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Abstract

This document describes the current status of the WP5 work, introducing the 6 building blocks supported in 5G NORMA architecture: the Software-Defined Mobile Network Controller (SDM-C), Orchestrator (SDM-O), Coordinator (SDM-X), the Mobility Management module (composed by the scheme selection and design), and the QoE/QoS Mapping, Monitoring and Management module. The functionalities of each block are detailed together with the different mechanisms designed to support network slicing and multi-tenancy, highlighting thus 5G NORMA innovations. The interactions between the different blocks are presented, emphasizing the complementarities of the different tackled technical problems to control and to orchestrate network slicing.

Keywords

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

Executive Summary

To build a flexible and an adaptable mobile network architecture capable of supporting a wide variety of services and their respective requirements, 5G NORMA has introduced a novel paradigm: ***a network of functions-based architecture***. This novel paradigm breaks the design principle followed by current network architectures, which are built around entities rather than functions. Our revolutionary approach builds on new technologies, such as Software-Defined Networking (SDN) and Network Function Virtualization (NFV), in conjunction with novel concepts such as the network slicing and multi-tenancy. The main contribution of this deliverable is to bring these technologies and concepts, which reflect the ***current trends*** in mobile networks, into a fully specified and ***completely defined mobile network architecture***. To the best of our knowledge, ours is a *pioneering* effort in this direction.

This document presents the initial design of the architectural concepts of 5G NORMA related to the controllers' design and specification. *Three different controllers* are considered in the architecture, namely: the Software Defined Mobile Network Orchestrator (SDM-O), the Software Defined Mobile Network Control (SDM-C), and the Software Defined Mobile Network Coordinator (SDM-X). The key ideas behind these controllers are as follows:

- ***SDM-O*** interacts via Application Programming Interface (API) with the service and business layer to gather their requirements and translate them into a set of Virtual Network Function (VNFs) and Physical Network Functions (PNFs) to be chained together to implement the service. SDM-O is in charge of defining the optimal placement/location and the optimal set of resources to be allocated to the different VNFs. In addition, SDM-O takes care of the scaling in/out of the different VNFs instances according to triggers that come from both the infrastructure (through its Virtualized Infrastructure Manager) or by the control framework . For each of these challenges, a set of innovative algorithms are proposed and described.
- ***SDM-C*** applies these same principles of the current Software-Defined Networking (SDN) to *wireless functionality beyond routing*. Indeed, the benefits of this technology when applied to wireless networks are even more significant than for wired networks, as the control functionality of wireless networks include many additional and more complex functions than just routing. This includes time-critical functions (such as scheduling control and self-organizing networks) and other less time critical (such as Radio Resource Control, power control and handover decision and execution). With SDM-C, all these functions can be implemented more easily by a programmable central control, which provides very important benefits for the flexible operation of the wireless edge network.
- ***SDM-X is*** responsible for the control of resources and network functions *shared among network slices*. Indeed, sharing the resources across a set of network slices is highly important for future 5G deployment. Such resources include the spectrum and the infrastructure, among others. Thus, to operate multiple network slices in the same infrastructure efficiently, a common entity named Software Defined Mobile Network Coordinator (SDM-X) is introduced in the architecture. The different interfaces between SDM-C/X/O are also introduced and discussed in this document.

In order to simplify the reading of this deliverable, the content has been divided into two distinct parts: (i) the definition of the global architecture, and (ii) the design of the underlying algorithms and protocols.

<u>**Part I**</u> of the deliverable focuses on the ***definition of the global architecture***. This includes the specification of the different modules and their interfaces, including the three controllers mentioned above as well as the various functions involved, including the control of inter and intra network slice resources, the Quality of Experience (QoE) aware-functionality, building on the Quality of Service (QoS) monitoring and modelling component, the network orchestration

component as well as the mobility-related functions. Throughout this part, we describe the consistency of the presented functions with the overall 5G NORMA architecture and detail the first steps towards the definition of the interfaces among the controller and the other elements of the architecture. In the interest of conciseness, the content of this part has been presented on a summarized manner, highlighting the key contributions and innovations and omitting cumbersome details. Further details on the design of the various functions is available in internal documents and external publications.

It is worth highlighting that the WP5 architecture definition has been described in two publications that have been jointly written by all WP partners. These two publications have been presented in two very relevant workshops in the area, namely 5Garch 2016 and CLEEN 2016, and have been very well received by the scientific and industrial communities.

Part II of the deliverable focuses on the ***design of the underlying algorithms and protocols***. Such algorithms and protocols are either required to implement some of the new functions within the proposed architecture (e.g., new algorithms are required in order to orchestrate the various network functions) or are enabled by the new capabilities of the architecture (e.g., the new architecture allows to perform mobility in a more efficient way). In particular, WP5 has proposed a total of ***19 technical innovations*** around its architecture, corresponding to either new algorithms, protocols or technical solutions, each of which fills a given gap within the architecture. The second part of the deliverable provides a detailed description of each of these innovations, describing the motivation, its full specification as well as the advantages and performance gains.

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. For example, the novel orchestration algorithms proposed in this paper has been published in a top journal such as IEEE TMC, several patents have been filed to protect the project ideas related to the QoS/QoE of video flows, and the proposals of the project on QoS monitoring and enforcement have been pushed into 3GPP.

Table of Contents

Executive Summary **3**

Table of Contents **5**

List of Figures **8**

List of Tables **11**

List of Acronyms and Abbreviations **12**

PART 1: ARCHITECTURE **18**

1 Introduction **19**
1.1 Objective 19
1.2 Structure of Part I 19
1.3 Key contributions of Part I 21

2 Key technologies and related work **22**
2.1 5G NORMA key technologies 22
2.1.1 Software Defined Networking 22
2.1.2 Network Virtualization 23
2.2 Related work 25
2.2.1 EU METIS and EU iJoin 25
2.2.2 3GPP RAN Sharing and Multi-tenancy 26
2.2.3 3GPP and SCF VNF Orchestration in Mobile Networks 27
2.2.4 ONF SDN for Mobile and Wireless Networks 28
2.2.5 3GPP LTE and ETSI NFV Security Architecture in Multi-tenancy and Multi-services 28

3 WP5 Functional architecture **29**
3.1 Functional requirements 29
3.2 Research challenges 30
3.3 5G NORMA WP5 building blocks 31
3.3.1 Intra-slice Management 32
3.3.2 Inter-slice Management 33
3.3.3 Mobility Management 34
3.3.4 Mapping with the overall 5G NORMA architecture 34
3.4 SDM-O: Slice Orchestration 36
3.4.1 Generic Resource provisioning 36
3.4.2 Resource pooling and reservation 37
3.5 SDM-C: Dedicated Slice Control 38
3.6 SDM-X: Shared Slice Resources Control 39
3.7 WP5 Summary of Processes 40
3.7.1 Network slice set-up and deployment 41
3.7.2 Network slice resources re-orchestration 42
3.7.3 SDM-X policies (resource sharing) 43
3.7.4 SDM-C application (Network slice creation) 44

PART 2: ALGORITHMS **45**

4 Introduction **46**
4.1 Objective and structure of Part II 46
4.2 Key contributions of Part II 47

5 Network Slice Orchestration **47**
5.1 Introduction 47
5.2 Service Management 49
5.3 Network Slice Brokering 51

5.4 Slice VNF Allocation/Life-cycle management ... 53
5.4.1 Examples of Management Flows ... 56
5.5 VNF chaining location ... 62
5.5.1 VNF Routing, Location and Chaining in Virtualized Network Infrastructures ... 65
5.5.2 Routing and VNF Placement ... 67
5.5.3 Mobility and VNF Placement ... 67
5.5.4 Integer Linear Programming Formulations ... 68
5.5.5 Extensions ... 70
5.5.6 Final Remarks ... 71
5.6 Optimized Management of Network Slice Resources based on VNF profiles ... 71
5.6.1 RAVA – Conceptual Overview ... 72
5.6.2 Performance analysis ... 74
5.6.3 Next Steps ... 76
5.7 Shared Resource Management ... 76
5.8 Constrained SFC sets ... 79
5.9 Slice hierarchical orchestration ... 81
5.9.1 4G toward 5G architecture evolution ... 81
5.9.2 Hierarchical VNF SDN orchestration for 5G networks ... 82
5.10 Edge Cloud MANO ... 84
5.10.1 Edge Cloud Infrastructure High Level Requirements ... 86
5.10.2 Edge Cloud Underlay Technologies Orchestration ... 87
5.10.3 VIM capabilities for VNF deployments ... 87

6 QoS/QoE Service Control ... 89
6.1 Introduction ... 89
6.2 QoS/QoE mapping ... 89
6.2.1 Introduction. ... 89
6.2.2 QoS/QoE Mapping in 5G NORMA ... 90
6.3 QoS/QoE enforcement and monitoring ... 101
6.3.1 QoS/QoE Monitoring and target definition ... 101
6.3.2 QoS/QoE enforcement ... 105
6.4 Video Pre-Scheduler ... 109
6.4.1 Research objective ... 109
6.4.2 Video Pre-scheduling SDN platform ... 109
6.4.3 Link and buffer aware scheduling algorithm ... 111
6.5 QoE aware eICIC ... 114
6.5.1 Introduction ... 114
6.5.2 Quality of Experience as a video utility ... 115
6.5.3 HetNet Inter-Cell Interference Coordination piloting by QoE for heterogeneous networks ... 117
6.6 QoE based routing ... 119
6.7 QoE assessment through vehicular simulator ... 121
6.7.1 Methodology ... 123
6.7.2 LTE performance assessment with vehicular use cases ... 125
6.7.3 Future work ... 128

7 Mobility Management ... 128
7.1 Introduction ... 128
7.2 Selection of Mobility Management scheme ... 130
7.2.1 Binding of Mobility Management scheme to Network Slices ... 131
7.2.2 Common vs. dedicated Mobility Management ... 132
7.3 Mobility management scheme design ... 133
7.3.1 Mobility design in terms of MM functions granularity description ... 133
7.3.2 Decision on MM criteria ... 134

7.3.3 MM processes to detail signaling and interaction between (logical) entities (MSC) ... 135
7.3.4 Mapping of potential MM design approaches to use cases ... 136
7.3.5 Cross-Layer design of MM approach ... 138
7.3.6 Cross-Technology MM schemes ... 141
7.3.7 Granularity consideration in MM protocols ... 141
7.4 Edge Mobility ... 142
7.5 SDM-C based mobility ... 145
7.5.1 RRC-PDCP ... 145
7.5.2 PDCP-RLC ... 147
7.5.3 Other Splits ... 151
7.6 Multipath ... 151
7.6.1 Problem statement ... 152
7.6.2 Forwarding strategies ... 153
7.6.3 Preliminary results ... 154
7.6.4 Next steps ... 156

8 Conclusions ... 156

9 Annex: State of the art ... 158
9.1 Multipath: ... 158
9.2 Mobility Management: ... 158
9.3 Network Sharing: ... 160
9.3.1 RAN Sharing ... 160
9.3.2 MORAN / MOCN ... 161
9.3.3 Dedicated Core Networks ... 161
9.4 Multi-Domain Interfaces: ... 162
9.5 QoE video optimization delivery: ... 163
9.6 QoS in LTE: ... 164
9.7 QoE-based Routing: ... 165
9.8 Vehicular mobility pattern: ... 166
9.9 Monitoring: ... 166
9.10 QoE Management: ... 167
9.11 Edge Function Mobility ... 168
9.12 Service Function Chain: ... 168
9.13 Virtual Network Function Orchestration ... 169
9.14 QoS/QoE Mapping – State of the art ... 170
9.14.1 Mapping Function Input Parameters ... 170
9.14.2 Mapping Functions Modelling ... 172
9.14.3 The Mapping Function Output ... 175

10 Bibliography ... 177

List of Figures

Figure 1: ETSI NFV MANO architecture 24
Figure 2: Different functional split supported in RANaaS, iJoin [10] 26
Figure 3: SCF VNF orchestration in mobile network 27
Figure 4: WP5 building blocks and their interactions 31
Figure 5: SDM-C interfaces 32
Figure 6: 5G NORMA architecture 35
Figure 7: The lifecycle of a network slice in 5G NORMA 36
Figure 8: Example of SDM-C based on OpenDayLight block diagram 39
Figure 9: SDM-X Reference Architecture 40
Figure 10: The interactions among different actors involved in the re-orchestration 43
Figure 11: Mapping of technical contributions to WP5 building blocks 46
Figure 12: Network Slice Orchestration Functional Blocks 48
Figure 13: Network Slice Brokering with 5G NORMA Architecture 52
Figure 14: 5G NORMA Main Management and Orchestration Blocks 54
Figure 15: VNF Package On-boarding Process 56
Figure 16: VNF Package Enabling Process 57
Figure 17: VNF Package Delete Process 58
Figure 18: VNF Instantiation Process 59
Figure 19: Automatic Intra-slice VNF Scale-out 60
Figure 20: VNF Instance Termination Process 61
Figure 21: NFV Fault Management Process 62
Figure 22: NFV logical architectural view as proposed by ETSI 64
Figure 23: A toy example showing the embedding of two virtual networks in a substrate network infrastructure. 65
Figure 24: Possible locations of three VNFs in two network nodes that can host these functions 66
Figure 25: Effect of VNF location on the selection of available (shortest) paths in the network 66
Figure 26: The effect of mobility on the location of VNFs; a location that does not take into account mobility might lead to an increased routing cost 67
Figure 27: Resource Utilization samples for a specific VM. 73
Figure 28 : PoC Testbed Overview 74
Figure 29: Load comparison between CN-2 and CN-3 75
Figure 30: Affinity Signature for the candidate compute nodes. 76
Figure 31: Radio resource scheduling process with the SDM-X 77

