : the best configuration for maximum value.

Each user i ϵ M (set of users) watching different videos has the following video utility (SSIM), denoted QoE-based utility:

$$q_{i,1} \cdot \log(q_{i,2} \cdot R_i + q_{i,3})$$

where Ri is the video encoding rate for the user i and qi,1 , qi,2 and qi,3 are video dependent parameters. The video utility function of eNodeB k ϵ N (set of BSs) is expressed with parametric encoding rate-utility model as follows:

$$U_k(R_i,q_i) = \sum_{i \in M_k} \mathbf{q_{i,1}} \cdot \mathbf{log(q_{i,2}} \cdot R_i + q_{i,3})$$

With Ri = αr_i. The weighting coefficient α reflects the bit added to encoded data due to the succession of protocol layers between the application layer and the MAC layer. The variable r_i represents the achievable radio throughput (in bits/s/Hz).

Distribution and Execution step: The centralized control entity sends periodically to the eNBs of P/V Mobile Edge Infrastructure the updating of the derived values of optimal radio settings (ABS and CIO) that are delivered by the optimizer. They are then used by the local schedulers for transmissions or muting or pico cell switch. SDM-C/SDM-X takes in charge this control function.

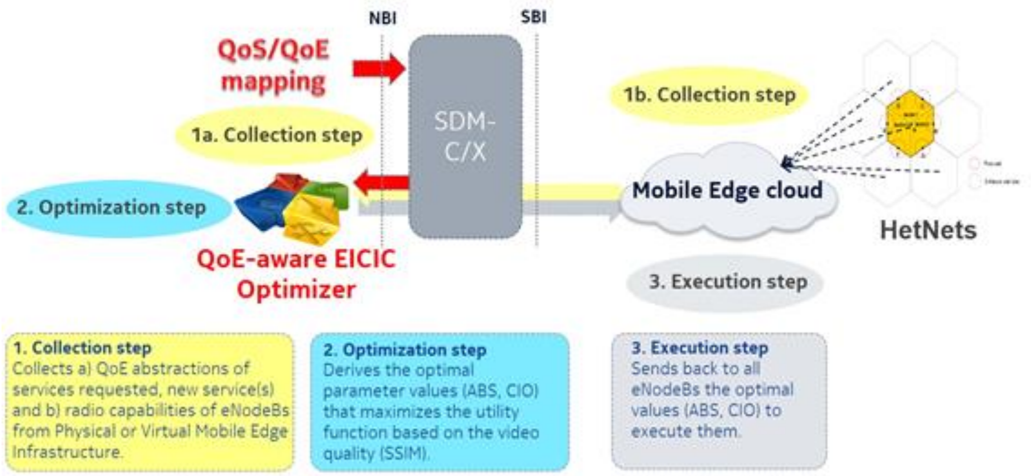


Figure-3-22: QoE-aware eICIC framework in SDN-based 5G network

3.5.3 Simulation results and Performance analysis

Simulator model

The simulations are performed using a Matlab-based 3GPP LTE radio-compliant simulator, developed by TU Wien’s Institute of Telecommunications [Vienna], that has been extended with an application layer delivering HAS video services and with a new QoE-based utility.

It includes an eICIC optimizer that derives ABS and CIO for each eNodeB (MC/SC) using the BR iterative algorithm that sequentially processes each cell. The optimization function maximizes the aggregated utility function either in SLR mode (user radio throughput metric) or in QoE mode (SSIM video quality metric). Among several options available for the L2 scheduler such as proportional fairness, absolute fairness (max-min), we opt for Proportional Fair Scheduling (PFS) algorithm used in LTE [Tuan] for the optimizer virtual scheduler. The users are served in Best Effort (BE) mode. The LTE transmissions in each cell are synchronized such that there is no intra-cell interference but only DL inter-cell interference.

The application layer emulates the HAS server functions for storage and delivery of both streaming videos and associated manifest files, also named Media Presentation Descriptor (MPD). Videos are encoded into different formats with multiple bit-rates and resolutions (named representation) and segmented into subsequent chunks (each duration of 2-10 seconds). Then, MPDs is then generated. It includes also the set of all actual discrete empirical pairs of (R ,SSIM) that are computed off-line (computation of SSIM for a discrete set of encoding rate R). [deliverable WP3]. MPDs files are sent to the network when an user requests a chunk at a selected encoding rate. Using e.g. curve-fitting methods, the set of all admissible values of the vector q = [q1;q2;q3] are derived within the network. Knowing q, the optimizer is then able to reproduce online the curve of rate-distortion of each video using (10) and then to quantify and track the evolution of the SSIM-based utility during the session.

Scenarios and Key Performance indicators

The extended simulator evaluates the optimization method for HetNet with the configuration parameters defined in Table I. We consider 9 video sequences extracted from various real time programs encoded in an H.264-AVC format [Schwarz] at 30 frames per second (fps), each sequence comprising 2800 frames. 10 profiles are considered for each video. The encoding rate considered ranges from 150 kbps to 20 Mbps. The HAS users deployed in the HetNet request different video contents encoded either in SD (640x480) or in HD (1920 x 1080). We run simulation sets with both the users and requested video services distributed randomly and uniformly in the cell for each run. To measure the performance of the proposed method, we use classical network metrics and user-centred metrics. Network metrics within and at the cell edge are respectively reported by median rate and cell edge rate. User-centred metrics within and at the cell edge are reported by median QoE, cell edge QoE and the QoE satisfied users density (per km2).

Table 3-1: Simulation Event Configuration.

Radio	LTE Rel. 8, SISO, 20 MHz, 3GPP recommended pathloss and shadow fading models
Topology	Hexagonal 1 ring, ISD 500 m, 1 site : 3 macro cells (MC) 2 small cells (SC) per MC at fixed location 0.5 ISD Antenna (MC/SC): Kathrein / omnidirectional Max Power (MC/SC) : 80W / 1W
HetNets	20 users / MC, 5 users / SC, a total of 570 users static users, L2 PF scheduling and Best Effort
Application	18 videos in SD or HD of 9 contents : Interview, Sport, Madonna, Football, Spiderman, Basket, Adele, Home, Bunny. HAS client
Optimization	$CIO \in \{0, 10\}\, dB$, ABS ratio $\in \{0, 5, 10, 15, 20, 25, 30, 35, 40\}\,\%$, Best Reponse, Sum Log Rate (SLR) or SSIM (QoE) utility

Table 3-2: Comparison of State-of-Art, QoE and without optimization mode.

SD / HD	Optim. Mode	Median Rate (Kbps)	Cell Edge Rate (Kbps)	Median QoE	Cell Edge QoE	User Satisfaction Ratio
0%/ 100%	W/o	907	121	0.46	0	40.5%
	SLR	981	**136**	0.52	0	45%
	QoE	**987**	127	**0.55**	0	**47 %**
100%/ 0%	W/o	907	121	0.82	0	76%
	SLR	981	**136**	**0.84**	0	**79 %**
	QoE	**987**	127	**0.84**	0	**79 %**

Simulation results and analysis

The goal of our evaluation is to compare the proposed eICIC algorithm involving QoE utility (QoE mode) with the optimization mode using SLR utility (SLR mode) and with no optimization at all (W/o OPTIM mode).

- Comparing the optimization modes: The performance results of the SLR, QoE and W/o modes are given in Table 3-2 for 2 opposite sharing schemes of HD and SD video streams and assuming a 20% amount of radio overhead data (a =0.2).
  - o Table 3-2 reports higher values metrics illustrating a gain when optimizing with SLR or QoE modes, instead when no optimization. This result bodes well with the eICIC objective of improving network system capacity.
  - o The cell edge rate values show that at the cell edge, the SLR mode provides higher user throughput than the QoE mode. But within a cell, the QoE mode offers a larger cell user throughput than the SLR mode. Indeed, the QoS utility allows a more fair resource sharing w.r.t rate for edge UEs whereas the QoE utility targets fairness in terms of QoE by allocating the resource to users allowing a

sufficient radio throughput for a QoE maximized. Thereby, it doesn't take care of users located at cell edge as well as the SLR mode does.

- o The cell edge QoE and QoE Median highlighting that involving QoE information provides gains in QoE only when the videos are all HD.
- o As for the cell edge QoE, cell edge QoE reports null values in all modes. The reason is that the user throughputs provided at cell edge are lower than the minimal encoding rate of the videos delivered (150 kbps).
- o The User Satisfaction Ratio (USR) shows, when 100% of HAS clients request HD videos, that the QoE mode provides a better USR than the SLR mode, achieving a USR gain of 3.5% with a USR equal to 46.6%. When 100% of users request SD videos, both optimization modes bring improvement and achieve the same USR performance of 78.6% with an identical gain of 3.5%. Although less spectacular the performance gains in the 100% HD scenario are highly promising because videos have much more impact on the cellular traffic than SD videos.

- Gain variation: to investigate in which applicative and radio layer configurations eICIC can benefit from QoE awareness, we plot in Figure-3-23 and Figure-3-24 the density of satisfied users (per km2) obtained in QoE mode and the gap between the total numbers obtained in SLR and QoE modes. The density value is indicated by the median density over all runs. The gap is measured in terms of users / km2. They have been evaluated for the following scenario: HD video percentage ranging from 0% to 100% and radio overhead data ranging from 0% to 40%. When the HD video percentage is higher than 50%, the QoE mode yields more satisfied users than the SLR mode. The density of satisfied users decreases when the HD percentage augments. The measured gap is positive and increases with the percentage of HD videos in both the figures. It can increase up to 10 users / km2 in case of 20 users/MC and to 16 users / km2 in case of 30 users/MC. The QoE mode yields higher number of satisfied users than the SLR mode when the users request more HD videos than SD videos.

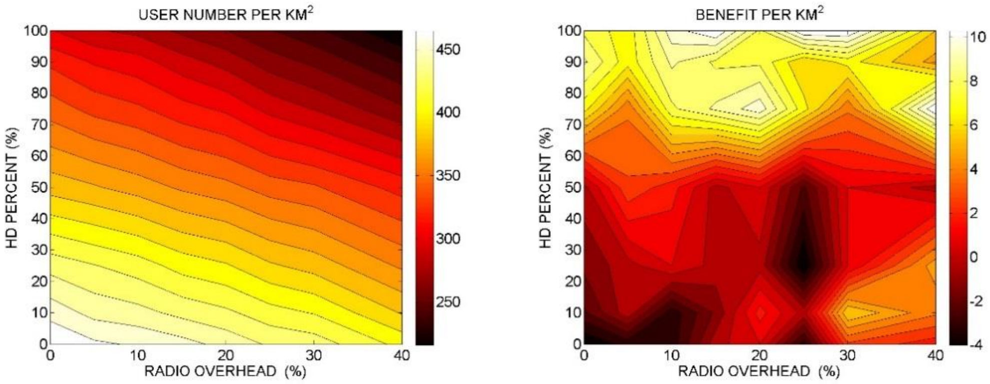


Figure-3-23: 20 users /MC and 5 users / SC

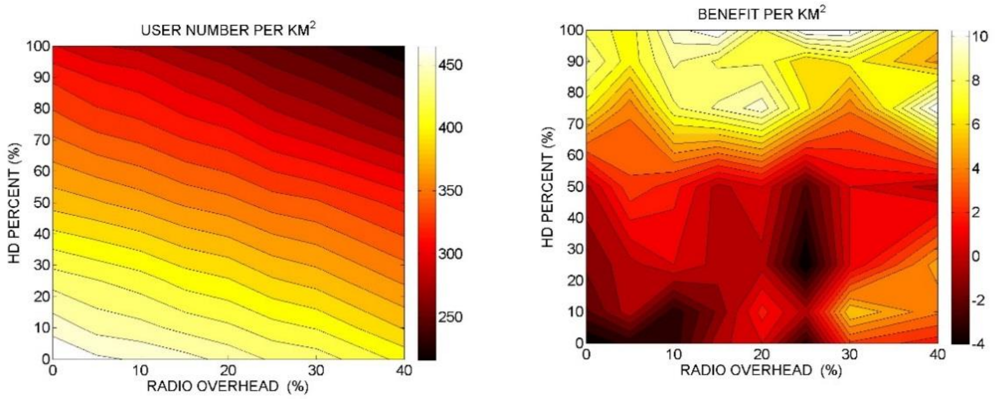


Figure-3-24: 30 users /MC and 5 users / SC

As conclusion, maximizing a QoE-based utility for interference mitigation is the best strategy to improve QoE when users request 100% of HD videos. The expected traffic growth caused by increasing HD video demands will all the more benefit from QoE driven interference mitigation. QoE adds value to dynamic eICIC for efficiently scheduling resource to mitigate inter-cell interference when the demands of users for high-data intensive videos grows.