Figure 32: Example for an RRM database and a heterogeneous radio resource scheduling strategy 78
Figure 33: High level architecture and reference points for 3GPP next gen core network 81
Figure 34: Network architecture evolution 4G toward 5G (source Netmanias) 82
Figure 35: Potential 5G network topology (source Korea Telecom) 82
Figure 36: Multi-domain SDN orchestrator (source COMBO, 5G Xcrosshaul) 83
Figure 37: 2017–2020 Orchestration Evolution toward an Orchestrator of Orchestrators (source Infonetics) 84
Figure 38: Typical datacenter reference architecture 85
Figure 39: Collapsed edge cloud architecture 85
Figure 40: Basic Mapping Function 91
Figure 41: Mapping functions executed in parallel 92
Figure 42: Normalization and Output Codecs 93
Figure 43: Interface with surrounding systems 94
Figure 44: QoS/QoE Mapping Module Building Blocks 96
Figure 45: QoS/QoE Mapping/Management Modules Interface Example 97
Figure 46: Example of a XML based Descriptor file 98
Figure 47: High level structure of adaptive QoE target definition and QoS mapping 102
Figure 48: Illustration of the bandwidth allocation and QoE of video session 106
Figure 49: QoE enforcement and resource management operation 107
Figure 50: Illustration of additive increase and multiplicative decrease CC 109
Figure 51: System architecture 110
Figure 52: Synoptic of the Queuing system 111
Figure 53: Exploiting time-channel variability 113
Figure 54: Proposed scheduling algorithm 114
Figure 55: SSIM as a function the encoding rate and content 117
Figure 56: 3GPP Interference Mitigation Mechanism 118
Figure 57 : QoE-aware eICIC optimization framework / operation description 118
Figure 58: Assessment of the 5G NORMA architecture through vehicular network simulation 123
Figure 59: Segment Popularity of the scenario (darker links mean higher loads) 125
Figure 60: eNodeB placement in the simulated scenario 126
Figure 61: Uplink delay CDF 127
Figure 62: Time series of the average delay for an eNodeB 127
Figure 63: Organisation of Mobility Management Task in WP5 129
Figure 64: Interaction of Mobility management task with others 130
Figure 65: Binding functionality – building blocks 131
Figure 66: Mapping the Binding functionality into 5G NORMA architecture 132

Figure 67: General message sequence chart for exemplary MM process Paging 136
Figure 68: User Mobility Model 144
Figure 69: RRC-PDCP split.. 146
Figure 70: MSC for the Handover procedure using the SDM-C Mobility Management 147
Figure 71: PDCP - RLC split 149
Figure 72: PDCP functionality (Control).. 149
Figure 73: PDCP functionality (User) 150
Figure 74: SDM-C ROHC Application 151
Figure 75: Multipath between VNFs 152
Figure 76: The multipath scenario 153
Figure 77: Throughput: 4 paths scenario 155
Figure 78: Throughput: 8 paths scenario 155
Figure 79: Network sharing methodologies.. 160
Figure 80: MORAN- Basic features 161
Figure 81: Dedicated core networks for exemplary service categories, use cases, or customers 162
Figure 82: LTE EPS bearer concept 165
Figure 83: Correlation between QoE and QoS. 167
Figure 84: The QoS/QoE Mapping General Problem.. 170
Figure 85: Objective Approach.. 172
Figure 86: Subjective Approach 174
Figure 87: Weber-Fechner law of psychophysics.. 176

List of Tables

Table 1 : Scope of SDM-C and SDM-X 35
Table 2: The four categories of processes 41
Table 3: Selection of SLA parameters to be specified by the tenant 50
Table 4: Exemplary output of Service Management for network slice properties for connectivity on a temporary construction site 51
Table 5: RRAS Report Snapshot for a Specific VM 73
Table 6: Operations for the Execution Environment 96
Table 7: Operations for the Deployable Units 96
Table 8: Example of an Event Notification Definition 99
Table 9: QoS parameters 104
Table 10: Simulation Parameters 124
Table 11 Mapping of selected MM feature impact on typical 5G NORMA use cases [D2.1] .. 136
Table 12 ROHC configurations 150
Table 13: QoS parameters and other QoE influence factors 171
Table 14: QoE metrics examples and classification 175

List of Acronyms and Abbreviations

Term	Description
3GPP-LTE	Third Generation Partnership Project-Long Term Evolution
5GN	5G Networks
A-CPI	Application-Controller Plane Interface
AE	Analytics Engine
API	Application Programming Interface
AS	Affinity Signature
BSS	Base Station
BSS	Business Support Systems
CAPEX	Capital Expenditure
CC	Congestion Control
CDB	Customer Data Base
CF	Customer-facing
CIO	Cell Individual Offset
CN	Core Network
CNE	core network elements
CoMP	Coordinated Multi-Point
CP	Control Plane
C-RAN	Centralized-RAN
D2D	Device-to Device
DASH	Dynamic Adaptive Streaming over HTTP
DC-GW	Datacenter Gateway
DCN	Dedicated Core Network
D-CPI	Data-Controller Plane Interface
DE	Decision Engine
DL	Downlink
DMM	Distributed Mobility Management
DPCF	Data Plane Control Function
DPI	Deep Packets Inspection
E2E	End-to-End
EA-VNE-NLF	Energy Aware-Virtual Network Embedding-Node-Link Formulation
EBI	East-Bound Interface
EC	European Commission
eICIC	Enhanced Inter Cell Interference Cancellation
EJB	Enterprise Java Bean
eMBB	Enhanced Mobile Broadband

EMS	Element Management System
ETSI	European Telecommunications Standards Institute
FW	Firewall
GSMA	GSM Association
GTP	GPRS Tunneling Protocol
GWCN	Gateway Core Network
H2020	Horizon 2020
HAS	HTTP Adaptive Streaming
HLR	Home Location Register
HSS	Home Subscriber Server
HW	Hardware
ICIC	Inter Cell Interference Cancellation
ICT	Information and Communication Technologies
IDS	Intrusion Detection System
IETF	Internet Engineering Task Force
ILP	Integer Linear Programming
InP	Infrastructure Provider
IOT	Internet of Things
IPS	Intrusion Prevention System
ISTO	Inter-Slice/Tenant Orchestrator
JAIN	Java API for Intelligent Networks
JAR	Java Archive
JSR	Java Specification Request
JVM	Java Virtual Machine
KPI	Key Performance Indicators
KQI	Key quality indicators
LCM	Life Cycle Management
LTE	Long Term Evolution
M2M	Machine-to-Machine
MAC	Medium Access Control
MANO	Management and Orchestration
MEC	Mobile Edge Computing
MIH	Media Independent Handover
MIHF	Media Independent Handover Function
MM	Mobility Management
MME	Mobility Management Entity
mMTC	Massive MTC
MNO	Mobile Network Operator
MOCN	Monolithic Operator

MOCN	Multi-Operator Core Network
MOS	Mean Opinion Score
MSC	Message Sequence Chart
MTC	Machine Type Communication
MTCP	Multipath TCP
MVNO	Mobile Virtual Network Operator
NAT	Network Address Translation
NBI	North-Bound Interface
NE	Network Elements
NF	Network Functions
NF-FG	NF Forwarding Graph
NFG	Network Forwarding Graph
NFV	Network Function Virtualization
NFVI	NFV Infrastructure
NFVO	NFV Orchestrator
NNI	Network-Network Interface
NSH	Network Service Header
OMA	Open Mobile Alliance
ONF	Open Networking Foundation
OPEX	Operational Expenditure
ORLC	Optimal Routing, Location and Chaining
OSM	OpenStreetMaps
OSS	Operation Support Systems
OTT	Over-The-Top
OVSDB	Open vSwitch Database
PE	Provider Edge
PHY	Physical
PNF	Physical network function
PoP	Point of Presence
PPMCC	Pearson Product-Moment Correlation Coefficient
QaC	Quality-aware communications
QCI	QoS Class Identifiers
QoD	Quality of Decision
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAN	Radio Access Network
RANaaS	RAN as a Service
RAVA	Resource Aware VNF Agnostic

RB	Resource Block
RF	Resource-facing
RRAS	Reference Resource Affinity Score
RRM	Radio Resource Manager
RRU	Reference Resource Unit
RU	Resource Unit
SBI	South-Bound Interface
SCEF	Service Capability Exposure Function
SCF	Small Cell Forum
SDM	Software Defined Mobile Network
SDN	Software Defined Network
SDM-C	SDM Controller
SDM-O	SDM Orchestrator
SDM-X	SDM Coordinator
SFC	Service Function Chaining
SFP	Service Function Path
SIP	Session Initiation Protocol
SLA	Service Level Agreement
SLEE	Service Logic Execution Environment
SO	Service Orchestrator
SON	Self Organizing Network
SO-NM	Sharing Operator Network Manager
SR-IOV	Single Root Input/Output Virtualization
SSIM	Structural SIMilarity
SW	Software
TED	Transmission Error Detector
TLV	Type Length Variable
UE	user equipment
UL	Uplink
UNI	user-network interface
UP	User Plane
V2I	Vehicle to Infrastructure
V2X	Vehicle to Anything communication
VHD	Vertical Handover Decision
VIM	Virtualized Infrastructure Manager
VM	Virtual Machine
VNF	virtual network function
VNF-FG	VNF Forwarding Graph
VNFM	VNF Manager

vSwitch	Virtual Switch
WBI	West-Bound Interface

Foreword

This document collects the key results, ideas and proposals of WP5 so far, along with its relationship with the global 5G NORMA concept and architecture. It is an official deliverable of the project, incorporates the content of Internal Report IR5.1 (which was produced as an internal and non-official document that captured WP5 results up to that moment), and adds the new results that have been produced in the project since IR5.1 was written.

This document is structured in two parts. These two parts have been written as almost independent documents on purpose, in order to reflect that this deliverable puts together two distinct documents into one:

- **Part I** provides the *overall architectural view* of WP5, including the different modules and interfaces that have been defined in WP5 in order to address the corresponding key concepts of 5G NORMA. This part also addresses the mapping of the WP5 modules into the overall 5G NORMA architecture as well as the processes that have been examined in order to validate the functionality provided by the architecture. This part of the document includes much of the content of IR5.1, which in some cases has been summarized in order to avoid that the document becomes too long and cumbersome.
- **Part II** addresses the design of the *individual technology components* of the proposed architecture. This corresponds to the design of specific solutions, algorithms or protocols that correspond to novel functions that are either enabled or required by the proposed WP5 architecture. It is worth to highlight that most of these novel solutions have a value by themselves in addition to fulfilling a specific role in the overall framework. In fact, most of these proposals have already been either patented, pushed into standard proposals or published in scientific conferences or journals.

In terms of the *key novelties* of this document, it is important to highlight that twofold contributions of the ideas contained in this document

- The overall functionality designed by WP5 is novel. Some of the concepts proposed, such as SDM-C (Software-defined Mobile network Control) are new ideas of 5G NORMA that had not been proposed before. Other ideas, such as network slicing, have been proposed before at a very general level, but have been brought by 5G NORMA into a specific and full-fledged definition.
- The individual technology components correspond to new algorithms, protocols or techniques that implement the high-level ideas of 5G NORMA. The novelty from these proposals comes from (i) the fact that 5G NORMA concepts pose new problems that require new solutions, and/or (ii) the fact that we devise new algorithms or techniques that perform better from similar ones in the literature.

An example that illustrates the twofold novelty of our ideas is the following. One of the key concepts of 5G NORMA is the “flexible functional decomposition and allocation”. While the underlying technology behind this concept (NFV) is well known, one of the major contributions of 5G NORMA is to bring this concept into a fully-fledged architecture and specification. This is one of the major novel contributions in Part I. Building on this concept, we have devised different algorithms and protocols to implement the required functionality, including an algorithm for the optimal placement of network functions as well as techniques to predict the availability of resources in an NFV environment. These are two of the novel solutions included in Part II. Of course, this is just an example, and a complete list of the various novel contributions is provided in the introduction of each of the two parts.

PART 1: ARCHITECTURE

1 Introduction

As explained in the Foreword, Part I of this document focuses on the description of the WP5 architecture, which builds and extends the content that had been included in IR5.1. In the following, we expose the main objectives of our architecture, describe the structure of this part of the document as well as the main contributions within this part.

1.1 Objective

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 Key Performance Indicators (KPIs): low latency, high capacity or service continuity.

Supporting all these requirements on the same infrastructure entails a re-engineering of the network architecture that goes beyond the extension of the current Third Generation Partnership Project-Long Term Evolution (3GPP-LTE) one. Building on the recent advantages on network virtualization and re-programmability, introduced by the Network Function Virtualization (NFV) and Software Defined Networking (SDN) paradigms, the architecture designed in 5G NORMA aims at these goals:

- Provide heterogeneous KPIs enabling different services, sharing the same infrastructure.
- Dynamically adapt the network capacity (and resource utilization) according to the demand.
- Seamlessly support new network services. That is, the architecture should be future-proof.

To achieve these goals, the 5G NORMA architecture leverages on five main pillars:

(i) the Adaptive (de)composition and allocation of mobile network functions between the edge and the network cloud depending on the service requirements and deployment needs,
(ii) the Software-Defined Mobile Network Control and Orchestration which applies the SDN principles to mobile network specific functions, and
(iii) the Joint optimization of mobile access and core network functions localized together in the central cloud or the edge cloud,
(iv) the Multi-service and context-aware adaptation of network functions to support a variety of services and corresponding QoE/QoS requirements, and
(v) the Mobile network multi-tenancy to support on-demand allocation of radio and core resources in a full multi-tenant environment. For more details on these concepts, we refer to [1].

The main objective of this part of the document is to define the control and orchestration planes of a mobile network architecture that implements the above five pillars. The combination of this architecture with the user plane functions defined by WP4 results into the overall 5G NORMA architecture.

1.2 Structure of Part I

This part of the document describes the current status of the Work Package 5 (WP5) architecture, which includes the following topics: Network Wide Orchestration, the service-aware QoE/QoS Control and the flexible service-tailored mobility management. Part I of this deliverable contains the following content:

- We first provide the description of technology trends.
- The architecture overview is presented next, along with the research challenges entailed by the proposed architecture.
- Then we describe the novel concepts behind the architecture: Software-Defined Mobile Network Controller (SDM-C), Software-Defined Mobile Network Coordinator (SDM-X), Software-Defined Mobile Network Orchestrator (SDM-O), Mobility Management, dynamic VNF management, QoE mapping, QoS Control and Enforcement.
- Finally, we present a summary of the WP5 processes (conducted by WP3) in order to validate the proposed WP5 architecture.

The three main conceptual contributions of the Work Package 5 are the following ones, which are particularly related to the innovation pillars of 5G NORMA project (i) and (ii) listed in Section 1.1:

Software-Defined Mobile Network Control (SDM-C): The key idea behind this concept is to apply the same design principles of SDN to the specific functionalities of mobile networks. Indeed, while SDN focuses exclusively on routing, the same principles of splitting control and data functions and allowing applications on top of the controller to operate the network in a flexible way can be very beneficial for specific functionality of mobile network. In this document, we describe the main concepts and the design guidelines of this approach and apply it to QoS/QoE functions as well as to mobility.

Network orchestration: This functionality is responsible, for example placement, scaling, migration, etc. of network slices and associated resources. To this end, we need to understand the requirements of the corresponding service that we need to satisfy, the constraints on the placement of functions that interact with each other and the features of the underlying infrastructure.

Network slicing: In order to be able to satisfy diverging requirements from different services, 5G NORMA instantiates different slices such that each slice may be potentially orchestrated in a different way and thus be tailored to the requirements of a specific service. This requires the coordination of resources between different slices, which leads to the introduction of a new hierarchical SDM architecture that allows controlling the resources inside each slice as well as between slices.

It is worth noting that all the above concepts are closely inter-related. For instance, network orchestration needs to consider QoS/QoE requirements, and hence Software-Defined Mobile Network Control and Network Orchestration perform a joint optimization problem involving the instantiation and operation of virtual network functions (VNFs). In addition, user mobility may trigger the re-orchestration of VNF as a user moves to a new location and may require certain functions to move with him, so there is a close link between orchestration and mobility. To tackle these interactions, one of the main contributions of this document is the design of a high-level architecture that brings together the above concepts along with the related modules for each of these concepts in a consistent way, addressing the interfaces required by each of these modules and the interaction among them. Along these lines, the content of Part 1 includes the following:

- **Overall architecture design:** We first present the overall design of the WP5 architecture, which is composed of three building blocks: Mobility management, inter-slice management and intra-slice management. We introduce the functional requirements of the architecture, the major research challenges as a motivation for the proposed architecture, and then design the architecture building blocks and their interaction in order to address these challenges.
- **Design of each building block:** As a second step, we dive into the design of each individual building block, decomposing it in further modules and describing the

interfaces between the different modules as well as providing some flow-charts describing their interactions.

- **Description of the individual modules of the architecture:** As a third step, we provide the description of the building blocks of the WP5 functional architecture and the first design iteration for the modules that comprises the respective building blocks. For each of these modules, we justify their need in the context of 5G NORMA, describe the novelties with respect to existing proposals and the functionality required. Note that this does not include the design of the corresponding protocols and algorithms, as this is precisely the focus of Part II of this deliverable.
- **Definition of the interfaces**: The last step is the definition of high-level interfaces, achieved by defining several processes. They have also been analysed to ensure that the proposed architecture can provide the required functionality.

Following the content described above, the rest of this document is structured as follows. In Section 2 we describe the current trends in the enabling technologies upon which 5G NORMA architecture is based, including related standards and previous projects. In section 3 we describe the overall 5G NORMA architecture with special emphasis on the building blocks of WP5, presenting the architectural requirements as well as the main challenges involved. Sections 2, 3.4, 3.5 and 3.6 are devoted to each of the three main building blocks of WP5 architecture: each of these section starts with a description of the interaction between the modules and interfaces involved followed by an individual description of each of the modules. Section Finally, Section 3.7 describes the different processes that have been analysed to validate the architecture.

1.3 Key contributions of Part I

As explained above, the key contribution of this document is the design of an architecture that comprises three novel concepts: Software-Defined Mobile Network Control (SDMC), Software-Defined Mobile Network Orchestration (SDMO) and network slicing. These innovative ideas have already been published in two workshops that focus on very closely related technologies to the ones addressed by 5G NORMA, which confirms the novelty of the key ideas behind the proposed architecture:

- 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 the 3rd International Workshop on 5G Architecture [2], 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 [3], which focuses on the design of cloud-based architectures for mobile network.
- One of these contributions is an IETF draft [4] 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 reader is referred to the introduction of Part II (Section 5) for a list of the most relevant contributions behind WP5.

2 Key technologies and related work

2.1 5G NORMA key technologies

Mobile Networks are evolving towards becoming a very dynamic and flexible environment consisting of virtual resources that can be instantiated and released on demand to timely meet customers' needs. These virtual functions are interconnected by virtualized links that are also dynamically setup to best support multiple services. The infrastructure could be also shared among different tenants in order to provide different services by means of the network-slicing concept. The first step towards that direction is represented by the Network Function Virtualization (NFV) and Software Defined Networking (SDN) concepts, which have been identified as the basic tools to properly provide flexibility to the future network design. In particular, in the following, we revisit the SDN and NFV principles, which are leveraged to design the three main blocks (i.e., SDM-O, SDM-C, SDM-X) in 5G NORMA by handling the control and the orchestration intelligence tailored to network slicing based on 5G NORMA architecture.

2.1.1 Software Defined Networking

The concept of SDN has attracted widely the research communities and industries after the introduction of OpenFlow, the first standardized SDN protocol as a way to experiment new protocols and applications [5]. OpenFlow laid the possibility of using its intrinsic feature of flow based traffic treatment to achieve traffic engineering, traffic monitoring, load balancing, provision of end-to-end QoS, and network virtualization, in various applications such as transport networks, data centres, local area network (LAN), wide area network (WAN), etc [6]. Initially, SDN drew its attention towards offering switching and routing solutions for fixed networks. Recently there has been many research works on aligning SDN to wireless networks. OpenRoads is the first research work analysing the capability of OpenFlow for mobile networks [7]. SoftRAN proposed an architecture of SDN controller that abstracted the radio access network (RAN) for coordinated scheduling, interference management and load balancing [8]. 5G NORMA aims to leverage SDN for wireless network via the SDMC approach and enable wireless network function and transport programmability. SDMC could be implemented in a propriety way (wireless control layer abstraction) or using open source projects developed (most of them) in Linux Foundation. Open source could be one of the following projects: POX, FloodLight, OpenDayLight (ODL), Ryu, Trema and Open Networking Operating System (ONOS). In the sequel we introduce the two biggest projects in the field.

OpenDayLight project:

The OpenDayLight (ODL) project is a collaborative open source project that aims to accelerate adoption of SDN and NFV for a more transparent approach that fosters new innovation and reduces risk. ODL is a highly available, modular, extensible, scalable and multi-protocol controller infrastructure built for SDN deployments on modern heterogeneous multi-vendor networks. It provides a model driven service abstraction platform that allows users to write apps that easily work across a wide variety of hardware and southbound protocols. The goals of ODL are, firstly, to create a robust, extensible, open source code base that covers the major common components required to build an SDN solution. Secondly, to get broad industry acceptance amongst vendors and users and finally to have a thriving and growing technical community contributing to the code base, using the code in commercial products, and adding value above, below and around. The OpenDayLight project is managed by the Linux Foundation and memberships covering over 40 leader companies (e.g. Cisco, IBM, NEC, etc). It was founded in April, 2013 and so far, there are more than 40 sub-projects and three versions of OpenDayLight have been released that including OpenDayLight Hydrogen, OpenDayLight Helium and the latest release is OpenDayLight Lithium. OpenDayLight project provides an open platform for developers to contribute, use, and even build commercial products as an individual. With 466 individuals contributed to the Lithium release making OpenDayLight one of the fastest-growing open source projects. It is being leveraged by a growing number of companies who offer solutions, applications, services, consulting and support to address a range of user needs.

ONOS project:

ONOS is an SDN operating system developed by ONOS Networking Laboratory. It provides modular structure separating the various subsystems into independent modules. The architecture of ONOS is composed of a three (3) tier structure namely; Northbound (NB), Distributed control layer and Southbound (SB).

The ONOS Northbound Interface is responsible for reception and transmission of information and network requests respectively to the distributed control layer. SDN applications reside on the Northbound and monitor network activities through a graphical user interface (GUI). Examples of such SDN applications include Topology Monitoring Applications, Device and Network Statistics Application. Applications leverage on the northbound application programmable interfaces (APIs) exposed by the subsystems or modules in the distributed control layer to synchronize the network state and present them to the user in real-time.

The distributed control layer is composed of a modular subsystem component exposing both NB and SB APIs to applications and infrastructure elements residing in the NB and SB respectively. The subsystems are independent modules, but reply on other subsystems for information pertaining to the network state. Network Elements are abstracted into generic models such that network elements like switches, host, and routers are not bound to specific protocols making them agnostic.

ONOS Southbound Interface is the lowest tier of ONOS architecture and communicates with network infrastructure with specific device protocols: Open Flow, NETCONFIG, OVSDB and SNMP for the various protocol specific devices.

2.1.2 Network Virtualization

The need of introducing high level of flexibility in the network design has fostered the industrial partners to focus on a complete virtualization of the main network components and functions. The researchers' effort is underway to virtualize network functions that had been realized in purpose-built appliances: specialized hardware and software (e.g., routers, firewalls, switches, etc.). Network function virtualization (NFV) was focused on transforming hardware appliances into software applications bringing a high flexibility. The network functions become building blocks that can be flexibly combined to build communication services. Different network operators (tenants) can deploy customized network services with different virtual NFs (VNF) on a common infrastructure, thus realizing network sharing.

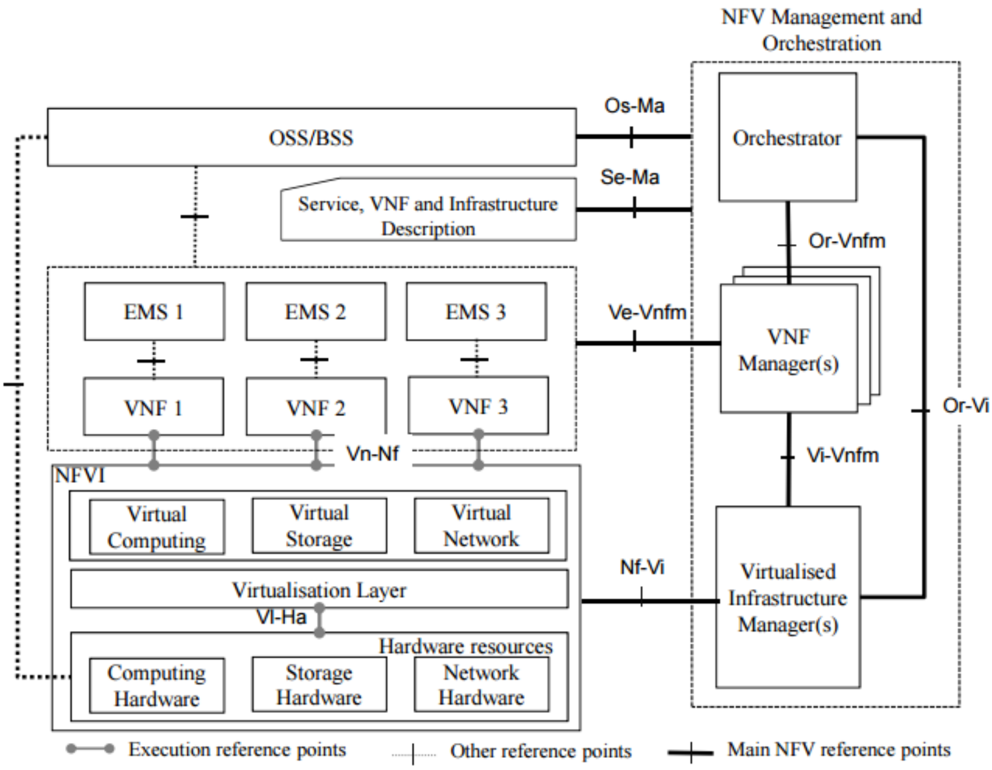

Figure 1: ETSI NFV MANO architecture[1]

Starting from the above functionalities of European Telecommunications Standards Institute (ETSI) NFV MANO (depicted in Figure 1), we propose a set of innovations and new functionalities toward supporting multi-tenancy and network slicing features in the 5G NORMA architecture.

Among the main differences between the WP5 functional architecture (described in Section 3) and the ETSI NFV MANO one, we list the following

- We take the concepts of multi-tenancy and network slicing [9] in full consideration, allowing the optimal orchestration of several network slices belonging to possibly different tenants on the same infrastructure.
- The WP5 architecture envisions a specific entity to deal with shared resources, a mandatory element (currently not specified by ETSI) to introduce the concept of network slicing within the architecture.
- Orchestration in WP5 takes an end to end perspective, including the orchestration of PNFs
- ETSI NFV MANO is mainly devoted to resource orchestration, with a specific focus on lifecycle management for network functions (i.e., allocating the necessary NFVI resources). 5G NORMA orchestration, as tackled by WP5, will include the concept of network service requirement into the orchestration.
- Service requirements are and additional trigger for re-orchestration. The NFVO only takes re-orchestration decision based on the monitoring of NFV resource utilization as it has no specific domain knowledge (e.g., the 3GPP domain). In Section 5 we describe

[1] http://www.etsi.org/technologies-clusters/technologies/nfv

how these additional capabilities may be used to take QoS and QoE triggered re-orchestration decisions.

Based on the above points we claim that, while preserving a high compatibility with the ETSI NFV MANO architecture, the orchestration architecture designed by WP5 introduces fundamental functionalities that will be paramount for the orchestration of future virtualized 5G Networks.

2.2 Related work

While we have identified the main key-enablers for the novel 5G architecture design, we need to explore how the other research projects and standardization groups have addressed the concept of multi-tenancy support and network slicing. This evaluation enables us to find out the main drawbacks and limitations of the proposed solutions in order to improve the current state of the art within our novel 5G NORMA framework.

In the following, the current network management and orchestration trends considering multi-tenancy and network virtualization for 5G networks are analysed by taking into account the results and gaps of previous EU projects, such as iJoin and METIS as well as various standardization efforts including 3GPP, ETSI NFV, ONF Wireless Group and Small Cell Forum (SCF).

2.2.1 EU METIS and EU iJoin

Network virtualization enters a mature phase with many EU projects considering the VNF aspects, mobility support and multi-tenancy not only for wireline scenarios, but also in the context of wireless and mobile networks. METIS [10], one of the leading EU projects for 5G has explored network virtualization in terms of functional decomposition to address highly dynamic RAN scenarios including Device-to Device (D2D) and provide a logical centralized orchestration using SDN principles. Differently from METIS, 5G NORMA is not concentrating only on the RAN but also in the core network considering a decentralized architecture. Such a difference is significant since novel network functions can be composed and allocated from selected sub-functions, i.e. the so called atomic functions, of both RAN and core networks.

iJoin [11] is another significant EU project that investigated VNF for enabling flexible Cloud-RAN scenarios considering the backhaul capabilities. In particular, iJoin introduced the concept of RAN as a Service (RANaaS), in where an SDN controller could flexibly allocate RAN functions, e.g. PHY, Medium Access Control (MAC), Radio Resource Manager (RRM), etc., either at a cloud platform located at the Base Station (BS) or baseband unit above the RAN considering the type of backhaul in terms of latency and capacity. The figure below illustrates the RANaaS concept elaborating the different functional splits that could be deployed. Once the RANaaS selects a particular functional split, then such a split is followed by all applications and services for long periods. 5G NORMA addresses a higher degree of flexibility by introducing different types of RAN functional splits per network slice allowing different services and tenants to follow a distinct split, while at the same time 5G NORMA offers functional composition and allocation considering both RAN and core network functions.