Simulations show that QoE helps eICIC to efficiently manage the usage of radio resources, via ABS and CIO, within HetNets while supporting a higher number for data-intensive quality video services. However, the 5G NORMA architecture aims at to support multiple services in the same physical and virtual infrastructure. Therefore, future research activities will investigate algorithms with modified utilities to benefit fully from QoE in case of multi-services for future 5G networks.

3.6 Radio Resource Scheduling at SDM-C/X

As described in Part 1, Sections 2.2.2 and 2.2.3 the SDM-X controls the applications which are used to share resources among slices. Therefore, the SDM-X uses policies provided during orchestration process by the SDM-O to the corresponding application, which gives the opportunity to react dynamically on performance deviations during runtime of the system. With radio resource schedulers, possible ICIC and RRM SON schemes the SDM-X controls very complex applications, which have interactions with nearly all P/VNFs of the radio protocol stack on PHY and MAC layer. Detailed information on the functional decomposition and corresponding information exchange between the control plane and user plane of the mobile radio protocol stack defined by 3GPP can be found in [Arnold]. To derive appropriate decisions on how to react on decreasing slice specific SLA KPIs, by influencing scheduling decisions and using possible ICIC and RRM SON schemes, the SDM-X needs detailed data flow based QoS monitoring information. This needs to be collected by a monitoring entity and sent to the SDM-X.

Figure-3-25 shows the necessary relationships and interfaces between the SDM-X and relevant applications and functionalities to be able to control shared radio resources. The SDM-X is in charge of de-/activating and influencing shared applications among slices, instantiated by the SDM-O during orchestration process, as described in Part 1, Sections 2.2.1and 2.2.3.

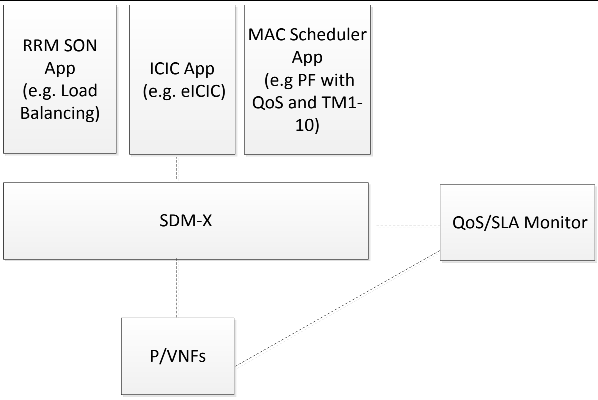


Figure-3-25: SDM-X Interfaces for radio resource scheduling

As emphasised in [COCOA] the SDM-X reacts on temporarily critical situations in the network with respect to slice specific defined SLAs during runtime. In Figure-3-25 the message sequence chart for the proposed algorithm is shown.

To meet slice specific service requirements in cases when BSs need to serve multiple slices with more than one service data flow each, it is crucial to react dynamically on critical interference situations in the network. The SDM-X needs the opportunity to optimize temporary appearing critical interference constellations in local parts of the mobile network. It should influence synchronous inter cell interference coordination (ICIC) schemes by dynamically adapting BS clusters (e.g. for Joint Transmission (JT), Coordinated Multipoint (CoMP) or coordinated beamforming) or it can adapt and de/-active asynchronous ICIC schemes (e.g. frequency reuse schemes, Carrier Aggregation (CA) based ICIC, enhanced (e)ICIC). It might by even possible to de-/activate the Medium Access Control (MAC) scheduler, if alternative schemes were orchestrated by the SDM-O.

Figure-3-26 shows the principle idea of the proposed scheme. A database with RRM applications, such as ICIC and scheduling schemes is defined and some of them will be placed to the physical nodes of the mobile network during the orchestration process by the SDM-O and executed as NBI application through SDM-X. The SDM-X takes care of the control of the RRM schemes during life cycle management.

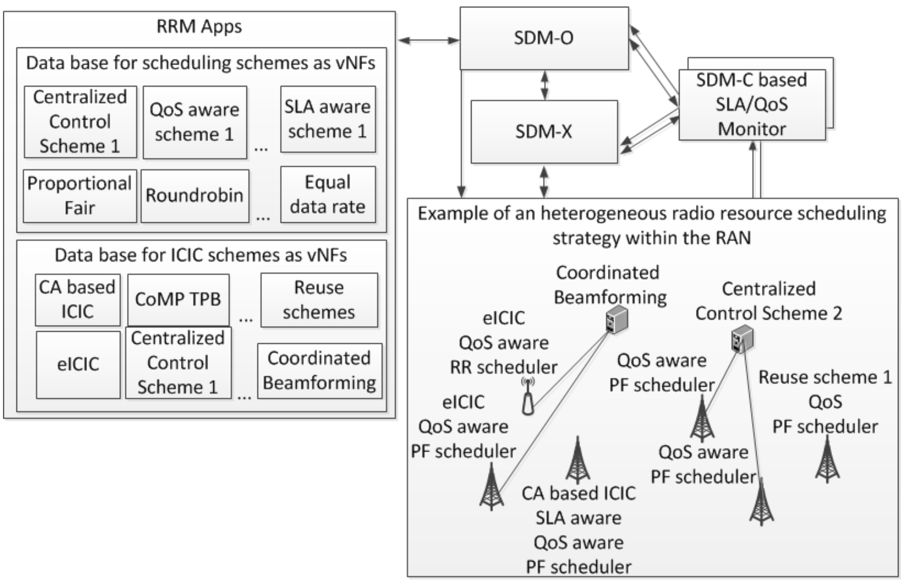


Figure-3-26: Principle of heterogeneous resource scheduling strategy to fulfil slice spe-

cific SLA requirements

Figure-3-27 illustrates a message sequence chart based on [D5.1] The procedure is described in the following:

After the SDM-O has set up at least one network slice on the physical infrastructure, service policies regarding QoS and SLA requirements for each slice are transmitted to the SDM-C based monitoring entity as well as to the SDM-X. In addition, it is necessary to provide further information to the SDM-X. It needs to know which VNFs are located to which physical nodes within the infrastructure. After successfully received the VNF mapping table the SDM-X takes over the control to influence the service chaining regarding the radio scheduling decision among shared resources of the MAC scheduler. As an alternative, the service chain adaptation could be included natively in the application in the sense if the app detects some trigger it will send new information via SDM-X to the VNFs. The SDM-X is in charge of de-/activating asynchronous ICIC schemes and defines dynamically radio resource and BS cluster maps for synchronous scheduling schemes based on the feedback of the slice specific QoE/QoS monitoring entities Once, multiple SLA indicators, derived from the QoE/QoS Monitoring module, such as a total amount of average throughput in a certain time period or a maximum delay probability are received the SDM-X checks whether a previously defined threshold violation occurs (step 1). Based on the analysis of slice specific threshold violation the SDM-X derives a decision to switch the ICIC, scheduling strategy or to change a BS cluster. This can be repeated several times to improve the SLA of a threated slice until a more critical Nth threshold is violated. After adapting the service chaining regarding the ICIC scheme or the scheduling metric, the SDM-X considers the monitoring information again (step 2). If the adaptation of the scheduling, ICIC scheme or the possible change of a BS cluster did not result into a performance improvement for currently instantiated slices and the SLA requirements cannot be fulfilled, the SDM-X needs to send a modification request to the SDM-O, which has to re-orchestrate (step 3) the slices based on alternative service chain templates.

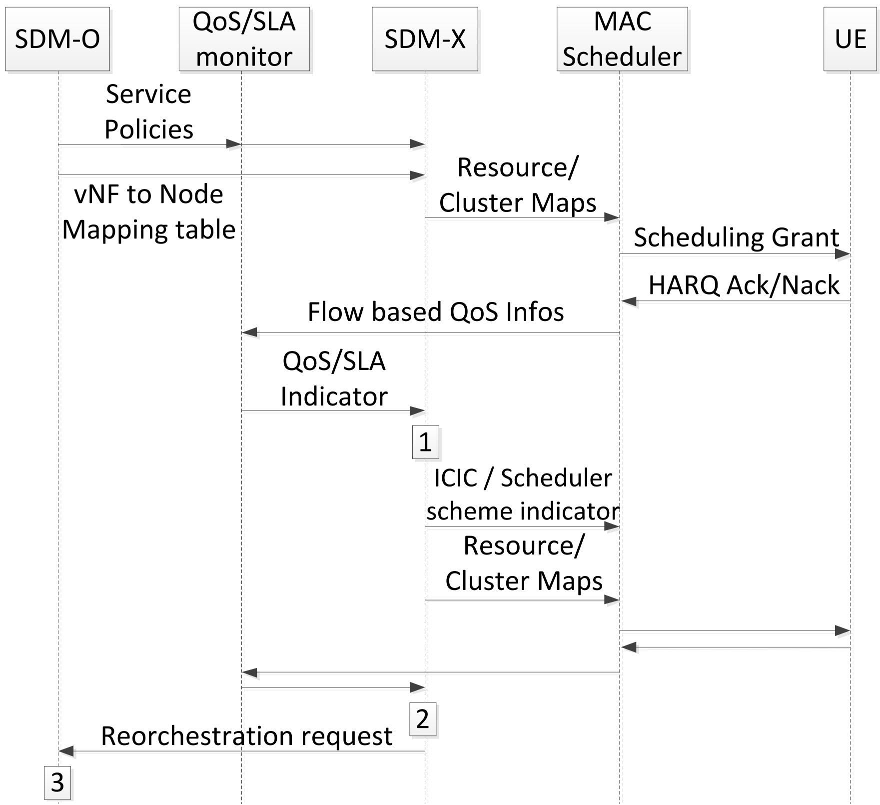


Figure-3-27: Message sequence chart for radio resource scheduling with SDM-X

In the following necessary signalling messages are defined, while the intention of each information element is summarized. Figure-3-28 gives an overview of the identified signalling messages.