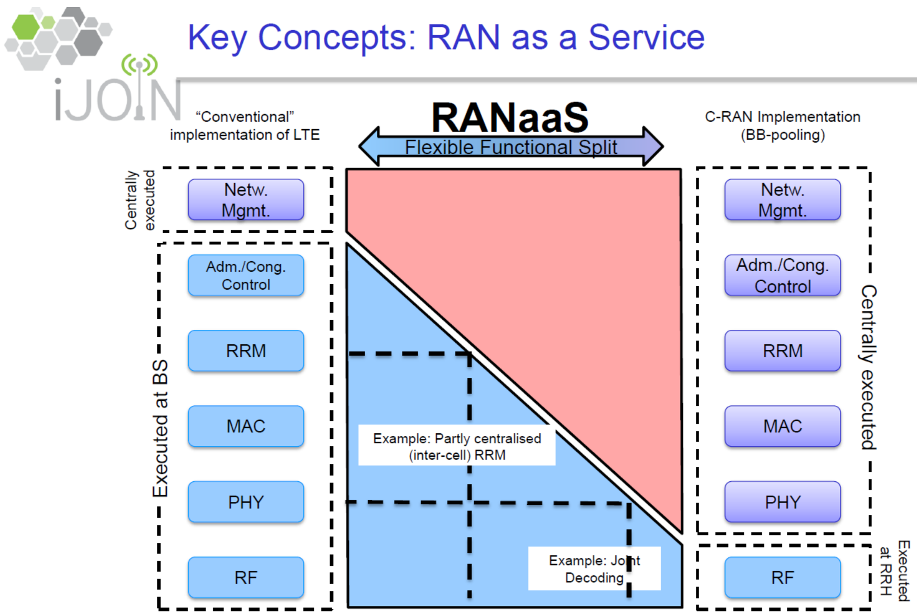

Figure 2: Different functional split supported in RANaaS, iJoin [11]

Overall, 5G NORMA goes beyond the research performed by these two European projects in several factors

- The work carried out in WP5 will increase the network flexibility defined by EU projects like METIS by introducing new concepts such as Software Defined Mobile Network Control
- The achievements of iJOIN will be one of the building blocks of the 5G NORMA architecture. By leveraging on these atomic Network Functions, the Network Orchestration will tailor resource allocation, introducing network slices per service and/or tenant.

2.2.2 3GPP RAN Sharing and Multi-tenancy

In 3GPP, two different architectures on RAN sharing are specified in [12] . The Multi-Operator Core Network (MOCN) where the shared RAN eNodeBs are connected via S1 interface to a separate core network owned by each operator and the Gateway Core Network (GWCN), where operators share additionally the Mobility Management Entity (MME). These approaches enable active RAN sharing but they still rely on fix contractual agreements between different operators, while they do not consider the support of Over-The-Top (OTT) application providers or vertical market players. 5G NORMA can be applied in both these RAN sharing architectures and at the same time it introduces the notion of network slicing, which considers the composition and allocation of virtual network functions and shared resources. These concepts require extensions to the 3GPP specification, like the definition of network slicing, which is currently considered in Release 14.

The network management aspects for enabling RAN sharing are specified in [13], which documents a set of extensions for the legacy 3GPP network management architecture in order to accommodate network sharing based-on long-term contractual agreements. The scenario considered in 3GPP assumes that a mobile operator allows participant sharing operators, i.e. Mobile Virtual Network Operators (MVNO), to access its network resources. In particular, the network management system can use the Type 5 interface, which can be established upon an agreement between mobile operators to provide connectivity among the network manager systems across different organizations, allowing network management information and KPI associated with shared resource to be forwarded towards the corresponding MVNO. Inside the Infrastructure Service Provider (InP) such monitoring performance information is conveyed through Type 2 interface between the management system and network element manager of an eNodeB. 5G NORMA will build on the top of such 3GPP network management architecture allowing:

- More dynamic short terms network slice allocations to different tenants considering not only resources in terms of capacity but also the composition and allocation of RAN and core network virtual functions.
- OTTs and vertical market players to acquire resources introducing new interfaces and
- SDN-Apps to program the network according to the service demands.

A step towards a more dynamic system that supports on-demand resource allocation requires enhanced network management and orchestration support that can be realized via the introduction of the capacity broker as described in [14]. The capacity broker can enable the mobile operator to support on-demand network slice request allocating resources for MVNOs, OTT providers and verticals. Hence, the mobile operator can share a particular and unused portion of the capacity for a specific period of time via signalling means. 5G NORMA is looking into providing deployment options of such capacity broker entity introducing a network slice broker responsible for admission control and resource allocation at the SDM-O.

5G NORMA will extend the 3GPP view of RAN Sharing and Multi-tenancy, providing a functional architecture that embeds the concepts of end to end network slicing, allowing efficient resource sharing via a specific coordinator module.

2.2.3 3GPP and SCF VNF Orchestration in Mobile Networks

The support of NFV in 3GPP is studied considering the network management perspective in [15], considering partially and entirely VNFs with respect to macro-base stations and core network elements (CNEs). This approach adopts the ETSI NFV MANO with the objective to identify requirements, interfaces and procedures, which can be re-used or extended for managing virtualized networks.

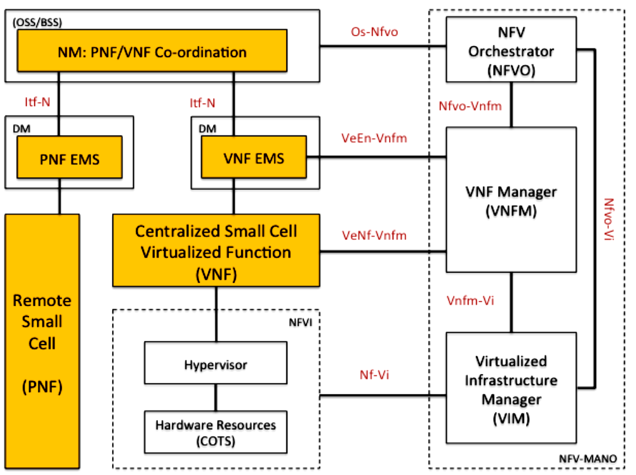

Figure 3: SCF VNF orchestration in mobile network

An equivalent NFV study focusing on small cells and on the adoption of flexible Centralized-RAN (C-RAN) is considered at Small Cell Forum [16]. In particular, four different functional splits were considered, including: (i) Packet Data Converged Protocol-Radio Link Control (PDCP-RLC), (ii) Split MAC, (iii) MAC-PHY and (iv) PHY split, introducing different front-haul requirements. The VNF orchestration is illustrated below adopting the MANO NFV paradigm. In particular, this scenario considers the remote small cell as a physical element and the Baseband unit or core cloud as VNF, which is orchestrated using the MANO architecture.

3GPP Rel.14 has introduced a specification on architecture requirements for virtualized network management [17] , considering complementary specifications on configuration, fault performance and life-cycle management. 5G NORMA is looking to extent such an approach by:

- Investigating functional decomposition into “atomic” functions.
- Allocating new functions into the optimal cloud location (front-end cloud, edge cloud and central cloud) considering the type of service and the optimization goals.
- Assuring content/context optimization, e.g. by optimizing the virtual functions alongside content delivery.
- Introducing a QoE/QoS monitoring function that assures performance targets and tunes network programmability to maintain the desired Service Level Agreements (SLAs).

In an effort to support devices/customers with different service characteristics including vertical market players, 3GPP SA 2, introduced in Release 13 the support of separate Dedicated Core Networks (DCNs) [18], with different operation features, traffic characteristics, policy, etc. Each DCN is assigned to serve different type of users based-on subscription information, assuring resource isolation and independent scaling, offering specific services and network functions including RATs.

5G NORMA goes beyond this concept towards a common RAN medium, common mobility management solutions and other core network functions. To enable an efficient resource sharing it also introduces a dedicated controller, called SDM-X that assure an efficient radio resource sharing between different network slices.

2.2.4 ONF SDN for Mobile and Wireless Networks

The ONF Group on Mobile and Wireless Networks concretes on using SDN technology to provide a logical centralized management that allows an efficient base station coordination and control. The main benefits of SDN come from the logical centralized control and the separation Control/User plane. In particular, the SDN can enable efficient resource management leveraging the benefits of its centralized control nature. For example, it fits well for interference avoidance and Cooperative Multi-Point (CoMP) as well as mobility management support especially in dense deployments. In dense RAN deployments, SDN can also facilitate more efficiently data offloading being able to select the appropriate offloading location for particular traffic sources.

The SDN paradigm can also support multi-tenancy allowing MVNO and third parties to share resources via the use of the Northbound API (NBI) of the SDN controller and facilitate a unified network management across heterogeneous radio technologies. In addition, it can provide path management services that can optimize the routing in the legacy LTE by allowing the mobile network layer to gain knowledge of the underlying transport layer that provides connectivity between mobile network functions.

5G NORMA leverages the benefits of the SDN introducing two type of controllers, the SDM-C and SDM-X for dedicated and shared resource/VNF respectively. The rational is to use these type of controllers to allow SDN-App interaction, coordination with the Virtualized resource orchestrator named SDM-O and QoE/QoS control, enabling flexible service chaining and network re-programmability.

2.2.5 3GPP LTE and ETSI NFV Security Architecture in Multi-tenancy and Multi-services

The NFV InP, offers to share the physical infrastructure with MVNOs using the same security architecture and hierarchical key management schemes for protecting the subscribers and MVNOs. The security impact of network sharing has briefly been pointed out by 3GPP [19] .Furthermore, there are five security basic features within the 3GPP security architecture [20]each of these features prevents certain threats and accomplishes certain security objectives. Those security objectives are network access security, network domain security, user domain security, application domain security, and visibility and configurability of security. These security objectives aim to avoid the possibility for an intruder to identify which subscriber is using a given resource on the radio and network path by listening to the signalling exchanges on the radio and network path.

On the other hand, ETSI pointed out vulnerabilities and security issues in NFV [21] [22]. ETSI also emphasized Monolithic Operator (MO) model in providing virtual infrastructure and virtual network function security and trust guidance on multi-tenancy and multi-network services [23] [22] . The MO model is similar to InP role in 3GPP. The MO offers NFV hosting services and provides edge cloud to tenants with security management. This security management catalog is based on OpenStack Keystone which can provide identity, group and role management, and tokenisation technique for securely accessing virtual network services. Furthermore, Universally Unique IDentifier tokenisation technique is chosen by default for protecting network service tenants.

Moving forward, when VNF service provisioning, deploying, duplicating, migrating and terminating require secure techniques to protect the tenants and subscribers. Combining the 3GPP security architecture features with ETSI NFV security specifications to become one secure system that is inevitably needed in providing multi-tenancy and multi-services.

3 WP5 Functional architecture

As described in Section 2, 5G NORMA will build on existing enabling technologies (i.e., SDN and NFV) go beyond the research activities carried out by other similar projects in the past few years to enable the functionalities of network slicing and QoE/QoS awareness. Moreover, 5G NORMA is easily adaptable to the current definition of Software Defined Networking defined by ONF or the Orchestration Framework defined by ETSI NFV MANO.

3.1 Functional requirements

5G NORMA features an architecture that leverages and goes beyond SDN and NFV technologies. This architecture has to support many services with different requirements in terms of latency, throughput and availability; all this in conjunction with a multi-tenancy network supporting network slicing. For more details, we invite the reader to the deliverable [24] where a deep analysis of the functional requirements is conducted according to a set of use cases. The functional requirement are grouped into a set of requirement groups to facilitate the design process and to redefine the legacy mobile network architecture: 5G NORMA will drive the transition from the current *network of entities* architecture to the *network of functions* architecture as already described by [25]. The main outcomes of this transition are hence the required flexibility and re-programmability features, two paramount features for the upcoming network slicing paradigm in 5G.

5G mobile network architecture designs are based on a set of dimensions that were not as critical for earlier network generations as they are nowadays because of the changing scenario in mobile networks requirements. Following are the key 5G requirements that are being addressed by WP5:

- **REQ 1:** Multi-tenancy: allows sharing the network infrastructure among several service providers. The range of tenants is not fixed and can be from virtual mobile networks operators to companies from vertical industries.
- **REQ 2:** Shared infrastructure: leverages the economies of scale to be expected when hosting multiple logical mobile networks on a single infrastructure.
- **REQ 3:** Efficient control frameworks: allows better usage of hardware/software/radio resources and functions by abstracting their usage on different architectural levels.
- **REQ 4:** Multi-service and context-aware adaptation and allocation of VNFs: It is accomplished thanks to the fine-granular (de)composition of functions into several VNFs allowing their adaptive and efficient allocation at the front-end cloud (e.g., radio

site), in the edge cloud, or central cloud. This entails the efficient VNF placement, configuration, scaling/migration etc.
- **REQ 5:** Optimization of the QoS/QoE according to the service and the infrastructure state.
- **REQ 6:** A service aware Mobility management system, capable of choosing the most appropriate solution according to the service requirement by leveraging on a software defined approach.

3.2 Research challenges

The main challenge is to address the above listed functional requirements. The design of 5G NORMA architecture should provide frameworks with their accompanying research challenges to be solved:

C 1: A management & orchestration layer that is in charge of:

- The creation (instantiation) of the slice on which the network services (service chain) run. The layer will take as input the KPI targets and output a slice description template including the functions graph, QoS parameters and containing instructions for its deployment, configuration and policy based rule for its orchestration. The generated slice template is then used by the orchestrator to instantiate the network slice instance. The orchestration needs to be at different levels – among the slices and within the slice- and at different timescales (at business long-term and at network run time). An overall view of all the slices across all resource domains (edge cloud, central cloud) is required for the management and orchestration of the different slices. We should thus consider the problem of orchestration coordination among multiple domain orchestrators when placing the VNFs at edge cloud node or central cloud node, or moving them as well.
- The orchestration framework should also offer mechanisms for dynamically adapting the service chain (by adding, updating or removing function/capability in the existing service chain) in order to meet Service Level Agreement (SLA) in spite of load/traffic variation.

Note: Please note that a complete list of functions is provided in D3.1.

C 2: A framework for mobility management of users.

- The user mobility management framework shall provide a compound solution to how the User Equipment (UE) connects to a network slice. Several approaches may be investigated: per UE type, or depending on the end to end (E2E) service type requested by the user. Also, a unified mobility management system spanning across several network slices may be targeted, allowing thus the presence of the same UE in multiple network slices at the same time. Advanced mobility management schemes may imply mobility of VNFs, as the reallocation should consider device/user location, network conditions and context, as well as QoS and QoE contraints.

C 3: A framework for controlling network slice (intra/inter slice)

- The role of the controller is to fulfil the requirements defined in the SLA by acting/configuring the Network Functions (both Virtual and Physical) belonging to a certain network slice. Example of such actions are routing optimizations or generic reconfiguration of already instantiated NF according to QoE/QoS optimization algorithms (e.g., a scheduler reconfiguration). For a better control of the SLA enforcement, the controller shall be able to trigger the orchestrator for re-orchestrating operations. This interaction has to be defined with the relevant controller-orchestator interfaces. Finally, specific interfaces shall be designed for the control and management of shared network resources across network slices.

C 4: A framework for real-time monitoring

- An efficient monitoring framework shall be a fundamental part of the network architecture. By including the QoE mapping to QoS parameters functionality, the efficient framework for real time monitoring is the main driver for all the re-orchestration triggers.

C 5: **A service layer able to handle:**

- SLA negotiation capability with the tenants or the vertical market player. Here the problem is to translate high level requirements of SLA into network requirements and policy rules to be enforced. The goal is to compose a chain/graph of network services with their specific service KPI goals that will meet SLA.
- Mapping the service into the dedicated network slice. The creation of the service causes the execution of the network slice template by the management and orchestration layer.

Note: The above challenge (i.e., C5) is addressed in WP3

3.3 5G NORMA WP5 building blocks

The requirements and the challenges described above are tackled by the WP5 functional architecture shown in Figure 4, which in turn is characterized by specifc functional blocks. They are all part of the overall 5G NORMA architecture. This work reflects the inputs provided by WP3 that have been detailed in the deliverable D3.1. The mapping between the WP5 building blocks and the 5G NORMA architecture is depicted and discussd in Section 3.3.4.

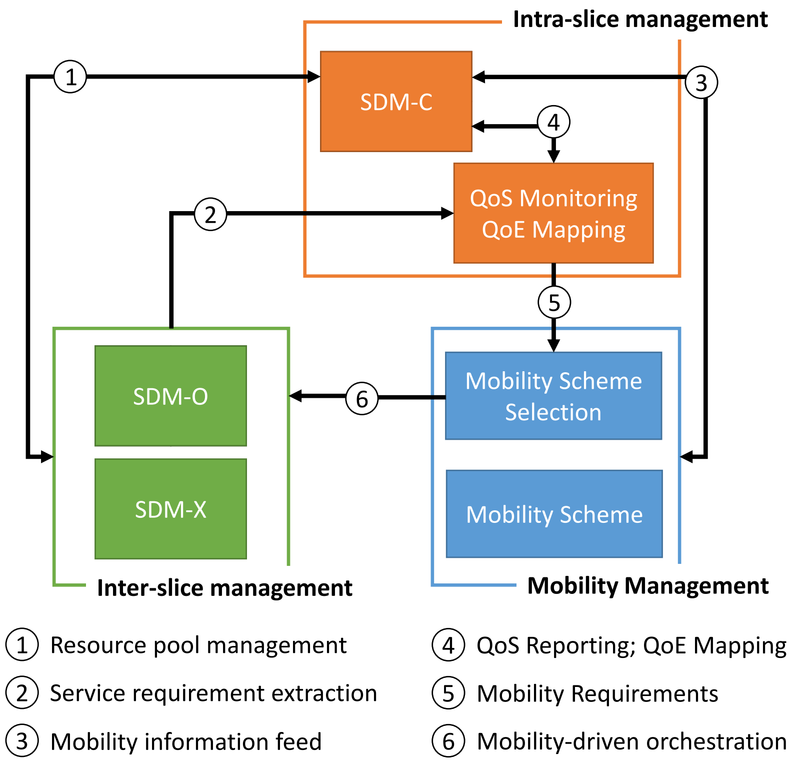

Figure 4: WP5 building blocks and their interactions

5G NORMA proposes an architecture based on 6 different building blocks: the Software-Defined Mobile Network Controller (SDM-C), Orchestrator (SDM-O), Coordinator (SDM-X), the Mobility Management module (composed by the Scheme Selection and Design), and the QoE/QoS Mapping and Monitoring module. They are grouped into three categories according to the main tasks they are designed to accomplish and heavily take into account the multi-service and multi-tenancy concepts as the fundamental drivers of our architecture.

3.3.1 Intra-slice Management

The Software-Defined Mobile Network Controller (SDM-C) and the QoE Mapping and Qos Monitoring modules are the ones in charge of controlling the resources assigned within a network slice. The most important innovation is the SDM-C, that introduces network function control beyond SDN. That is, the QoE Mapping and Qos Monitoring can be seen as SDM-C applications. More details about this block are provided in Section 6.

SDM-C enables a flexible network management and operation within a network slice. It is responsible for controlling both data plane and control plane nodes following NFV and SDN technologies in a centralized way. The SDM-C specifies both northbound and southbound interfaces which enable different functionalities. The northbound interfaces are used to control network operation in terms of QoE/QoS and mobility management, whereas the southbound interface conveys the required actions within a given network slice. The SDM-C receives the network requirements through the northbound interfaces and, once processed, triggers the necessary operations through the southbound interfaces.

Figure 5 depicts the stated northbound and southbound interfaces offered by the SDM-C:

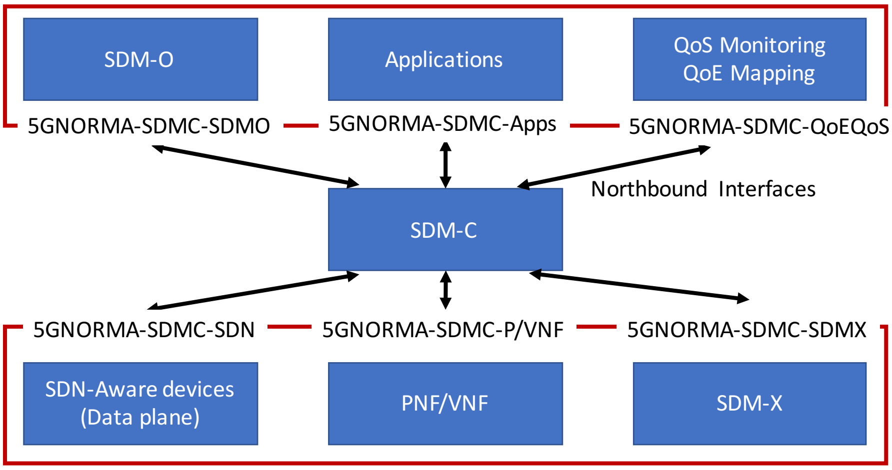

Figure 5: SDM-C interfaces

Interface 5GNORMA-SDMC-SDN. It acts basically on the data plane of the network slices and has the objective of building the path(s) that connect the VNFs of a service chain. This interface is a natural extension of the SDN model. It can be seen as a specialized version of the 5GNORMA-SDMC-P/VNF interface that only controls SDN devices. While in the current ETSI-NFV-MANO architecture this functionality is off-loaded to the VIM, in our architecture it is a fundamental part of the network-slice control, to be directly accessible by all the SDM-C Application using the 5GNORMA-SDMC-Apps Northbound Interface.

Interface 5GNORMA-SDMC-P/VNF. It controls and configures parameters of the P/VNFs. Unlike the NF-Vi interface of the ETSI NFV MANO architecture, this interface brings the Software Defined Networking principle to all the network functions of mobile wireless networks. That is, the functionality once deployed monolithically in different physical devices will be split into the SDM-C Applications that run the logic of the Network Function and the agents deployed directly on the data path. The 5GNORMA-SDMC-P/VNF southbound interface is hence used to control these (Physical or Virtual) Network Functions.

Interface 5GNORMA-SDMC-MANO is the interface to MANO, allowing the orchestration entities to deliver a set of raw computation (Central Processing Units, memory), networking (SDN transport network, spectrum) and target KPIs as defined by the SLA agreed with the tenant. All these resources may be controlled directly by the SDM-C through the 5GNORMA-

SDMC-P/VNF interface (if dedicated) or through the Interface 5GNORMA-SDMC-SDMX interface (if common). All this information is required by the SDM-C to fulfil the targeted SLA. All the decisions about resource allocation within a particular network slice is the responsibility of the MANO since it has a global view of the entire network and, hence, can take an optimal decision based on the current status of the network.

Again, this shares some similitudes with the ETSI-NFV-MANO architecture, especially with the Or-Vi, Vi-Vnfm and Or-Vnfm interface. In the framework of 5G NORMA, the 5GNORMA-SDMC-MANO interface, performs some of the functionalities already envisioned by the ETSI-NFV-MANO architecture, mainly the ones related to resource orchestration. However, the semantic of this interface is much broader in 5G NORMA, in particular for the lifecycle management of the Network Functions belonging to a network slice, especially for the re-orchestration triggers due to QoE/QoS constraints. More details about this process may be found in Section 3.7.2

Interface 5GNORMA-SDMC-Apps is used by SDN-Apps to provide a well-defined service. Three examples of SDM-C applications are the following:

- Enhanced Inter Cell Interference Cancellation (eICIC): it is an application seen from the SDM-C, which could be instantiated and controlled within the eMBB slice in order to meet users QoE requirements.
- Video aware pre-scheduler: it provides configuration guidelines for the scheduler, specializing it for meeting the KPI requirement of specific video flows.
- Mobility: the mobility management of a network slice can be seen as a SDN application itself.

More details on the specificity of the SDM-C Applications can be found in Section 3.7.4.

Interface 5GNORMA-SDMC-QoS/E is used for QoS monitoring, to timely report about the status of the network resources. The input coming from this interface is fundamental when triggering re-orchestration request via the Interface 5GNORMA-SDMC-MANO interface.

Finally, **Interface 5GNORMA-SDMC-SDMX** is used for controlling shared resources through SDM-X. The processes that make use of this interface are detailed in Section 3.7.3 while further algorithmic details are described in Section 5.

QoE/QoS Mapping and Monitoring: enables the monitoring of QoE/QoS parameters within a network slice, allowing the SDM-O to act accordingly in order to fulfil the network requirements and agreed SLAs. It allows to allocate the minimal amount of resources for achieving the required QoE avoiding churn and increasing energy efficiency. The communication with the SDM-C happens through the 5GNORMA-SDMC-MANO and GNORMA-SDMC-QoS/EMonitor interfaces.

3.3.2 Inter-slice Management

The second functional block is related to the management of multiple network slices (possibly belonging to different tenants) over the same infrastructure. Some functionalities fulfilled by the Intra-slice management block have a counterpart on the NFV-O entity in the ETSI NFV MANO, especially for the resource allocation purposes. However, the Software Defined Network Orchestrator (SDM-O) orchestrates resources from a QoE/QoS perspective, knowing the requirements of each network slice. This means that the decision about which network functions have to be included in a network slice or their placement inside a computational network cloud is taken by the SDM-O, and it is an extension compared by the functionalities currently fulfilled by NFV-O. Also, the optimal sharing of resources (both computational and networking-related) among network slices through the Software Defined Network Coordinator (SDM-X) belongs to this block.

The **SDM-O** enables the support of multi-service and multi-tenancy by the means of network slicing and resource orchestration. The SDM-O combines service and NFV MANO resource orchestrator. The SDM-O analyzes service requests requirements and feeds the results to the network slice creation lifecycle.

The **SDM-X** enables the control of shared network functions or resources among selected network slices. It receives information both from the SDM-O and MANO (through the SDM-O) blocks and processes this information in order to decide whether it is necessary or not to modify a network slice's shared resources upon a request coming from SDM-C. It is responsible for controlling VNFs/PNFs in the common data and control layer and, hence, will need to ensure the fulfilment of the received requirements within its corresponding network slice.

3.3.3 Mobility Management

Mobility management is implemented in 5G NORMA as a SDM-C application that gathers information from the QoE/QoS module and enforces new rules through the SDM-C southbound interfaces. Also, it may trigger (through the SDM-C, as every other SDM-C application) re-orchestration requests. However, due to the importance of the functionality, we emphasized it through two submodules.

Mobility management scheme selection and design: enables the management of all devices in the network, ranging from static to high speed (i.e., vehicular) terminals. It follows a modular approach to adapt the network configuration to the network slice demands. It is a highly flexible module that achieves high resource performance without increasing operation burden. It is composed by two sub-modules: the mobility management scheme selection and the mobility management scheme design. The latter includes all the algorithms needed to perform a certain mobility management scheme, while the former performs the selection of the most appropriate scheme based on the slice requirements.