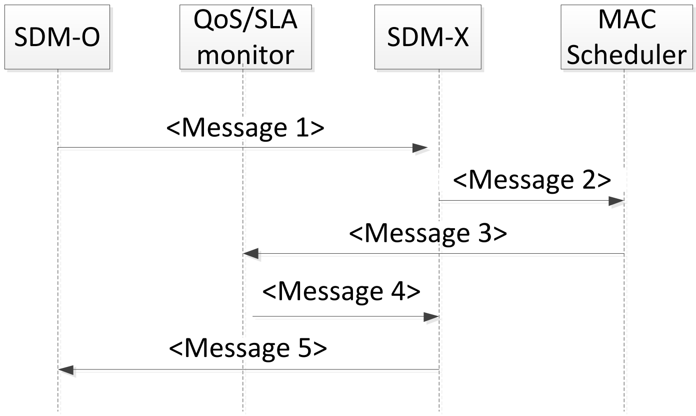


Figure-3-28: Identified signalling messages for radio resource control with SDM-X

SDMO-SDMX < Messsage 01>:
- Slice-ID: needed to know for which slice the service policies are valid
- Service-Policies: Lets the SDM-X know which instantiated applications can be used and how they can be influenced during runtime of the slice
- P/VNF-to-Node-Mapping: Lets the SDM-X know which NFs are instantiated at which physical node

SDMX-MAC < Message 02>:
- Slice-ID: needed to know for which slice the information are valid
- Radio-Resource-Maps: Let the MAC scheduler know which radio resource patterns can be used
- Site-Cluster-Maps: Let the MAC scheduler know which sites could correspond to which clusters
- Policy-ID: Identifies the policies which shall be applied, e.g. temporarily cell edge performance improvement while sacrificing spectral efficiency
- Policy-category: Gives an information about the category of the application which should be activated, e.g. scheduling metric, ICIC or SON
- KPI target: Gives information what KPI should be improved (e.g. delay, cell edge throughput, spectral efficiency)
- Modification-permitted: Gives the MAC scheduler the possibility to permit to activate the recommended application, if unforeseen dynamic changes have happened
- Rule-Activation-Time: Trigger at which time to activate the policy

- Rule-Deactivation-Time: Gives information for how long the decision holds true

MAC-QoS Monitor < Message 03>:
- Slice-ID: needed to know for which slice the information is valid
- Observation-Time: When where the information collected by the MAC scheduler
- Observation-Time-Window: For how long were information collected
- Cell based performance indicator:
    - Avg. RB usage per TTI over the defined time window
    - Processing-power-Usage-Per-BS
    - Policies -applied
    - Policy-Deactivation-Time

- Data flow based performance indicators:
    - Number of used PRBs
    - BLER
    - Use-of-TM
    - Use-of-MCS
    - Queueing-Delay
    - Transmission-Delay

QoS Monitor-SDMX : < Message 04>

- Slice-ID: needed to know for which slice the information are valid
- QoS/SLA status indicators: Aggregated information on the performance of the slice consistent of:
    - Statistics of slice throughput and delay (e.g. 5 percentile and mean value of the CDF over all users attached to a slice.

SDMX-SDMO : < Message 05>:

- Reorchestration Trigger: Request to reorchestrate
- Reason: Information why to reorchestrate, e.g. unsatisfied SLA in a specific sub group of cells
- Affected-Slices: IDs of slices were the SLA could not be satisfied
- Affected-Sites: IDs of affected sites were SLA could not be satisfied
- Recommendation of action: How to react, e.g. improve cell edge performance or delay

3.7 QoE/QoS assessment for vehicular Scenarios

Our reference application is a collision warning service that lets connected vehicles warn each other about dangers they detect. The service runs on all vehicles, and is triggered by a vicinity-based hazard-detection algorithm. Specifically, as vehicles move along city roads, they may have to suddenly decelerate due to unanticipated congestion, hurried pedestrian crossings, or sharp turns by cars in front. To avoid collisions in these situations, the cooperative warning system forces vehicles to announce hard braking to all vehicles nearby.

The collision warning service requires car-to-car communication, which is implemented through LTE. Thus, connected vehicles send and receive warning notification via the mediation of eNodeBs. Warning messages are small packets (2 KB in our simulations) designed for minimum latency, generated by the vehicle detecting the hazard, and transmitted to the serving eNodeB in the uplink direction. The eNodeB then forwards these packets in downlink to target cars, selected depending on the scope of the notification.

The two most sensible Key Performance Indicators (KPIs) in the context of such an automotive service are the throughput and the end-to-end delay experienced by connected vehicles. The user throughput is the data rate observed at the user's PDCP layer, after packet loss, retransmissions and link adaptation.

In our warning notification system, many vehicles may send warning messages at the same time to the same eNodeB causing congestion, due to a limited number of resources, which becomes worse for vehicles with bad channel conditions. The throughput KPI is also a good indicator for such cases, besides serving as a standard measure for network quality. The end-to-end delay represents the total time needed for a message to be transferred from warning source vehicle to a recipient car over the infrastructure. This time includes LTE inherent extra delay for scheduling, uplink grant access, HARQ and processing/decoding delays.

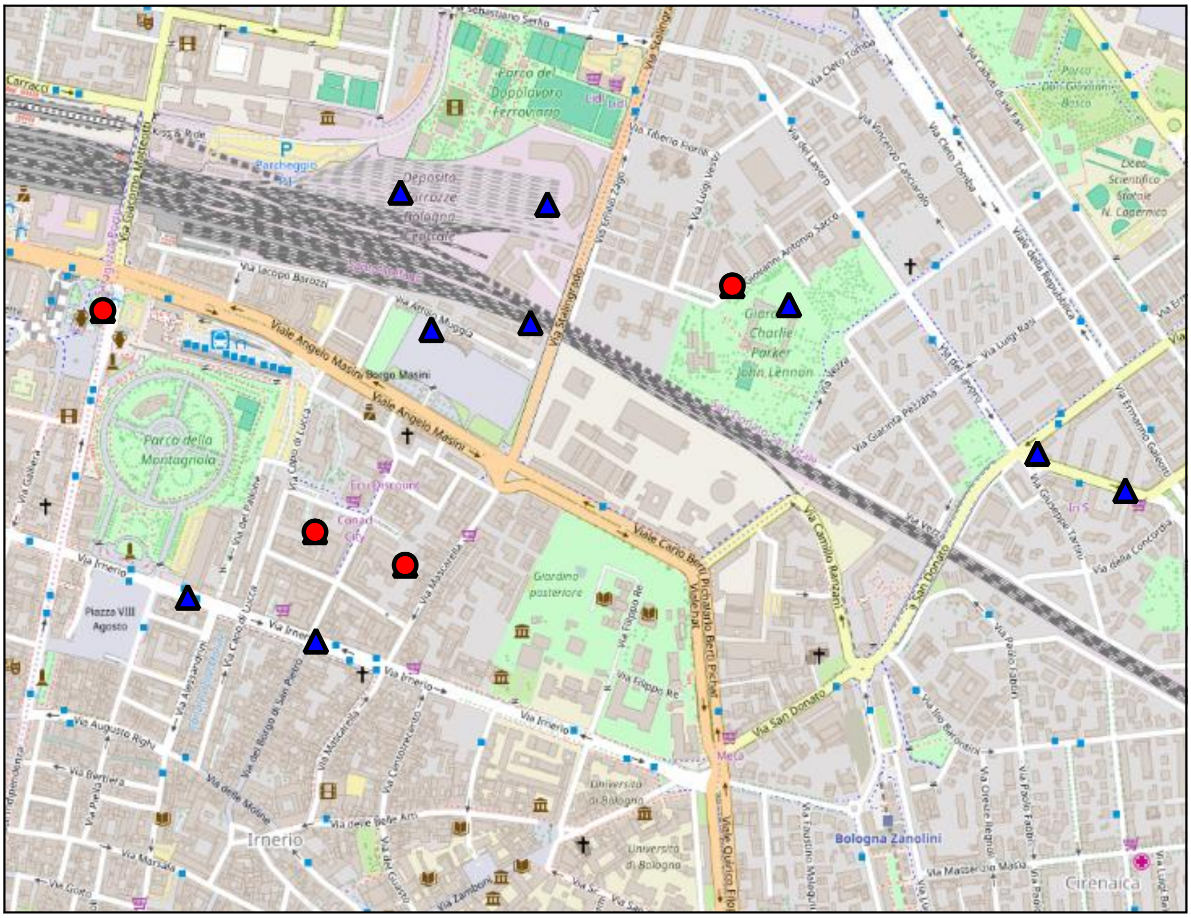


Figure-3-29: High (Red) and Low (Blue) loaded eNBs in the simulated scenario

The collisions warning service is simulated in a representative neighborhood of Bologna, depicted in Figure-3-29. The selected area is a representative portion of the Bologna covers 0.6 km^2 characterized by a significant presence of all mobile network operators. It also encompasses important landmarks of the city such as the railway station and main bus terminal.

3.7.1 Results and insights

Our choice of LTE-based automotive service, jointly with the degree of realism and detail of the simulation, prove especially useful to understand the limitations of the current radio access technology with respect to applications for connected vehicles. This is true at different levels, and we organize our discussion of results by separating network design issues.

Resource Deployment: The actual performance of the cellular network depends very much on the planning of the radio access infrastructure, when superposed to the movement patterns of terminals. This is particularly true for automotive services, where connected vehicles often cluster in crowded, yet predictable, platoons.

Elements like intersections, traffic lights or roundabouts introduce perturbations on the vehicular movements that cause two negative effects on the infrastructure: *i*) connected vehicles attach to eNodeBs in a very uneven manner, causing over-subscription at certain locations, and *ii*) dedicated applications like the one we evaluate here generate a high volume of data traffic, since inter-vehicle distances are reduced and collisions are more likely to happen.

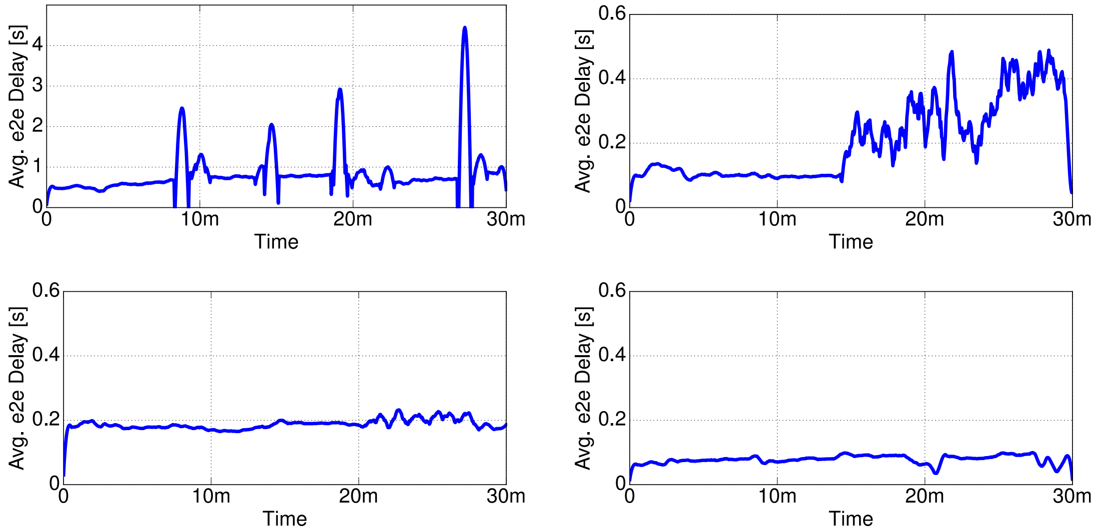


Figure-3-30: End to end delay

We evaluate this problem by measuring the load, in terms of average end-to-end delay, of each eNodeB. Results are shown in Figure-3-30, for four representative eNodeBs. Clearly, the physical placement of an eNodeB plays a fundamental role in determining its performance.