3.3.4 Mapping with the overall 5G NORMA architecture

Figure 6: 5G NORMA architecture depicts the Service Layer functions, which serves two major objectives: (i) it shall hold an end-to-end management and orchestration view of a network slice and (ii) for 3rd parties, it should serve as the "entry point" into the telecommunications service provider's administrative domain in order to request the commissioning and operation of a network slice. Particularly, Service Management acts as an umbrella entity for evolved Operations Support Systems (OSS) as well as for the SDM-O and has the end-to-end view of a network slice. It exposes interfaces for network slice creation, operation, and termination requests from internal and external stakeholders (e.g., vertical sectors, OTT providers), thereby accommodating different expert levels. For example, a creation request can consist of direct network slice selection or, alternatively, of information on service requirements such as service level agreements and key quality indicators that describe the required characteristics of the requested telecommunications service. By (partially automated) means of business and policy decisions, network slice management maps a request to a chain of network functions that, as a whole, form the network slice blueprint which are further managed by OSS and SDM-O. These chains are obtained from a catalogue of available templates and are the base for the virtual machines instantiation on the NFVI taking into account all the processed KPIs. The SDM-O can be further broken down into Service Orchestration, Slice Orchestration and Inter-slice/Inter-tenant Orchestration. It has a complete knowledge of the network, managing the resources needed by all the slices of all tenants. This enables the orchestrator to perform the required optimal configuration in order to adjust the amount of used resources and, hence, making an efficient use of the network. Each network slice has an SDM-C, responsible for managing the inner network slice resources and actually build the paths to join the network functions taking into account the received requirements and constraints which are being gathered by the QoE/QoS Mapping module. This module is also responsible for performing a continuous evaluation of the network slice status and reporting to the SDM-C. The SDM-C, based on these reports, may decide to adapt to a new situation either by reconfiguring some of the VNFs in a network slice or by reconfiguring data paths in a SDN-like style. If the requirements cannot be

met by any of these methods, the SDM-O can perform a slice reshaping by requesting for more resources for the given network slice. The described network slice lifecycle is depicted in

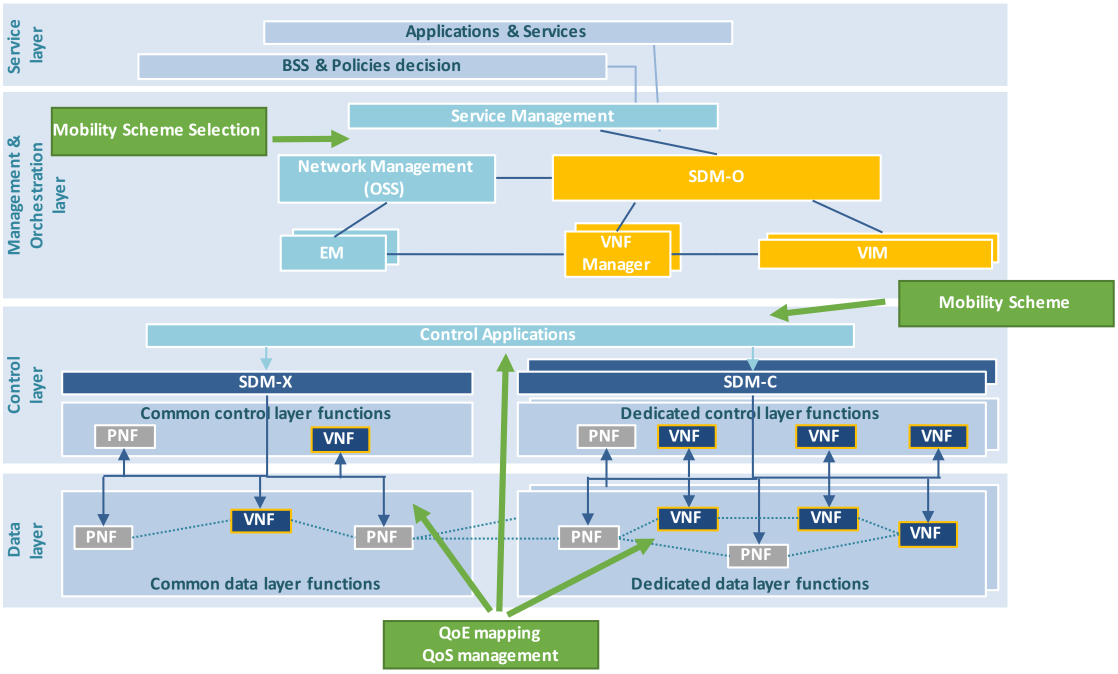

Figure 6: 5G NORMA architecture

Network slices, which are defined as logical end-to-end networks, operate on top of partially shared infrastructure. They are composed of shared and dedicated as well as physical and virtualized network functions. For the control of shared functions, 5G NORMA introduced an extended SDM controller, called SDM-X.

As outlined in Table 1, SDM-C and SDM-X:

- control PNFs and the software application of VNFs,
- but do not control/orchestrate a VNF's underlying NFVI resources.

In case of VNFs, this implies that SDM-C/X only control software running inside a Virtual Machine (VM)/container (also referred to application logic). The virtualization container of the VNF (VM, Docker container, etc.) is controlled by the NFV-MANO entities. This ensures a consequent split between management/control of mobile network functions on the one hand and NFVI resources on the other. For PNFs, which exhibit a tight coupling of hardware and software, SDM-C/X control the entire HW/SW system of the network functions.

Table 1 : Scope of SDM-C and SDM-X

	Shared (common) functions	Dedicated functions
PNF (network element)	**SDM-X** Control of SW and HW	**SDM-C** Control of SW and HW
VNF	**SDM-X** Control of SW only	**SDM-C** Control of SW only

As shown in Table Scope of SDM-C and SDM-X, SDM-C directly interfaces with dedicated NFs, while SDM-X controls shared NFs. In order to access shared functions, e.g., for including them in a particular network slice, an SDM-C needs to use the according interface 5GNORMA-

SDMC-SDMX of the SDM-X as shown in Figure 5. The SDM-X therefore also coordinates between multiple SDM-C instances and the associated network slices.

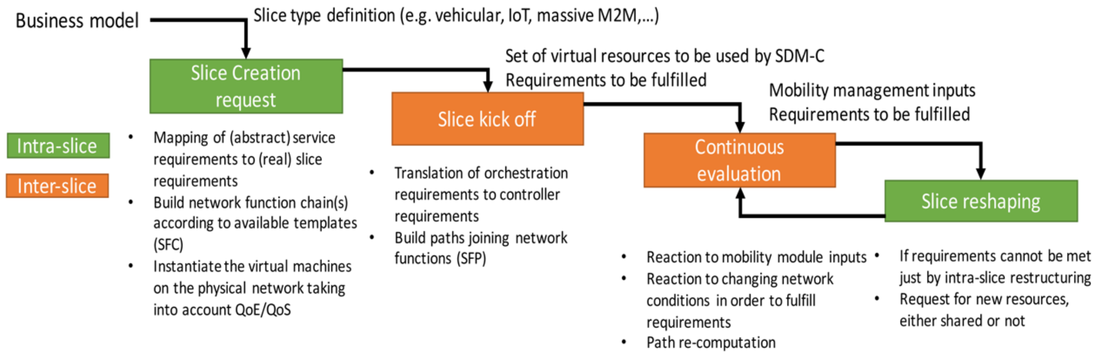

Figure 7: The lifecycle of a network slice in 5G NORMA

In case more shared resources are required in another part of the network, a slice reshaping may also be requested by the SDM-X to the orchestration, decreasing a slice's assigned resources that will be used to fulfil the newly received requirement.

3.4 SDM-O: Slice Orchestration

The inter-slice orchestration is a key-feature of the novel 5G NORMA architecture as it fosters and supports multi-service and multi-tenancy systems by levering on the network slicing control application. In particular, the functional block, namely SDM-O, blends resource orchestration together with the network service orchestration in order maintain the network slice instantiation lifecycle. The inter-slice orchestration process consists of two main functions: (i) resource provisioning (considered as NFVI generic resources) and (ii) resource pooling/reservation. Please note that SDM-O is also involved in intra-slice orchestration operations but in this section we will describe the complex inter-slice orchestration aspects.

3.4.1 Generic Resource provisioning

Resource provisioning is performed to calculate and provide the right amount of virtualized infrastructure resource, e.g., computing, storage. Specifically, the SLA between tenants (asking for a network slice) and the infrastructure provider is regulated by the resource provisioning process. It depends on the QoS service requirements attached to the network slice that are efficiently mapped onto latency, bandwidth, computing and storage requirements. Several mapping schemes are defined to flexibly and dynamically manage heterogeneous tenant slice requests. However, traditional models provision resources only accounting for the peak demands. Dynamic resource provisioning allows each tenant to acquire resources based on the current demand, which can considerably lower the operating cost. Please note that a single tenant can also require and handle multiple slices with various needs. One solution is to consider that the provisioning is performed on resource pools (e.g., CPU or storage) of virtual resources for the overall set of network slices, so that provisioned resources are shared amongst each network slice. This introduces huge flexibility as resources can be dynamically allocated and released between tenants: this brings a multiplexing gain while reducing the total amount of resources to provision, which in turn reduces the operating cost. The proposed approach consists of three different steps:

a) Establish a performance model to determine how many resources (e.g., computing, storage) to allocate for each slice in order to fulfil the QoS requirements as function of the load. The challenge is to model each VNF in terms of needed computing/storage/connectivity resource to sustain the QoS requirements with respect to the level of load (number of calls, number of users, etc). Additionally, for each slice the service graph is considered to identify the resource in terms of bandwidth/latency needed between VNF in function of the load level. Then, the model targets to evaluate the total resource (compute; storage; networking) for the slice.

b) Establish the pattern of load during the life cycle of the slice. Load can vary at large time scale (the growing number of users that adopt the service, the growing number of network subscribers). It can vary at small time scale during the run-time of the service (peak hour, flash crowd events). It will depend on modelling the arrival of users consuming the service along the life cycle per type of service/slice, and the geographical distribution of users.

c) Determine an algorithm for automation of dynamic provisioning of shared resource pools among slices. Different strategies could be combined, i.e. provision in a proactive or reactive manner. In the proactive manner, the algorithm could work at large time scale to provision based on prediction of load. It could be able to reactively adapt provision to small time-scale events.

3.4.2 Resource pooling and reservation

The infrastructure providers can easily combine and jointly manage large-scale resources to simultaneously serve multiple tenants through resource pooling and resource reservation. On the one side, physical and virtual resources are dynamically assigned (and adjusted) according to tenants' demand, thereby realizing multiplexing gains through resource pooling. The resource pool is the total amount of resources the infrastructure manager (e.g. VIM) is managing and can efficiently allocate for specific VNFs. On the other side, resource reservation refers to a policy that preserves a given amount of resources for a particular consumer (e.g., a tenant or a service) even though they are currently not needed. The benefit of such a resource allocation strategy is to improve the operational reliability for a particular network slice with stringent requirements, e.g., QoS/QoE guarantees. Unfortunately, resource reservation reduces the multiplexing benefits and cost savings achieved from pooling.

The above trade-off requires a resource management policy that carefully trades off the need for resource reservation against the resulting deterioration in pooling gains and cost efficiency. In practice, such amount of reserved resources has to be estimated a-priori based on expected traffic load. A good estimation of the resource reservation positively influences the efficiency of the system: If the reservation is over-dimensioned, it might imply waste of resources. If the reservation is insufficient, it might result in difficulties in handling the traffic and poorer user experience. Reserved resources might include a collection of physical resources with particular affinity constraints, e.g., dedicated to a specific network slice. Moreover, reserved resources are particularly beneficial for latency-sensitive applications for which the delay introduced by scaling might be critical. On the other hand, shared resource pools, i.e., utilizing one resource pool by instantiating different VNFs belonging to different domains/network slices might be a good approach for decreasing the potential waste and minimizes the problems related to over-provisioning. However, this flexible approach would require a rather homogenous resource pool (general-purpose hardware) that can host a large variety of VNFs. For RAN domain functions and their hardware requirements, this might be more challenging whereas core domain functions are suitable candidates. An interesting approach is to find a mixed pooling/reservation solution wherein resources are shared (pooled) among a subset of all slices. For example, in case of a large tenant, e.g., an energy company operating multiple network slices, resources could be reserved for tenant itself but pooled for all its slices. Besides improving isolation of VNFs from different tenants, such schemes could combine the benefits from both pooling and reservation. Further, such resource reservations would have a dedicated share of overall resources and act independently in the case that there is no sharing policy defined.

The 5G NORMA architecture accounts for static reservation policies allocated to certain tenants (or network slices) as well as for more dynamic partitioning wherein reservations "breath" within defined thresholds based on network slice requirements. We refer to those resource allocation solutions as "constant bandwidth allocation" with fixed share per consumer and "proportional fair allocation" with fixed weight per consumer. State-of-the-art resource allocation algorithms combine them based on the performance figure to be optimised.

3.5 SDM-C: Dedicated Slice Control

The Software Defined Mobile Network Controller (SDM-C) is a key function of the 5G NORMA architecture. It controls all of the network slices' dedicated PNFs, VNFs and associated resources (network, radio) and their respective configuration. Based on service function chain, SDM-C dynamically influence and optimize the performance of the network slice and reconfigure the different VNF/PNFs when needed. The (re-)configuration occurs after (re-)instantiation and can be considered to take place at a different time scale (with extents in the order of several seconds). It is assumed to have an SDM-C instance per network slice.

Following the SDN logic, the SDM-C has both a northbound and a southbound interface which enable different functionalities. The SDM-C receives the network requirements through the northbound interface and, once processed, triggers the necessary operations through the southbound interface. The NBI interfaces with 5G NORMA-MANO functions, whose scope is two-fold. The 5G NORMA-SDMC-MANO interface is used to define all the QoE / QoS constraints that have to be fulfilled for a given traffic identifier, that may range from a single flow to an entire network slice. The granularity of this API (that goes beyond the simple network function re-configuration) will be determined during the project, but we can provide some examples of its envisioned operation. For instance, the shaping of the rate for each video flow will be configured by the SDM-C to provide the needed QoE-related KPIs to HD Video Users flows, while maintaining resources for Best Effort user flows.

In the case that the QoE/QoS targets cannot be met, the SDM-C may request re-orchestration. For that purpose, it uses the 5G NORMA-SDMC-MANO interface to trigger a re-instantiation request.

SDM-C is composed of an abstraction layer providing a set of common APIs to the application layer (referred to as the northbound interface) and implementing protocols to interact with instantiated VNFs (referred to as the southbound interface).

The SDM-C brings a set of advantages summarized below:

- **Flexibility**: A current problem for mobile network operators is the high amount of capital and operational expenditures (CAPEX and OPEX) of their networks independent of the actual traffic load and service usage, and thus the earning for products they sell to customers. By means of SDM-C approach, operators would be able to fit the network to their needs by simply re-programming the controller and thus reducing costs, while enhancing reliability.
- **Programmability**: It allows third parties to acquire network resources on-demand satisfying their individual SLAs. In addition, programmability can enhance the user perceived QoE by customizing the network resources accordingly.
- **Simplified/Unified control**: Adopting a logically centralized control unifies heterogeneous network platforms and provides a simplified operation of the wireless network. With SDM-C, network operators only need to control a set of central entities (namely, the controllers) that control the entire network, which possibly includes heterogeneous radio technologies.
- **Enabling new services**: By modifying the behaviour of applications that run on top of the SDM-C (northbound interface), many new services that were not included in the initial architecture design can be enabled by modifying the network behaviour and adapting its capabilities for the introduction of new services within few hours instead of weeks.

SDM-C could be implemented using for example OpenDaylight [26] , which is an open source project with a modular, pluggable, and extensible controller platform at its core.Figure 8 depicts the internal architecture of an SDM-C based on Opendaylight open source project. This controller is implemented strictly in software and is contained within its own Java Virtual Machine (JVM). 5G NORMA will introduce some new components and features in order to include the knowledge of the RAN which is ignored in most of the available open-sources. For that, we will propose extensions as depicted in Figure 8.

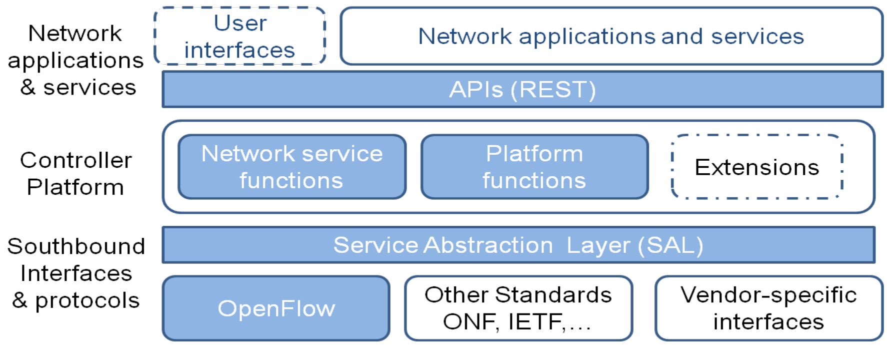

Figure 8: Example of SDM-C based on OpenDayLight block diagram

3.6 SDM-X: Shared Slice Resources Control

An end-to-end network slice can be instantiated as a subset of dedicated and shared resources. Shared resources, e.g., transmission points, radio resources, transport and fronthaul capacity, are properly managed by the 5G NORMA functional block, called SDM-X. Such resources are collected in a common pool before being allocated to a specific network slice or tenant. While the SDM-O needs to map different VNFs to the required physical resources during the orchestration process, the SDM-X needs to interact with the slice controller and control in a dynamic way the use of shared physical resources during operational flows, as shown in Figure 9. This interaction is specified following the well-known master/slave paradigm: the SDM-X controller specifies control policies for shared resources (master) guiding (multiple) SDM-C while applying operational functions (slave). Specifically, radio and transmission resources over different media, processing resources within areas of computing resources, and storage resources for user/data plane and control plane information, are considered in our architecture as physical resources. While resource pooling for storage and processing power may be less demanding due to theoretically large resource pools, the scarcity of radio resources in many cases requires an advanced resource management solution. As mentioned before the orchestrator considering policies and priorities manages the exclusively allocated resources while SDM-X implements dynamic allocation mechanisms.

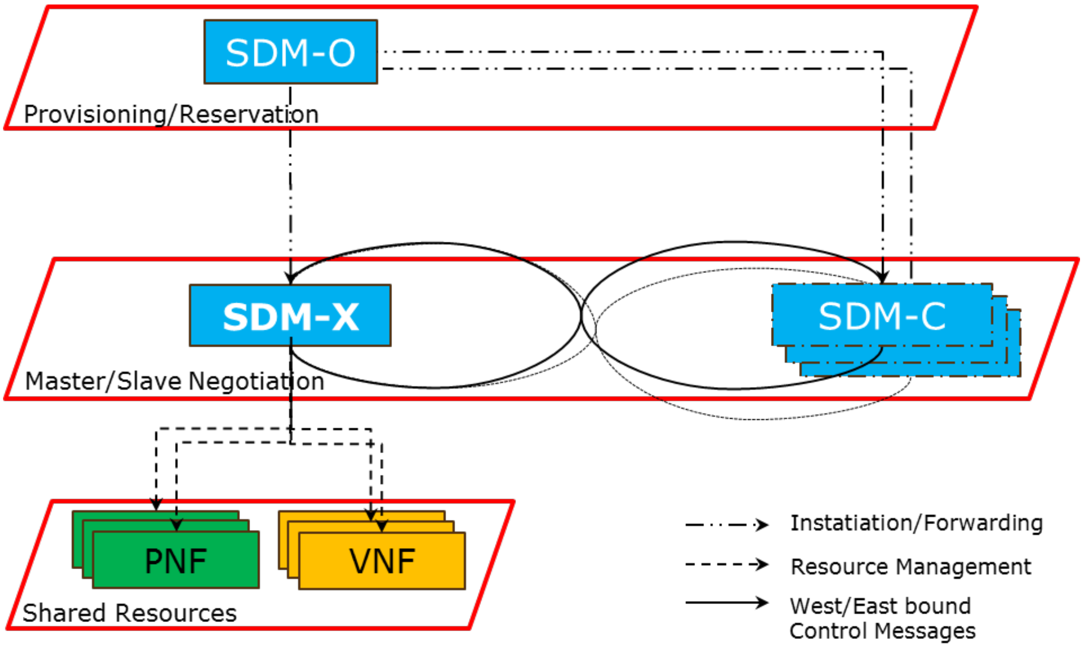

Figure 9: The role of SDM-X within the overall architecture

Based on the policies provided by SDM-O, a SDM-X/SDM-C negotiation is established in order to decide how to fulfil the demands of several partially competing network slices simultaneously. Slice performance demands might be identified in terms of: i) throughput, which requires a management of the radio resources, ii) latency, which requires a management of the placement of the network functions and usable storage entities, iii) management of processing / compute and storage (cache) resources in the neighborhood of access nodes which may also impact latency and error recovery performance, iv) reliability and resilience which is also greatly influenced by proper mechanisms for dynamic sharing of all three kinds of resources.

The main objective of the novel 5G NORMA architecture is to extend the concept of managing shared resource between slices to a broader scope thereby putting it into a SDN/NFV context. A straightforward example for the SDM-X is the radio resource management. In particular, extended scheduling strategies are needed to fulfil the slice/tenant dependent requirements, such as defined SLAs, while dynamic control of the scheduling strategy is needed to be able to react instantaneously to a change of the data flows' specific service requirements. Based on feedback information of the radio scheduler, the SDM-X might need to change the scheduling strategy from, e.g. centralized to decentralized scheduling or de-/activate an Inter Cell Interference Cancellation (ICIC) scheme, to improve the cell edge performance while sacrificing some ms in terms of delay. Therefore, the design of the interfaces of the SDM-X requires, on the one hand simplicity to support a fast allocation of the radio resources and on the other hand, the consideration of the total space of possible decisions and complex dependencies of slices/tenants/services.

3.7 WP5 Summary of Processes

As already indicated in Deliverable 3.1 [25], processes are a way of analysing the 5G NORMA architecture internals, i.e., how it reacts to external and internal triggers and how the sequence of events unfold.

The networking aspects studied in the framework of WP5 can be structured into several processes, ranging from the rather classic aspects of UE mobility support, to the more advanced network slice orchestration related aspects, but also the innovative ones regarding the SDM-C and SDM-X controllers.

The non-exhaustive list of processes included in this document is hence a way of validating the WP5 functional architecture described previously, but also a necessary intermediate step needed to identify and design the various interfaces that have been identified between the different modules.

One of the key concepts of the WP is flexibility: it drove the design of the functional architecture and it is also driving the rationale of the design of WP5 processes. For this reason, we defined four categories of processes, which define high-level guidelines for all the fine-grained processes that belong to them. That is, the high-level interactions between the WP5 actors are described by the process families.

The processes families are described in Table 2, which includes also some exemplary fine grained processes. While the table is not expected to provide an exhaustive list, the four process categories are expected to cover all the possible processes that may be issued in future 5G networks. In the subsequent sub-sections we briefly describe these four processes in terms of the *trigger(s)* required to activate a process, and the related *actor(s)* with the summary of their respective tasks to execute the process.

Table 2: The four categories of processes

Process -1 **Network slice set-up and deployment**	**Process -2** **Network slice resources re-orchestration**	**Process -3** **SDM-C application (network slice control)**	**Process -4** **SDM-X policies (resource sharing)**
Network slice deployment request	Resource re-orchestration due to lack of IT resources	Network slice selection when UE performs attach procedure	Inter network slice resource brokering
Network slice blueprint customization and onboarding	Resource re-orchestration due to QoE/QoS	Handovers	Shared resources control
		Paging	
		Mobility Management (MM) scheme selection	
		QoE-aware RAN extension	

3.7.1 Network slice set-up and deployment

Triggers

The network slice set up process is a business-related process, triggered by the Service Layer and managed primarily by the 5G NORMA MANO Layer.

Actors and Associated Tasks

Service Management:

- It receives network slice creation requests from the business layer and makes a decision about the following problems
- Mapping of the high level business KPIs into network and infrastructure specific ones (SLA). The SDM-O supports dynamic SLA
- Selection of the NF blueprint

SDM-O:
- Instantiation of the NF into the IT infrastructure

SDM-C:
- The SDM-C is in charge of building the Service Function Path (SFP) among NF, starting hence the network slice operation.

SDM-X
- It manages the shared non-NFVI resources, identifying which NFs are actually shared by the network slices
- It re-configures common NF to accommodate new network slices

VIM
- It coordinates with SDM-X to control the NFV shared resources

3.7.2 Network slice resources re-orchestration

Triggers

The re-orchestration process happens according to two different triggers: the re-orchestration due to a lack of generic IT resources (also referred to as NFVI resources) and the re-orchestration due the failure to meet QoE/QoS parameters. The first sub-category is related to the state-of-the-art VNF elasticity and lifecycle management process as defined by ETSI, so it is managed in the same way directly through the VIM. That is, the re-orchestration is triggered by some issues in the virtualization containers hosting the VNF. Conversely, the second sub-family is related to the VNF itself, that at some point in time are not capable of providing the requested QoE associated to the network slice anymore and have to ask for a re-orchestration. This procedure is performed by the SDM-C and the related SDM-C application as they are aware of both the VNF context and semantics.

Actors and Associated Tasks

VIM

The role of the VIM for the network slice re-orchestration process is very similar to the one envisioned by the ETSI NFV MANO framework. The VIM is in charge of managing the physical and virtual resources associated to a network slice. Therefore, all the elasticity related procedure (i.e., scale-in, scale-out, scale-up, scale-down) are managed by the VIM according to the usual workflow. Using the well-defined interfaces such as the Vi-Vnfm. The final decision is taken by the SDM-O that grants (or not) the requested resources to the network slice.

SDM-C and Applications

While the VIM knows the physical load of the VNF containers (i.e., CPU load, memory utilization), the SDM-C and the related SDM-C applications have knowledge about the VNF semantics and the current target QoE and QoS constraints for the user flow. The usual SDM-C application behavior is related to the control of such VNFs (i.e., changing the VNF parameters) in order to keep meeting these constraints. However, when this is not possible by changing VNF parameters anymore, a re-orchestration is needed. Therefore, the SDM-C may raise this request to the SDM-O in order to obtain a different and better orchestration of the network slice according to the changing conditions.

SDM-O

The Orchestrator is the actor that takes the final decision about re-orchestration requests coming from either the VIM or the SDM-C. The ones received from the VIM are managed according to the procedure defined by the ETSI NFV MANO and the network slice is expanded (or shrunk) according to the available resources. Conversely, two different action may be taken if the request comes from the SDM-C.

- A different placement of the VNFs belonging to the chain: VNF may be moved from the central cloud to the edge cloud or vice versa. Or VNF context may be migrated to one edge cloud to another.
- New network functions, or services such as caches or video optimizers may be added to (or removed from) the function chain.

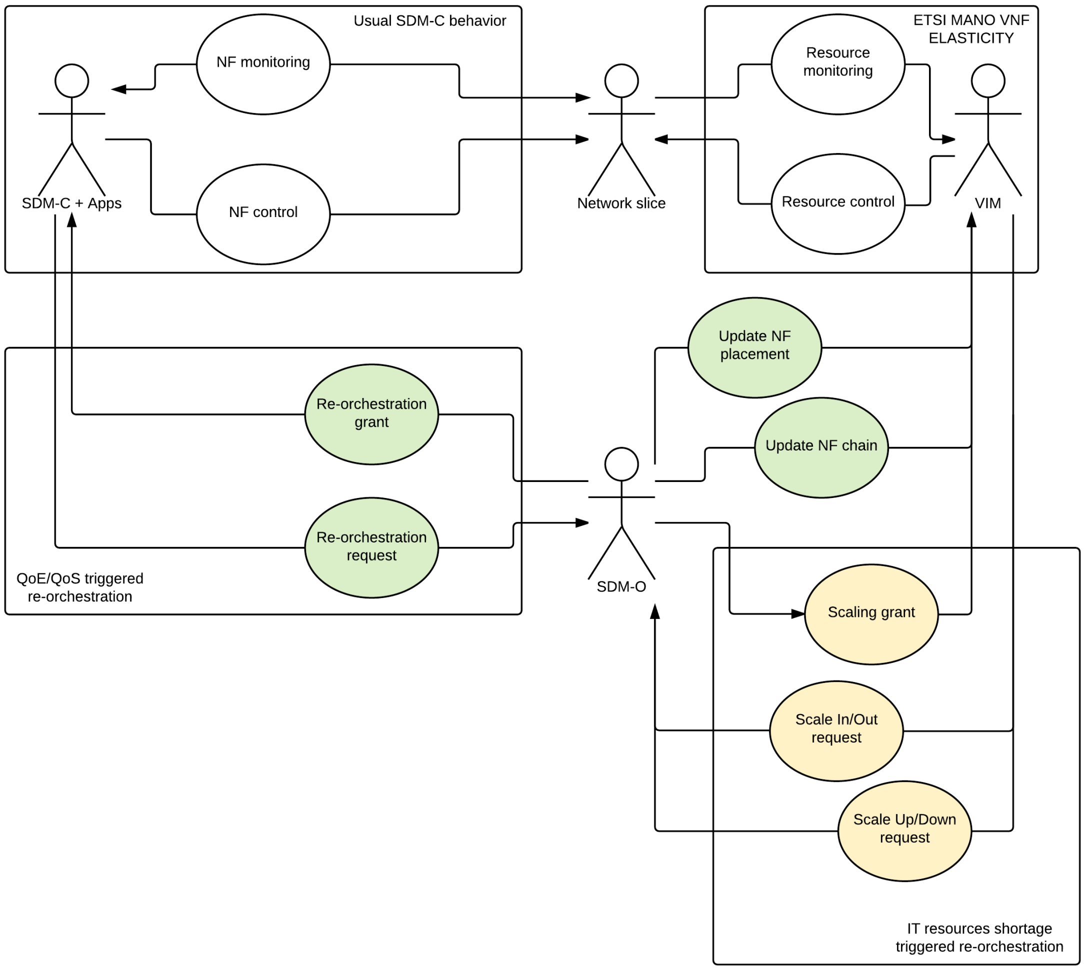

Figure 10: The interactions among different actors involved in the re-orchestration.

The overall behaviour of the Network Slice re-orchestration process is depicted in Figure 10, in which green boxes are actions related to the QoE/QoS triggered re-orchestration and yellow ones are actions related to IT resources shortage triggered re-orchestration

3.7.3 SDM-X policies (resource sharing)

Triggers

The shared resource control is triggered by the Slice Orchestrator when shared resources must be managed, e.g., spectrum or shared network functions. Scheduling policies at the SDM-X entity will be supported by (multiple) SDM-C functional blocks through a west/east bound interface 1/n. This ensures peer-to-peer communication levels between SDM-X and SDM-C and prevents master/slave communications.