Several eNodeBs are overloaded at times, generating spikes in the end-to-end delay and a higher average latency in general. Other eNodeBs experience very low load from connected vehicles, hence they can guarantee a very low latency.

By looking at where the high-load eNodeBs are in Figure-3-29, we observe that they serve the area close to the Bologna bus terminal, which is also in proximity of a very busy crossroad. There, slow traffic and stop-and-go patterns induce a very high load on the infrastructure, with a much-degraded latency performance when compared to that of the less loaded eNodeBs. Based on such results, we stress how understanding vehicular movement patterns to deploy network resources will be critical in 5G network}. Even more so, when considering the introduction of paradigms such as NFV and SDN, which will allow a dynamic assignment of resources. The latter shall be reallocated according to the road traffic dynamics, substantially improving the network performance. On demand and anticipated provisioning of resources becomes foreseeable when considering the regularity of road traffic. Although the design and validation of such optimized resource orchestration algorithms is out of the scope of this document, our work demonstrates and quantifies for the first time the existence of the problem, and is thus a preliminary step towards automotive-aware resource orchestration algorithms for virtualized mobile networks.

Optimized resource usage: Automotive services usually rely on frequent transmissions of very small packets. However, LTE is designed for long-lasting data flows accommodated into continued sessions: in fact, all the control messages needed for the correct setup of a DRB are an unnecessary burden for the network infrastructure, if frequent and connectionless packets need to be exchanged. This not only limits the number of devices that may be connected to the network (as state must be maintained for each attached user equipment), but it reduces the performance of the served end users. This problem, which is common to all machine type communications (MTC), is exacerbated by the high mobility of vehicles that will rely on an automotive network slice.

A related problem is the waste of network resources caused by the small packet length. Common LTE MAC schedulers adopt strategies like Proportional Fairness or Round Robin that aim at maximizing the long-term transfer rate of user equipments. In an automotive service environment, such a long-term service rate may not be the correct goal to target. This calls for the implementation of automotive-aware schedulers that can optimize the relevant KPIs for vehicular communications. Service-aware scheduling allows for a better utilization of Physical Resource Blocks (PRB) that are easily misused when assigned to flows using the legacy LTE QoS framework.

These situations are reflected in our high-detail simulation, as shown in Figure-3-31. The plot shows the actual share of the available bandwidth used by each operator during the whole simulation. The available bandwidth is calculated by means of the Shannon theorem and the used capacity, instead, is the actual amount of data exchanged at PDCP level. All values are averaged over all the user equipments at every second.

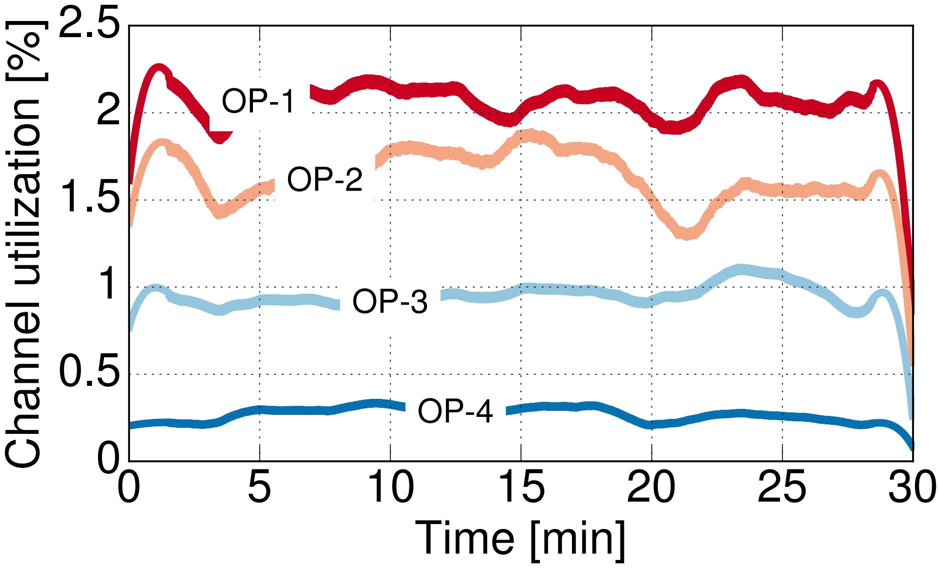


Figure-3-31: Channel Utilization

Although the real PRB utilization pattern depends on the decisions taken by the scheduler at superframe level, the trend shown in Figure-3-31 helps us understanding how a proportional fair (PF) scheduler may fail to share the available spectrum with other types of telecommunication services. Hence, the sharing of resources among heterogeneous services that use the same infrastructure (e.g., enhanced Mobile Broadband) shall be jointly optimized for all services, including the automotive one.

Automotive KPIs awareness: Among all the envisioned 5G telecommunication services, automotive communications impose the most stringent requirement in terms of latency. This is understandable, when considering the the end-to-end delay required for applications like collision avoidance or for any other kind of cooperative awareness system where reaction is needed in a very short time. Although there is not a fixed value for the maximum latency requirements, it is expected that for many applications (e.g., traffic signal violation or left-turn assist) the maximum bound is 100 ms, while for others such as pre-crash sensing this limit goes down to 20 ms.

Low latency is not the focus of LTE, which was historically designed to support high bandwidth communications, so it is expected that such a tight latency requirement will not be met without any modification in the stack. In this context, our simulations demonstrate how far the current technology is from fulfilling the KPIs needed by automotive service deployed at scale.

Figure-3-32 depicts the end-to-end latency experienced by messages generated by our hazard warning application. Clearly, the current LTE architecture falls short of meeting even the most relaxed latency requirement. No operator in our scenario can guarantee a significant probability of vehicle-to-vehicle communications below, e.g., 100 ms. In fact, the operators serving the largest market shares incur in very high delays well beyond 200 ms for the clear majority of the connected vehicles they serve. Although many factors concur in determining such a high latency, our simulations highlight those that play major roles. Specifically, i) the time needed to set up data radio bearers for all the UEs in the network, ii) the queuing delay at PDCP, and iii) retransmissions. Therefore specific techniques, capable of mapping vehicular data traffic to the most appropriate vehicular aware network functions (e.g. lightweight signalling procedures for vehicular UEs) are needed to correctly support vehicular traffic in future 5G networks.

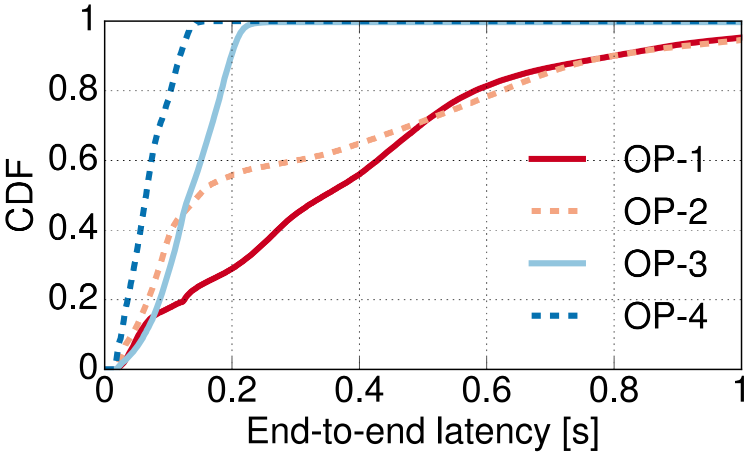


Figure-3-32: End to end latency CDF

4 Network slice mobility management

The current *softwarization* trend will trigger the transition from a network *of entities* to a *network of functions*. For example, in the current mobile network architecture, the Mobility Management (MM) functionality is a process that involves different physical entities in the network (i.e., eNB, MME, gateways). To that end, an essential functionality as MM must also be transformed and made aware of the novel QoE/QoS, Orchestration and control mechanisms

This novel concept entails a paradigm change: future 5G networks shall extend the software-defined routing/switching approach currently defined by ONF, to all kinds of network functions from both data and control layer, with a focus on wireless control functions such as e.g., scheduling, interference control, etc.

That is, future 5G Network controllers will apply the split between the *logic* of the network function and the part that can be controlled, implemented by a network function. Thus, following these design and architectural principles, the mobility management (MM) can be implemented as an application running on top of such enhanced network controllers. Moreover, as this kind of novel controllers will manage information coming from a unified QoS framework, the management of user mobility becomes a thorough process that involves network function control and orchestration to achieve an optimized functionality.

By exploiting these characteristics, the network flexibility is increased, but the adaptation of the network capacity according to the instantaneous traffic demands and required KPIs entails the re-configuration and re-orchestration of the network at many levels. Therefore, besides the selection of the most appropriate MM algorithm or the parameters that may influence the MM algorithm behavior, the MM shall be able to control different network configurations seamlessly. So, this section entails the solutions regarding control and orchestration for mobility management purposes.

- Different slices have different KPIs that may be handled by different mobility management schemes. Section 4.1 provides a description of how they can be mapped to the final network slice deployment.
- Novel mobility management processes may take advantage of the novel technologies and flexible RAN and transport architecture that are going to be the core of 5G innovations. Hence, we describe in Section 4.2 and 4.3 how a novel SDM-C mobility management application can provide the needed functionality in a softwarized environment while jointly optimizing access and core network functions.
- Cloudified networks will span a hierarchy of network clouds and, mobility management mechanisms, should be thoroughly designed to handle this specificity that is one of the fundamental design paradigm of future 5G Networks. Section 4.4 describe possible strategies for solving this problem.

Contributions in this field have been disseminated most prominently to standardization bodies.

4.1 Service/slice specific Mobility Management design

A specific scheme for Mobility Management (MM) has to be designed according to the required granularity and other features for a dedicated service or network slice which is described by the MM function in terms of various parameters and different VNF configurations. The corresponding decision or choice on the considered MM criteria has to happen during slice set-up (e.g. by selection of a set/range of MM VNFs for typical eMBB applications).

MM processes which allow to detail signalling and interaction between (logical) entities (usually depicted as MSCs) have been presented in D5.1 – e.g. an IoT slice requiring paging after sleep mode / efficient paging for moving (vehicular) UEs as the only MM action.

A mapping of potential MM design approaches to major use cases has been detailed in [D5.1] to decide on major issues for differentiation between different levels of handover execution and provided seamlessness.

In this section an enhancement of (exemplary) performance estimation for different schemes will take into account more specifically the message content and corresponding size required for different underlying protocols. Depending on the different MM protocol specifics (Tunneling, Routing, Anchoring, name/location separation, …) e.g. GTP/(P)MIP, DMM [DMA16], HIP [HIPv2] / LISP [LISP] / ILNP [ILNP] / ILA [ILA-mob] which are reviewed and described shortly in Annex A. The analysis comprises 3GPPs GPRS Tunneling Protocol (GTP), traditional IP-based tunnelling protocols as host-based Mobile IP (MIP) [MIP6] and network-based Proxy MIP (PMIP) [PMIP6] specified by IETF, DMM (Distributed Mobility Management) as far as it is already described, LISP (Locator/ID Separation Protocol), ILNP (Identifier Locator Network Protocol) (RFCs 6740 - 6748) which has been defined in framework of routing RG at IRTF, and recently proposed ILA (Identifier Locator Addressing) protocol.

As a summary from the analysis of different MM protocols given in Annex A the application to 5G NORMA architecture i.e. the specification of logical (virtualizable) network entities (VNFs) to be controlled by an MM App via the SDM-C (potentially in cooperation with SDM-X in case of joint MM for multiple slices) should be possible since all these approaches basically allow for c-plane/u-plane separation and virtual implementation and modification of the functional entities.

A Table shows for each protocol the various virtual and physical functions at c-plane and u-plane level together with usual network entities at which they may be located. The header length given shall address typical values required for each approach in addition to simple IP packet header

Table 4-1: NFs for each mobility protocol possibly to be addressed by MM-App via SDM-C.

Protocol \ function	**CP VNF**	**UP VNF**	**CP PNF**	**UP PNF**	**Header**
GTP	MME, SGW	SGW, PGW	MME, SGW	SGW, PGW	20B (UDP+GTP)+8B (extension) +26B (IPSec)
MIPv6	HA, CoA	HA, CoA			40B+16B ext.+16B routg.+40B tunneling
PMIPv6	MAG, LMA	MAG			40B+16B ext.+16B routg.+40B tunneling
DMM	CPA	DPA			(P)MIPv6+2B (for on-demand mobility)
LISP	EID-to-RLOC mapping	xTR			52B
ILNP	SBR, ILCC	SBR			40B
ILA	ILA nodes	ILA nodes			40B

.

4.1.1 MM scheme design application

Based on the identified parameters for construction of a MM scheme which has to be offered as set of NFs enabling for slice specifically tailored mobility support a mapping between different approaches (in terms of Handover procedures) and use cases has been given in Del. 5.1 [D5.1].

Reported here is a qualitative evaluation (analytical estimation) of performance impact for the four mobility use cases identified such as eMBB / Industry Control (with potential Ultra Low Latency, ULL, and Ultra-High Reliability, UHR demands) … with the outcome being a break-down of procedures for service requirements and infrastructure capabilities' mapping for selected use cases to MSCs (Message Sequence Charts) as already included in ICC workshop paper [YGF+17]. Handover procedure as exemplary MM process have been differentiated in Intra-RAT HO (between Source and Target RAP of same technology), Inter-RAT HO (where RAPs operate at different technologies and a corresponding modification of the GW-App may be required), and Inter-domain HO where not only the Target RAP but also the New GW-App belong to a different network domain (see Figure-4-1)

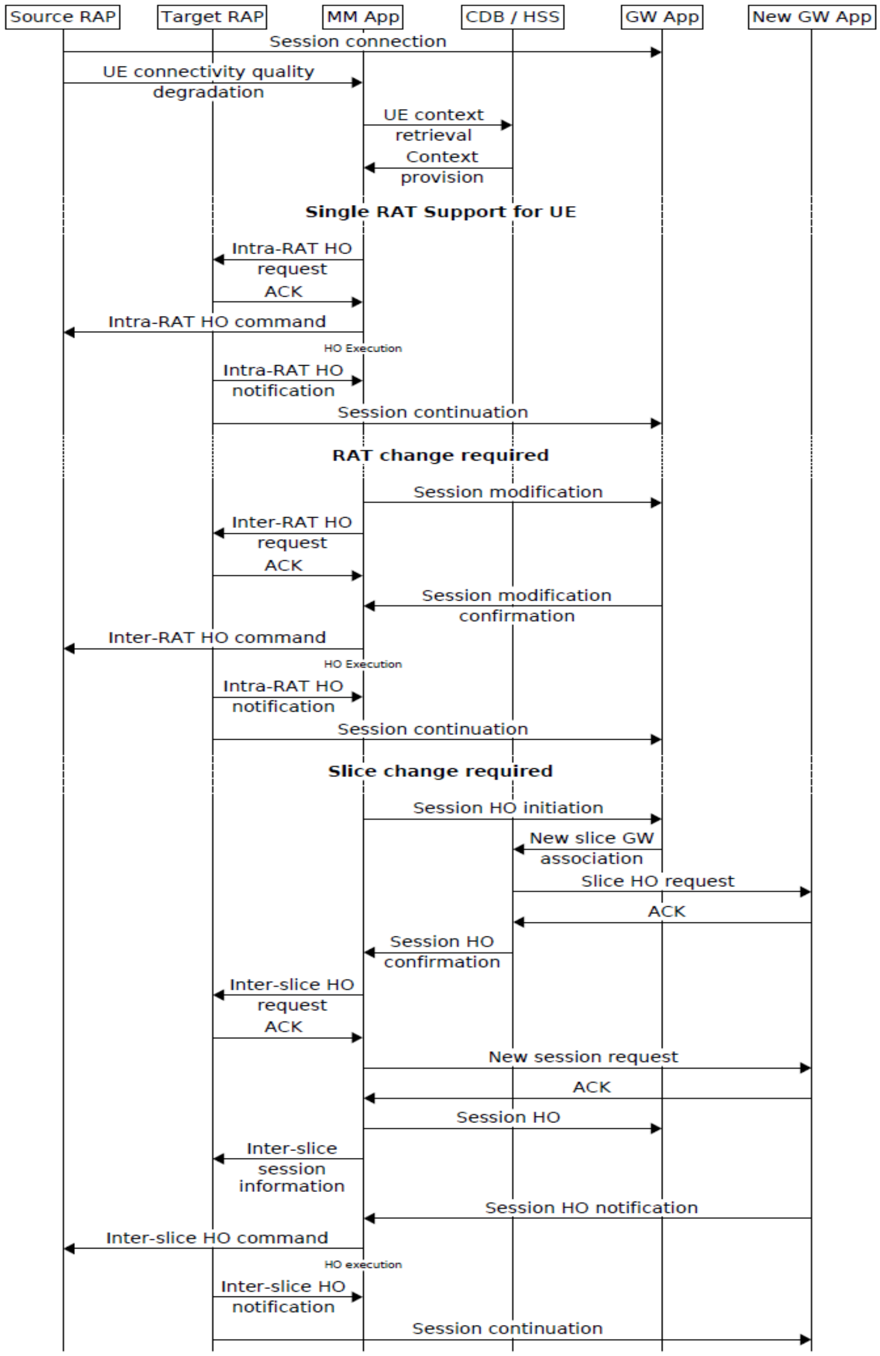


Figure-4-1: Message Sequence Chart for different types of Handover decisions

As a rough qualitative analysis of the different schemes the MM (HO) processes to detail signaling and interaction between (logical) entities (MSC) are compared for the three types depicted in Fig. 4 3 (intra-RAT, inter-RAT, and inter-slice aka. inter-domain HO) with an additional no mobility (static use case) scenario (here the 'slim MM App' has just to check for connectivity and in case of NACK invoke a paging process) and an additional Ultra High Reliability (UHR) and Ultra Low Latency (ULL) use case is assumed with HHO (Horizontal HandOver) but multiple connections in parallel so that – similar to MBB (Make Before Break) also the case for no HO delay – is enabled. VHO (Vertical HandOver) denotes the inter-RAT HO. If such multi-path is enabled within the same AN no interaction of MM App would be required (beyond registration and notification of such AN feature) but in general we assume that different ANs and AN technologies (represented in Fig. 4 3 by different RAPs) are involved so that the signalling effort is at least doubled compared to the simple HHO case.

In Table 4-2 we compare for each HO scenario the amount of involved entities and messages to be exchanged before HO is completed. As a reference case we see the static scenario without any HO demand during an ongoing session. Here SRAP/TRAP denote Source/Target RAP with an index for differentiation between different slices or domains, whereas CDB denotes a Customer Data Base (e.g. HSS). MMApp / GWApp finally denote the SDN Application for MM tasks and for controlling the GW between the slice domain and the internet or external packet data network, respectively.

Table 4-2: NFs for each mobility protocol possibly to be addressed by MM-App via SDM-C.

HO type	Involved entities	Increase in number of entities compared to reference case	# of messages to exchange	Msg amount incl. early detect (X-Layer)	Potential dditional effort
No HO (static): reference case	SRAP TRAP MMApp	0%	0	0	paging
Simple HHO	SRAP TRAP MMApp CDB	33%	4	7	-
VHO	SRAP TRAP MMApp CDB GWApp	67%	6	9	-
X-D HO	SRAP TRAP MMApp CDB GWApp nGWApp	100%	14	17	-
MBB (xHHO)	SRAPi TRAPi SRAPj TRAPj MMApp CDB GWApp	133%	12	18	-

As can be seen the effort for provision of layer 3 seamlessness increases from static to a highly-sophisticated mobility-related use case in terms of involved entities and number of messages to be exchanged, to name only a few. The need for paging in case of static (wireless) connectivity is omitted in the mobile cases as a continuous monitoring of reachability during connectivity or the continuing session is assumed here.

4.1.2 Results

Exemplary results have been presented and published at I4CS 2017 in [Hug17] with estimations of overhead for three different MM schemes in terms of amount of IoT devices supported per cell in case of sharing access capacity with different types (e.g. complexity or quality in terms of seamlessness) of mobility services. An extended evaluation taking also into account the terminal speed is shown in Figure-4-2 and Figure-4-3, demanding clearly for more overhead in case of higher terminal speed (i.e. higher HO rate).

Regarding multi-link 3GPP RAN TSG recently agreed on the issue that in Non-standalone (NSA) 5G NR mode for the enhanced Mobile BroadBand (eMBB) use-case the connection is anchored in LTE while 5G NR carriers are used to boost data-rates and reduce latency [3GPP17].

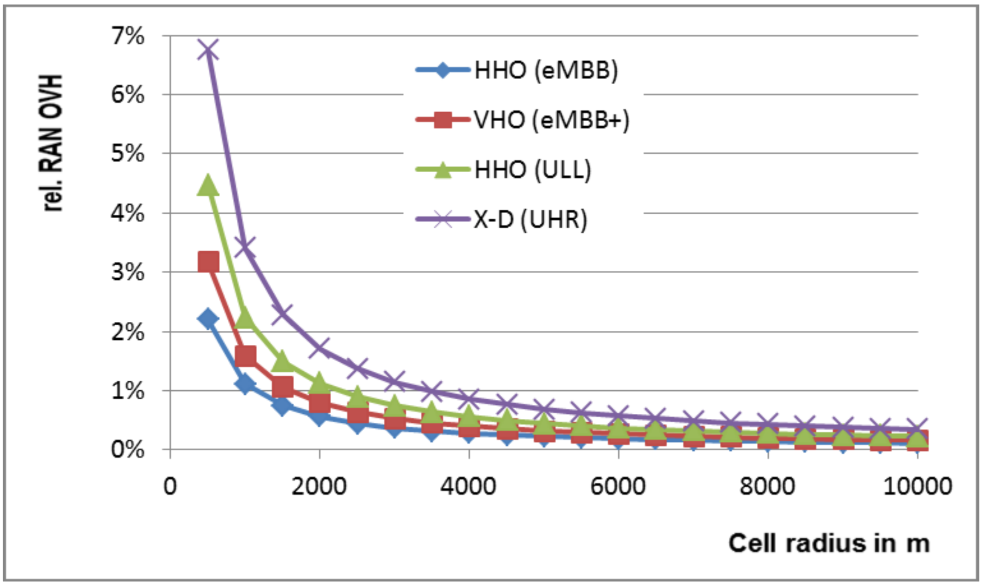


Figure-4-2: HO Signalling OVH on RAN side for different MM schemes for different cell sizes at an average UE velocity of 50 km/h

From the Figure 4-4 on HO signalling maximum OVerHead for UHR signalling (denoted as rel. RAN OVH – compared to signalling in the reference case for a static scenario) is nearly 7% (given the assumed parameters as e.g. 350 Mbps data rate per cell and 91 UEs served with 20 MB per minute) - and with simpler HO schemes and larger cells this value reduces. Also for higher velocity (e.g. 70 km/h) a higher value of 9.5% is reached (see Figure-4-3) whereas at 30 km/h a relative HO signalling of only 4.1 % is expected. At the same time the HO delay on IP level is kept limited but increases with cell size due to propagation delay and multiple message exchanges assuming a simple network topology with the (virtual) core network entity only one hop away from access nodes which amounts to a distance in the order of cell size. That is shown for velocity of 70 km/h in Figure-4-4. As can be seen the ULL use case achieves lowest delay at a cost of higher signalling overhead. High reliability (as shown for x-domain, X-D HO) both requires high signalling and creates longest delays. The impact of velocity was considered in an only very rough manner and may need further investigation.

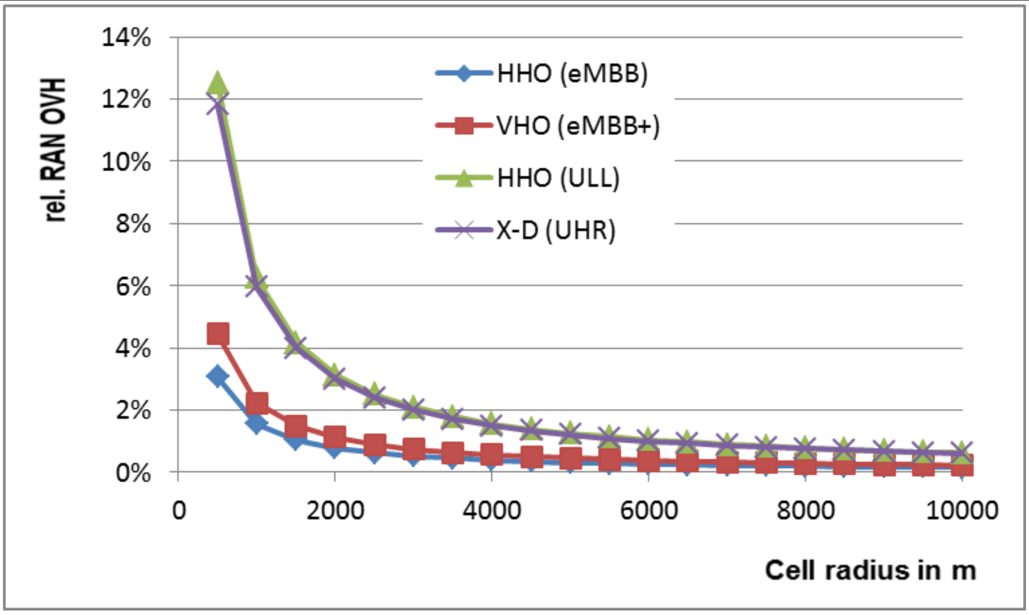


Figure-4-3: HO induced delay for different MM schemes as a function of cell size at an average UE velocity of 70 km/h

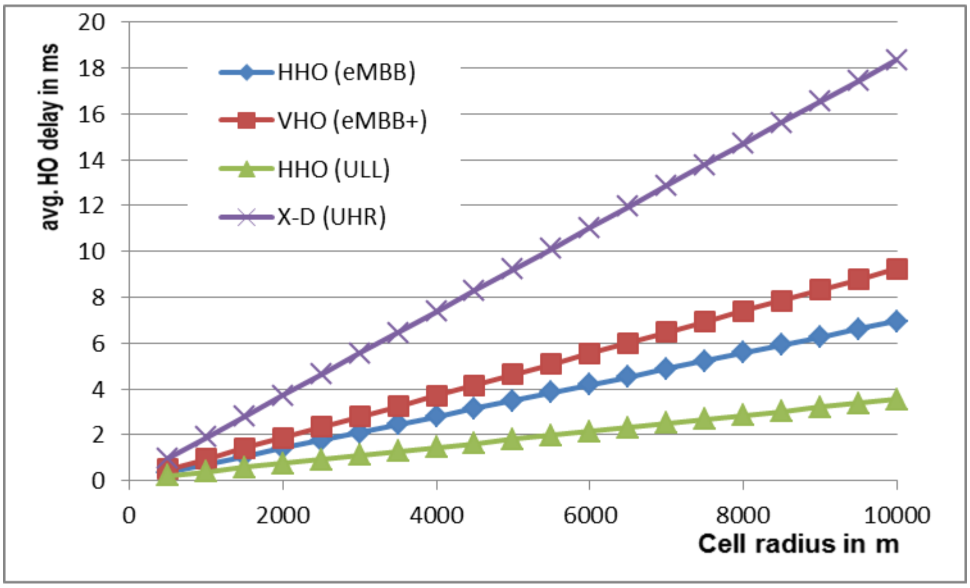


Figure-4-4: HO induced delay for different MM schemes as a function of cell size at an average UE velocity of 70 km/h

4.1.3 Analysis and future steps

The results presented in section 4.1.1 shall illustrate mainly two features of next generation 5G communication namely the flexibility to provide service tailored sub-network configurations and the aspect of common resource sharing for multiple network slices concurrently. Design and selection of different instantiations of network (sub) functions for Mobility Management was chosen were the MM feature ranges between “no” and “full seamless highly reliable” mobility support. A static IoT slice (mMTC) built up by 5G could increase the scalability performance (in terms of number of devices) by a factor of up to eight utilizing the same frequency resources. A highly-sophisticated MM scheme would require much more overhead than a simple one resulting in fewer resources available for a parallel best effort type of service.

While the rough estimation only can give a qualitative result, further investigations are needed taking into account a detailed analysis of the information exchanged between functional entities of a 5G system architecture and the protocols and interfaces required. Such aspects as well as simulations for realistic scenarios and partially also experimental verifications are planned within the project 5G NORMA. In addition other types of (e.g. specifically vehicular) types of mobility support between cars or vehicles and dedicated roadside infrastructure or between neighboring end user terminals have not yet been considered here. The overall system concept however including increasing computerization of traditional radio hardware in AN and CN as is envisaged in cloud computing, software defined (mobile) networking, and network function virtualization should be flexible enough to allow for such extensions.

The ongoing research activities continue to investigate and evaluate means to efficiently provide prospective future community communication services beside other business driven services to end customers. The perspective of both, operators and service providers as well as a wide range of community types and tenants end users is in focus of these activities. Analysis and assessment of different solution proposals, currently under discussion, is foreseen as well as contributions of prospective approaches to standards defining organizations and bodies which is a major step to make the vision of a flexible service-aware network architecture reality.

4.2 SDM-C based mobility management for cRAN

One of the key technologies for the enhancement of the flexibility is cRAN [iJOIN]. This capability, envisioned as one of the future pillars of 5G networks [D5.1], allows to split the currently monolithic RAN stack into atomic functions that may be orchestrated in different ways, exploiting either the multiplexing gain of baseband processing centralization or the flexible resource utilization of decentralization of edge computing. This approach is also envisioned by the Small Cell Forum, which already the interfaces between different entities [SCF], and the 3GPP in its Rel. 14.

The role of an enhanced SDN controller will become fundamental in the context of cRAN deployments. RAN functions, e.g. PHY, Medium Access Control (MAC), RRM, located either at a remote radio header (RRH) or in a cloud baseband unit (BBU) may be flexible controlled by this future 5G SDN controller such as SDM-C.

The figure below illustrates the cRAN concept elaborating the different functional splits that could be deployed. Once the cRAN selects a functional split, then such a split is followed by all applications and services for long periods.

A cRAN functional split takes place independently of other network management functionalities, but an integrated SDN controller (such as SDM-C) that implements them as applications logic on its northbound interface shall

1. Jointly optimize RAN and Core network functions by leveraging on its centralized network control capabilities..
2. Steer user flows across different network functions according to the cRAN functional split implemented in the network.

The functionality outlined here is implemented within an SDN application, while the latter is provided by a set of *plugins* installed on the Southbound Interface of the controller. The overall idea of software defined network management algorithms is to cope with the changing environment of a cRAN -enabled network, as sketched next. Depending on the selected functional split, different optimization options and network control challenges arise.

PDCP-RRC**:** this functional split is a pure control user plane split, as PDCP is the highest layer that deals with user data. It handles GTP traffic towards the gateways and from there to the Internet. By enhancing the SDN approach, the functionality currently carried out by NAS, MME and RRC is centralized and provided as a SDN application. That is, a pool of virtualized Radio Access Points (RAP) that include the RRH and implement the RAN stack up to the PDCP, may be controlled by a centralized MM application that can take optimal handover decisions considering several parameters such as the load of RAPs, the UE movement patterns and the service KPIs. On the other hand, the controller southbound interface needs to interact with both the

RAPs and the gateways (that may be joined in a single entity) by managing directly NAS, RRC and GTP session requests from the d-layer network functions. This split is depicted in the figure below.

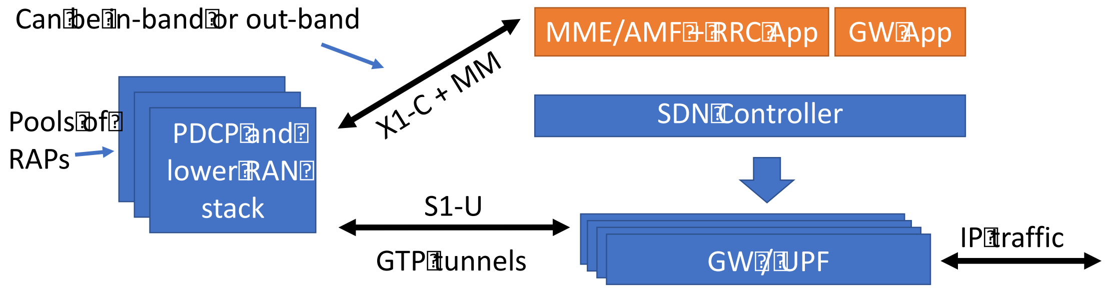


Figure-4-5: SDN for a RRC-PDCP split

RLC-PDCP**:** this split is done by separating two d-layer functions and thus involves the direct management of data radio bearers between the pool of RAPs that implement the RAN stack up to the RLC and a centralized network function performs several functions in addition to the former split (i.e., PDCP-RRC) including e.g., (de)ciphering. These previously distributed network functions are now centralized and hence enhanced routing optimization, multipath or radio bearer based mobility can now be performed. On the other hand, the southbound interface shall be able to manage, among other information, data radio bearers and their mapping to the RLC channels. The following figure describes this case.

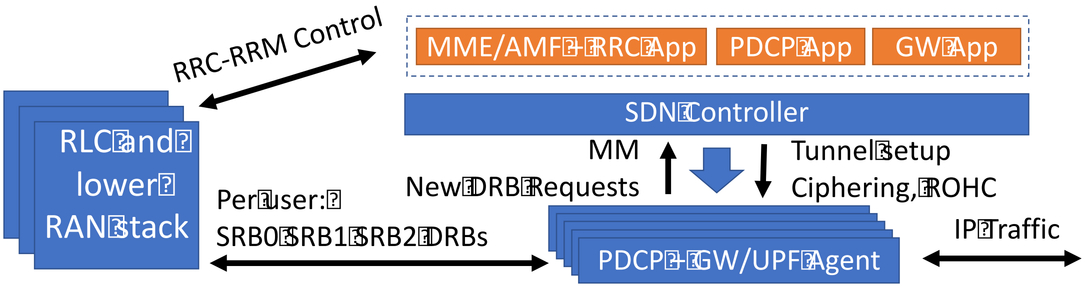


Figure-4-6: SDN for a PDCP-RLC split

These two examples just serve as illustration of how enhanced network management algorithms can take optimal decision depending on the *cloudification* of the network and the requirements that must be fulfilled. For these reasons, the first step towards the possible optimizations described above is the extension of the Openflow capabilities, to support the steering flows between the Network Functions involved in a cRAN setup.

4.3 Slice-aware MM Design and joined RAN-core optimization

As the signalling mechanisms defined in 3GPP LTE are inefficient for transmission of small packet payloads 5G NORMA introduces the concept of User-centric Connection Area (UCA) [Aziz] which reduces the signalling load especially towards the Mobility Management. A UCA is defined as a set of access points to which the UE context is known in advance. Such a set of access points compose a coverage area within which a single anchor node is defined for every user. The anchor node maintains the connection of the user to the core network as long as the user remains within the UCA. The UCA concept defines an additional RRC state called “UCA Enabled” in order to avoid signalling towards the core network due to inactivity/activity change of the user and corresponding transitions between RRC Idle and RRC Connected. Even if UE has data to transmit it permanently remains in the “UCA Enabled” state. The UE transitions between RRC Connected state and RRC Enabled state is not visible to the core network as no signalling towards the core network is expected due to this transition. Also, core network does not have to page the UE when the UE is in UCA Enabled state as both control plane and user plane remain established between the RAN and core. In such a way, considerable signalling reductions can be achieved. The UCA concept has been already part of the 3GPP standardization where UCA Enabled state is named RRC Inactive [3GPPTR23799]. More details regarding the UCA and its implementation in 5G NORMA can be found in [D4.1].

Generally speaking, the UCA is defined in terms of the number (and the list) of APs that belong to it, i.e. the size of the UCA coverage area, as well as the corresponding anchor point. The UCA is defined separately for each UE. The size of the UCA highly influences the amount of signalling messages. The UCA size is particularly important parameter due to:

- signalling that happens within UCA (UE context sharing among access points in UCA, forwarding between anchor and best serving access point)
- data forwarding via backhaul which is required for UL and DL within UCA, i.e. size of the UCA is limited due to the load on backhaul / X2
- the probability of erroneous location information that the anchor node has regarding the user
- limiting the area in which the RAN paging occurs in order to discover the current best serving node (in the case that info at anchor node about new best serving node is lost)

The UCA concept has been primarily designed for signalling reduction during small and sporadic data transmission. However, this concept especially the design consideration regarding the UCA size can be extended to the notion of different network slices/services. Based on the slice characteristics, tenant requirements as well as agreed SLAs between a tenant and a service provider the size of UCA might be different. In order to derive the optimal UCA size the UE mobility characteristics such as speed, trajectory along with anticipatory information on user movement can be taken into consideration. Furthermore, the number of users in the UCA as well as current load on anchor nodes and backhaul influence the decision on UCA size.

Having two network slices with different QoS requirements in terms of e.g. latency and reliability will lead to recommendation to configure two different UCA sizes. E.g. for users camping to mMTC slice with moderate QoS requirements the UCA size might be larger as compared to V2V slice with stringent QoS requirements. As a consequence, in the case of mMTC slice the larger UCA will allow for significant signalling reduction, as compared to the V2V slice where due to stringent QoS requirements and correspondingly small UCA only minor (if any) signalling reduction might be achieved.

Joint RAN and Core network optimization through the Mobility Management App

The detailed description of the UCA concept and its implementation in 5G NORMA has been included in [D4.1]. The definition of UCA cluster is done within a SON function. The definition considered in [D4.1] is UE specific, based on UE measurements and anticipatory data. The SON process defines for each UE separately the UCA in terms of the anchor node and other nodes comprising the UCA. Such process is mainly RAN specific.

Hereby we aim at extension of initial UCA definition process towards slice-aware process that gives the recommendations on the most suitable UCA cluster size. In order to derive such recommendation more slice-specific information in terms of e.g. QoS requirements are necessary. The Mobility Management App on top of SDM-C might have such insight on the slice characteristics and be able to define the suitable UCA size based on such information. Apart from the slice related information (e.g. QoS requirements, acceptable level of service degradation, increase in delay) the Mobility Management App needs to take additional information into account for better estimation of the UCA size, e.g., number of users served by anchor node, current load of a backhaul along with the UE mobility pattern with potentially available mobility prediction information. The UCA size recommendation can be then signalled towards the SON function which finally implements the UCA cluster in the RAN as described in [D4.1]. In such a way the optimization and implementation of UCA cluster is done jointly between Core network (MM App) and RAN (SON). Such joined optimization taking into account information available in the core and RAN leads to more suitable mobility management decisions and results in more efficient usage of network resources while fulfilling the service requirements.

4.4 Edge Function Mobility

In this section, we will discuss a proposed solution for a replication/migration decision method. As mentioned in the section 3.2 of Part 1, there are many possible reasons for replicating/migrating VNFs. The focus here will be to decide if/when to make a replication/migration when a group of users being served by an edge cloud moves to another edge cloud.

The decision method aims at minimizing service outages, while also preventing QoE degradation. There is a trade-off between these two requirements. Migration should occur when the impact of keeping the VNF(s) in the original cloud is much larger than the replication/migration costs.

When a user moves away from the area covered by an edge cloud, three decisions can be made: the VNF continues to run at the original edge cloud, rerouting its packets through the central cloud; the function is migrated to the new edge cloud; or migrated to the central cloud. Various factors like delay requirements, reallocation/instantiation costs and QoE should be taken into account for this decision. This method should use different criteria and provide the optimal position for the function to be at any given time.
Before designing the placement method, a user mobility model and a migration/communication cost model should be established.
The user mobility model is a uniform 2-D random walk model, where users move within a hexagon cell structure. At each time step, the user has the probability ***m*** of moving to any of its neighbour cells, and probability **1 – 6*m*** of staying in the same cell.

The migration/communication cost model is based on distance between the edge cloud hosting the VNF (called hosting cloud) and the edge cloud serving the users (called serving cloud). The migration costs represents the effort necessary for migrating a VNF, and the communication cost represents the “price” of sending packets from one point to another. Many factors are important when modelling migration and communication costs, but we are interested in comparing them head-to-head in our decision method, so it’s best for them to have the same basic input parameter.

A function called constant-plus-exponential is used.

$$c(d) = 1 - \theta^d$$

Variable ***d*** represents the length of the shortest path between two edge clouds. Parameter $\boldsymbol{\theta}$ should be adapted as to create any cost function that fits the migration and communication costs for a certain network function. This cost function allows for the quick calculation of the migration and transmission costs of all cells in the considered grid at a certain time. The central cloud is considered equidistant between both original and serving edge clouds. In figure ??, EC means a cell being covered by the original edge cloud, CC means the virtual location where the central cloud would be, and USER represents which the user is, currently being served by another edge cloud.

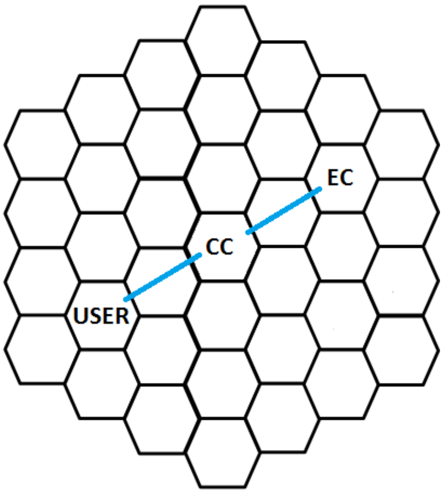


Figure-4-7: User Mobility Model

The placement decision method uses Markov Decision Processes (MDPs). MDPs are models for sequential decisions when outcomes are uncertain. The set of available actions, the rewards and the transition probabilities depend only on the current state and action [Puterman]. Solving a MDP entails finding for each state an optimal action that will maximize some cumulative function. In this work, the expected discounted sum.

User movement is random, migration and communication costs are not constant, and however VNF movement is arbitrary. This leads to a scenario where outcomes are partially random, so MDPs can be used.

These are the parameters for the MDP:

- The set of state **S** consists of all positions in the hexagon structure where the users can be located.
- The action set **A** has three possible actions: no migration a_{nm}, migrate to central cloud a_{mcc} and migrate to serving cloud a_{msc}
- The state transition probabilities are given by the mobility model: the user has the probability m of moving to a neighbouring cell, while the probability of no movement is $1 - 6m$. This holds regardless of which action is taken
- The MDP defined here must determine which action will give the best reward on the long term. Since migration either to the central cloud or to the serving cloud will lead to service outages, the decision for migration should only be taken when it represents the option with the best long term outcome. The reward function varies depending on the action taken:
    - For a_{nm}, the reward is the migration cost minus communication cost, always using the distance between the central cloud and hosting cloud.
    - For a_{msc}, the reward is the communication cost minus migration cost, always using the distance between the central cloud and hosting cloud.
    - For a_{mcc} , the reward is the communication cost between the central cloud and serving cloud minus the migration cost between the hosting cloud and the central cloud.
- The discount factor γ can be set through fine-tuning. As mentioned before, the goal here is to find the optimal action that will maximize the expected discounted sum of random rewards. This discounted sum will use this discount factor value.

The MDP is solved using modified policy iteration. Every time the users change cloud, the MDP will give you the action that entail the best cumulative reward over an infinite horizon.

To evaluate the proposed approach, simulations were made using MatLab. These are the relevant aspects of the simulation that differ from the above given description of the method:

- The hexagon cell structure has 49 cells. This fact changes the user movement probability in in cell with fewer than 6 neighbours.
- The migration cost function chosen used $\boldsymbol{\theta} = 0.4$
- The communication cost function chosen used $\boldsymbol{\theta} = 0.2$
    - This means that communication costs grows slower than the migration costs, and migration costs are always higher than communication costs
- After some fine-tuning simulation runs, the discount factor was set as $\boldsymbol{\gamma} = 0.99$
- If in a time step the VNF was moved to the central cloud, then in the next it is moved to the serving cloud. This is done with the understanding that the best QoE would be achieve in the serving cloud, and that moving to the central cloud is an intermediate step with a good reward at that moment.

Here are some conclusions from the simulations:

- The user movement probability $\boldsymbol{m}$ has a big impact on the decision
    - Below a value of 0.65, the MDP returns migrate to central cloud as the best option
    - Between 0.65 and 0.75, it returns mostly migrate to serving cloud, but sometimes to central cloud
    - Above 0.75, the best action is always migrating to serving cloud
- This can be explained by the fact that low values of $\boldsymbol{m}$ make it almost certain that the users will eventually be far from the hosting cloud. So the intermediary step of migrating to the central cloud pays off better
- For high values of $\boldsymbol{m}$, the users don’t move much, so if they move, it’s better to just migrate to the serving cloud
- The policy of never migrating is the worst of all three, while the best depends on the user movement probability, as mentioned above

5 Conclusions

This document has reported on the final outcomes of WP5 in the 5G NORMA project. The effort of the partners involved in the WP has been focused on two intertwined activities that have been carried out in a coordinated manner, such to maximize the impact of the specific technical solutions devised by the partners and be a useful input towards WP3 and WP6. Also, the interaction with WP4 has been beneficial. As a matter of fact, the control – data layer architecture is shared by the two WPs and it is further consolidated by WP3.

The proposed functional architecture has been designed to be ready for the requirements that future 5G Networks will need to support in a relatively short time frame. That is, by leveraging the most advanced trends in network softwarization on both NF control and orchestration (i.e., Software Defined Networking, Network Functions Virtualization and their relative management architecture), we designed a modular functional architecture that fully embodies the novel paradigms that are considered as the fundamental pillars of future 5G Networks, such as multi tenancy, network programmability and network slicing. The latter is especially important to our architecture, as all the designed modules have distinctive characteristics depending on their relative involvement to operations that should be performed within a Network Slice or across several network slices.

For this purpose, we designed three innovative controllers: The Software Defined Mobile Network Controller (SDM-C), Software Defined Mobile Network Coordinator (SDM-X) and Software Defined Mobile Network Orchestrator (SDM-O), that take care of several aspects of QoE/QoS-aware network connectivity. We defined such elements to *i)* provide innovative functionality needed to fulfil the 5G requirements and *ii)* extend the current state of the art solutions for network control and orchestration (e.g., the ones standardized by the ONF, the Linux Foundation or the ETSI MANO NFV) without breaking their fundamental architecture, to maximize the outcome of the project and facilitate the migration paths towards a fully softwarized architecture such as the one proposed by WP5 and, by extension, by 5G NORMA.

Even though the functional architecture itself is already a very valuable innovation itself, the second fundamental aspect of the WP5 work is the composition of individual solutions that build on top of the defined architecture to provide solutions to the different problems posed by softwarized network architecture. More specifically we focus on three areas: Network Slices Orchestration, QoE/QoS Network Slice Control and Mobility Management. All these solutions, detailed in Part II of the deliverable, are the engine of the 5G NORMA overall concepts. Together with the ones already described in [D5.1], WP5 described more than 20 technical innovations that implement the concepts described in Part I. Among the proposed solutions, we remark:

- Novel algorithms for network orchestration that consider different aspects such as the availability of multiple paths, the awareness on the mobility management algorithms or the resources available at each computational node.
- The application of the software defined networking paradigm to all the NFs belonging to a network slice: we provide exemplary applications regarding video pre-scheduling, eICIC or the choice of MAC scheduler. All of them consider the case of dedicated or shared network functions.
- Mobility Management algorithms are one of the main categories of SDM-C applications. We describe how this category of algorithms benefits from the Software Defined approach to provide the user with per-slice specific mobility management strategies.

Hence, the main achievement of WP5 are

- We have proposed a new architecture comprising key 5G concepts such as SDN-based control (SDM-C), NFV/orchestration (SDM-O) and slicing (SDM-X). The main value of this architecture is that it consolidates current trends in mobile networks, such as NFV, SDN and orchestration, which have only been proposed as high-level concepts so far, into a fully-fledged and completely defined architecture, being a **pioneering** architecture in this respect.

- We have identified key **modules and interfaces**, detailed them through exemplary processes and validated via the implementation of the proposed solutions.
- We have provided the design of more than **20 different algorithms/protocols** required for or enabled by this novel architecture (They are described in this document and in [D5.1]. All these proposals contain novel ideas and most of them have been patented, standardised or presented in major scientific venues.

Besides these major achievements, the work of WP5 will last beyond its end. First, work on the functional architecture design will be included in the upcoming D3.3, which will describe the last iteration of the architectural design process. Also, WP5 concepts will be implemented in two final demonstrators: the SDM-C concept in Demo #1 and the network slicing service aware orchestration in Demo #2.

Annex A Analysis of existing approaches for mobility support

The GPRS Tunneling Protocol (GTP) has been enhanced from original specifications as Mobility Management protocol for 3GPP's 2G GSM/GPRS to support LTE in its latest version [3G29060], [3GTS29274]. GTP creates transport tunnels for user traffic on top of an IP infrastructure. Generally, GTP is used in MNO's backbone between any pair of CN nodes (S/GGSN in 2/3G) and is split into c-plane (control plane) protocol, GTP-C, in charge to signal how tunnels are switched, and u-plane (user plane) protocol GTP-U, defining how to encapsulate user packets. eGTP as encapsulation method in EPC transmits IP packets via chain of tunnels (eNB-SGW, SGW-PGW) for so-called PDN connection, i.e. an IP point-to-point link between User Equipment (UE) and PGW, enabling UE to access target PDN through PGW.

MME is main actor in GTP-C's mobility procedures when UE moves between eNBs, thus coordinating SGW–eNB tunnel switch after handover.

Within 5G NORMA architecture this coordination is done by SDM-C with AN (e.g. NR) nodes (instead of eNB) as PNFs and terminating entities (AMF/UPF in SA2 terminology) as VNFs (expected to replace SGW/PGW in EPC).

The traditional IP-based tunnelling protocols are host-based Mobile IP (MIP) [MIP6] and network-based Proxy MIP (PMIP) [PMIP6] specified by IETF. MIP ensures connectivity and reachability in case of client mobility by defining an additional IPv6 address role in terms of a Care-of-Address (CoA), assigned to the client in addition to current IPv6 address allocated in the home network (i.e. where no mobility support is required since the location and address is well-known) with the logical entity Home Agent (HA). Here the client is responsible for managing mobility in terms of sending binding updates to HA including each newly assigned CoA, which acts as anchor router and registrar. The tunnel is established between UE at CoA and HA for secure packet exchange.

PMIPv6 is based on MIPv6 with the Mobile Access Gateway (MAG) as network entity managing mobility-related signalling on behalf of UE at access router. Local Mobility Anchor (LMA) is introduced as topological anchor point which handles UE's binding state. MAG is responsible for tracking UE's movements to and from access link and signalling it via the MAG-LMA tunnel to UE's LMA.

DMM (Distributed Mobility Management) describes an architecture with distributed mobility anchors and can be based both on MIP or PMIP. DMM aims to separate control and data plane, thereby enabling aggregation of control plane for elastic scaling, but maintain a distributed data plane for efficient network usage. Mobility states as c-plane information is eliminated from the data plane. By dynamic selection of control and data plane nodes and potential relocation of anchor functions if required or useful for efficient network usage it is well prepared for 5G NORMA approach. Allowing also provision of network properties to the mobile node – which also can be a router itself hosting multiple terminal devices (seen as part of the logical E2E network slice) completes the 5G view of DMM which introduced also different mobility features as on-demand, temporary or continuous mobility [YMK+].

In DMM anchoring environment, multiple anchors are available for mid-session switching of IP prefix anchor. To start new flow or handle flow not requiring IP session continuity as an MN (Mobile Node) moves to new network, flow can be (re-)started using new IP prefix allocated from and anchored to new network.

For flow requiring IP session continuity, anchoring of prior IP prefix may be moved to new network. MM functions and their operations and parameters are general for different configurations. Mobility signaling may be between anchors and network nodes in network-based mobility solution. It may also be between anchors and MN in host-based solution. MN may be host, but also router carrying network requiring network mobility support.

HA, MAG, and LMA are mainly realized as VNFs whereas CoA may be located at an AR resembling a PNF.

In [DMA16] the possibilities for logical mobility functions and their association to Data Plane and Control Plane Anchors (DPA/CPA) are described in detail. These VNFs have to be controlled by SDM-C via MM-App in 5G NORMA.

Different modes of DMM implementation for SDN have been analyzed in [NBH16] and HO latency and overall delay remain comparable to legacy approach. A non-tunneling based solution may run into scalability problems due to high signaling overhead.

For flow requiring IP session continuity, anchoring of prior IP prefix may be moved to new network. MM functions and their operations and parameters are general for different configurations. Mobility signaling may be between anchors and network nodes in network-based mobility solution. It may also be between anchors and MN in host-based solution. MN may be host, but also router carrying network requiring network mobility support.

Routing based protocols often introduce a new identifier, e.g. next to the location-specific IP address. HIP (Host Identity Protocol) actually HIPv2 (RFC7401, [HIPv2]) allows compliable hosts to securely establish and maintain shared IP-layer state, while separation of identifier and locator roles of the IP address enables communication continuity across IP address change during mobility-caused transition to a new point of attachment. Utilising a Diffie-Hellman key exchange, public key identifiers derived from a new Host Identity namespace can be used for mutual peer authentication and HIP is also resistant to denial-of-service (DoS) and man-in-the-middle (MitM) attacks. Mobility support and multi-homing for end hosts is also enabled by corresponding extensions [HIPv2].

LISP (Locator/ID Separation Protocol) separates control from data plane where the latter is encapsulated while for control of routing two namespaces are defined, i.e., End-point Identifiers (EIDs) and Routing Locators (RLOCs) to identify end-hosts by names and network attachment points, respectively. Thus LISP-capable routers – i.e. Ingress/Egress Tunnel Router (ITR/ETR) jointly denoted as xTR - can create overlay network across which encapsulated packets are exchanged according to EID-to-RLOC mappings stored in a local map-cache populated by the LISP Control-Plane protocol.

The xTR functionality is typical u-plane VNF whereas the mapping system is the c-plane VNF both to be configured by MM-App via SDM-C.

ILNP (Identifier Locator Network Protocol) (RFCs 6740 - 6748) was defined in framework of routing RG at IRTF and resembles a new architectural approach. splitting an IPv6 address into locator (L) and identifier (I). It is claimed that ILNP uses a purely end-to-end architecture, and does not require proxies, middleboxes or tunnelling to support mobility. Not requiring middleboxes or proxies also obviates performance bottlenecks, single points of failure and targets for attack by malicious users. ILNPv6 is a specific realisation of that approach - soft handoff with ILNPv6 (In-kernel Linux implementation) minimises gratuitously packet loss during handoff, while maintaining similar performance to hard handoff in terms of handoff delay, application level packet delay and signalling overhead. ILNP architecture defines an IPv6 capable Site Border Router (SBR) which needs to support ILNP only in case of optional advanced deployment scenarios described in [RFC6748] to e.g. control mobility of the hosts. To facilitate required I-L mapping at e.g. DNS an implementation specific ILNP Communication Cache (ILCC) is foreseen which contains for each (local and correspondent) node the currently valid set of Locators and set of Identifiers together with Precedence, activity state, and (in case of L) associated local interface(s).

Beside standard Routing and name resolution at e.g. DNS on c-plane level ILCC was described, on UP level SBR is introduced as potential VNF for ILNP.

Discussion is ongoing whether LISP can also use a simple IP core and smart end points as it supports multiple address families not being limited to IPv6.

ILA (Identifier Locator Addressing) protocol is designed as u-plane protocol for task communication and migration on L3 level [ILA-nv] can be enhanced to support user mobility [ILA-mob] e.g. to 4G 3GPP EPS. ILA is fundamentally based on ILNP but differs insofar that ILA does not require changes to transport layer and does not need/use IPv6 extension headers. While ILNP involves existing DNS to distribute mapping information, ILA assumes mapping information is not part of naming.

ILA also differentiates between location and identity of a network node. Part of an address expresses immutable identity of node, another part indicates location of node which can be dynamic thus it can be used to efficiently implement overlay networks for network virtualization as well as solutions for use cases in mobility.

The introduced process of ILA translation, i.e. creation and maintenance of mapping table between identifiers and locators is executed at an ILA Router which is a network device performing in addition packet forwarding and re-direction for path optimization. The ILA translation is also performed at each ILA host for outgoing and incoming packets. The ILA resolver protocol is used here to have identifiers and locators properly mapped to each other for the destinations of communication requests.

ILA nodes (both hosts and routers) have both c-plane and u-plane tasks as VNFs in ILA architecture

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