Actors and Associated Tasks

SDM-O:

The SDM-O includes the admission control/ service brokering and slice orchestration, which monitors the overall system resource availability and grant network slice with required resources. The sub-tasks of SDM-O are a follows:

- *Admission Control / Brokering*
  - Monitoring resource availability based on granted network slices traffic requests
  - Advanced data traffic analytics for tenant traffic requests
- *Slice Orchestrator:*
  - Instantiation of the NF into the IT infrastructure
  - Forwarding Graph re-adjustment to the SDM-C

SDM-C:

- The SDM-C directly communicates with the SDM-X sending out resource management policies retrieved from the Slice Orchestrator. In addition, the SDM-C provides QoS indicators for dynamically adjusting resource allocation in order to fulfil the agreed SLA.

SDM-X

- Takes the real control of shared resource: it gets the resource management policies from the SDM-C and send it back the resource allocation information of the shared resources.
- Resource management policies could be envisioned as resource block masks, which each slice traffic request is assigned to.
- Advanced shared resource mechanisms could be designed for admitting additional network slice requirements.

3.7.4 SDM-C application (Network slice creation)

Triggers

In a generic view, SDM-C is composed by three layers: (i) the application and services; (ii) the controller functions and the network intelligence, and (iii) the elements for southbound communications.

The connection at the upper-level layers is based on northbound interfaces such as REST APIs, the most deployed one. On the lower-level part of SDM-C, southbound APIs and protocol plugins interface the forwarding elements or the controlled VNFs. They provide a common interface for the upper layers, while allowing to use different southbound APIs (e.g., OpenFlow, OVSDB) and protocol plugins to manage PNFs or VNFs (e.g., SNMP, BGP, NetConf). This is essential both for backward compatibility and heterogeneity, i.e., to allow multiple protocols and device management connectors.

Actors and Associated Tasks

The controller part of the SDM-C is characterized by a combination of the abstraction part and the network intelligence. The abstraction is used to implement the communications between the different plug-ins and the different network function modules (topology manager, switch manager…). The network intelligence hosts all the information like measurements, reporting… targeting to maintain a global view of the network. As a result, the network appears to the applications and policy engines as a single, logical switch.

In the following, we list the different steps followed from an NBI application perspective:

- The Service Function Chain template should be communicated from the SDM-O
- The SFC (internal module of SDM-C) should be supported.
- SDM-C should support the right plugins to interact with the SDN environment and the different VNFs and PNFs.

- The SDM-C interacts with the application via REST APIs.
- If one module, required by the application, is not supported, the application is removed.

PART 2: ALGORITHMS

4 Introduction

This part of the documents complements the architectural vision provided by Part I by filling the different modules of the architecture with the algorithms and protocols required to perform the functionality defined by the corresponding module. Given that the description of the different algorithms and their evaluation requires very substantial space, all this content has been placed as a different part of the document, to clearly separate the overall vision of the architecture from the detailed design of the underlying algorithms. The ultimate 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.

4.1 Objective and structure of Part II

The objective of this part of the document is to describe the different algorithms, protocols and techniques behind the different modules of the architecture. Each of this algorithms and protocols corresponds to a standalone design of a technical solution that fits a certain role within one of the modules of the architecture.

Following the above, the structure of this part of the deliverable corresponds to a collection of subsections each of which details a technical contribution (either an algorithm, a protocol or a technique) that plays a certain role in the new architecture. Many of these solutions are novel because of the fact that they solve a new problem posed by one of the novel concepts of the architecture. Other solutions solve an “old” problem in the context of the new architecture, but rely on new ideas or techniques that improve on the state of the art.

The various subsections of this part of the document have been groups in three main subsections, each of which corresponds to one of the main three building blocks of the architecture. Figure 11 shows the mapping between the technical solutions reported in this part of the document and the three main building blocks of WP5 architecture.

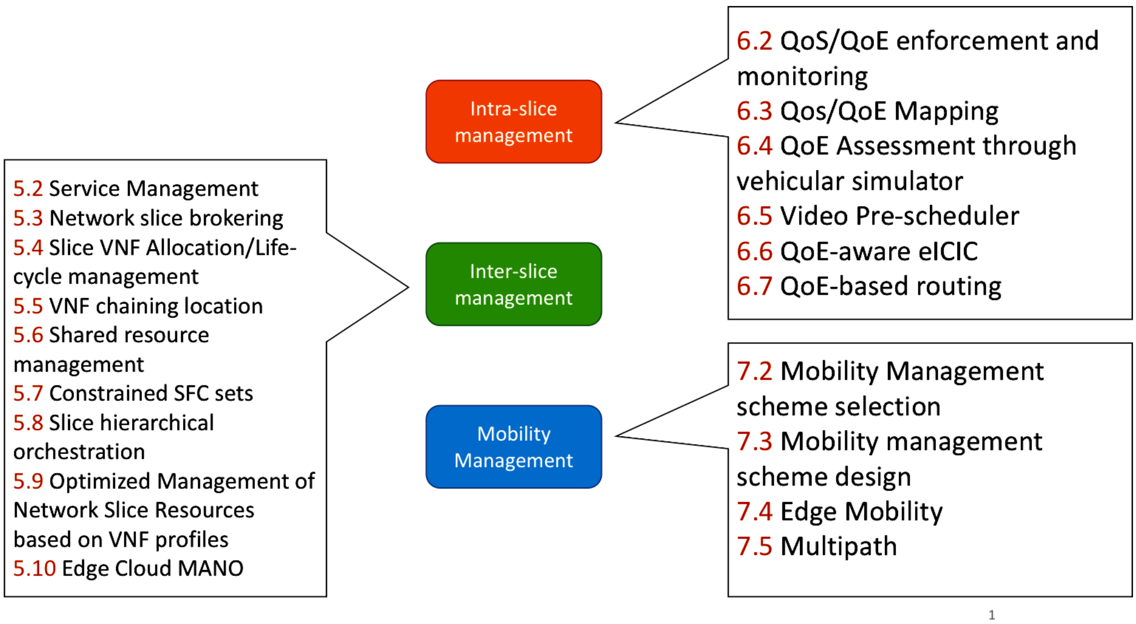

Figure 11: Mapping of technical contributions to WP5 building blocks

4.2 Key contributions of Part II

Most of the technical solutions included in this part of the document have either been patented, pushed into standards or published in scientific venues, and rely on new ideas and concepts. The following bullets explain the novel aspects and results obtained for the main contributions included in this part of the document:

- One of the proposals of the WP5 for mobility management has also been submitted as an IETF Internet draft [27]. This work is closely related to one of the three main building blocks of WP5, namely the 'Mobility management' building block.
- In addition to the above contributions, it is also worth highlighting the novelty of the algorithms and protocols design for each of the individual modules. In the following, we summarize some of these contributions:
- Novel algorithms are being designed as SDM-C applications running on top of the SDM-Controller in order to manage QoS functionality of the underlying mechanisms. These algorithms include video scheduling, routing control as well as policy control.
- New monitoring algorithms for QoS related parameters as well as algorithms for QoE modelling and mapping are also being designed. The purpose of these algorithms is to detect the current QoE provided to users in order to take actions when this QoE is not satisfactory.
- Mobility management protocols are being design which leverage on the SDM-C functionality provided by 5G NORMA. Key novelties behind those algorithms are the flexible allocation of functions as well as the use of SDN and the possibility of employing different schemes in different slices (which requires detecting the mobility requirements of the users). Extensions to the SDN functionality (as currently envisioned by the ONF) are going to be submitted.
- Solutions for multipath communication are being devised, involving the combination of multipath transport with mobility management protocols as well as leveraging multipath functionality for network orchestration.
- Optimal algorithms for network orchestration are being designed to decide the optimal location of each VNF.
- A new framework for network slicing that includes the coordination between different slices, along with the protocols and algorithms required for this purpose, are also being designed.

5 Network Slice Orchestration

5.1 Introduction

Network slice orchestration is a widely studied problem that is carefully addressed here. Different network slice orchestration operations are considered, both inter-slice and intra-slice operations. The network slice orchestration function involves the (*i*) Service Management, (*ii*) SDM-O and (*iii*) SDM-X functional blocks as depicted in Figure 12.

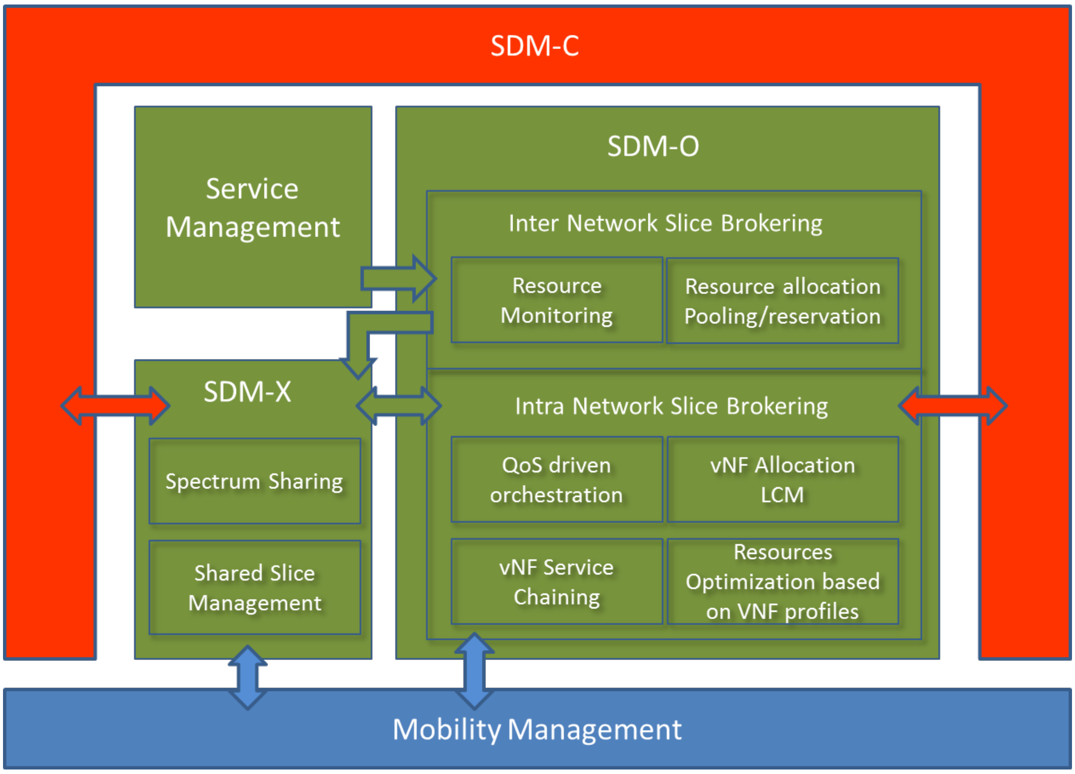

Figure 12: Network Slice Orchestration Functional Blocks

The Service Management receives service requests from multiple tenants either virtual operators, OTT providers and verticals and performs an analysis considering mapping the desired SLA to particular service requirements and application services, e.g. DPI, video optimizer, parental control, etc., which are fed to the SDM-O.

The SDM-O functional block is in charge of the network slice orchestration and it includes *i*) inter-network slice resource brokering functions and *ii*) intra-network slice brokering functions. The former functional block takes the service analysis input and SLA from the Service Management and allocates network slices based on admission control policies. In particular, it considers the requested SLA in terms of network resource considering bandwidth, VNFs and PNFs as well as in terms of timing, e.g. starting time and duration, service type e.g. guaranteed, best-effort, delay tolerant, etc., and the mobility profile, e.g. stationary, low, medium, high. Based on such input and analysis, the inter-network slice resource broker allocates dedicated and sharing resources performing admission control for a particular network slice request creating a "resource/topology-graph" and the essential VNFs, which are issued to the intra-network slice brokering block for each tenant. The latter receives the "resource/topology-graph" and the essential VNF from the inter-network slice resource broker and performs the network slice composition and allocation as well as the network slice life-cycle management through the following functions:

- VNF composition and allocation, creates service-tailored VNFs based on "atomic" functions considering the inter-network slice resource broker input and performs the allocation and instantiation of such VNFs at particular cloud locations.
- VNF service chaining function computes and arranges the sequence of combining VNF for particular services considering the VNF location, routing and mobility parameters.
- QoS driven orchestration and life-cycle management function is responsible for performance measurements in order to ensure that the desired performance parameters for each network slice are satisfied. Once the VNF composition and allocation function is completed, the output is then fed to the VNF service chaining function that creates the service-chaining graph.

- Optimized management decisions based on VNF profiles, enhances the network service manager i.e., the SDM-O Quality of Decision (QoD) to make service-aware and resource efficient lifecycle management decisions (e.g., scaling, migration etc.) ensuring that the future service/resource demands of the network service are met.

The output of the service-chaining graph and the information regarding the allocation of network functions is sent to the SDM-C through the interface depicted in the picture. The SDM-C then instantiates the service chain.

The QoS driven orchestration and life-cycle management also performs potential corrective indications towards the VNF composition and allocation function and towards the SDM-X and SDM-C that perform short-term resource management. The QoS driven orchestration and life-cycle management function as well as VNF composition and allocation function interact with the Mobility Management task exchanging information regarding the decisions of e.g. mobility schemes, and the orchestration of the VNFs. Finally, an architecture module that looks into the openMANO aspects and into the interfacing with SDN, in our case SDM-C and SDM-X is also considered.

The SDM-X controls and manages shared resources and functions considering both PNF and VNFs. The main role of the SDM-X is to co-ordinate the utilization of shared network resources and functions based on a set of polices received from the SDM-O. The SDM-X is composed by *i*) Shared spectrum and *ii*) Shared Slice Management. The first block assumes that radio resources are not strictly partitioned, i.e. isolated, among network slices but are shared providing flexibility in Resource Block (RB) allocation considering QoS and user mobility. Such flexible resource allocation is based on the policy received by the SDM-O, which aims to guide the SDM-X on the amount of resource that should allocate per slice. An additional coordination means is also provided by a direct interaction between the SDM-X and SDM-C. The second functional block assumes that certain network slices may share resources either bandwidth or network functions considering both VNF and PNF. Network slices that share capacity resources, i.e. bandwidth, are expected to support best-effort traffic, while the sharing of resources for dedicated network functions either VNF and PNF are expected to support network functions either expensive or their functionality need to be stressed beyond a single network slice. As in the case of shared spectrum, a coordination means between the SDM-X and SDM-C is needed. Both shared spectrum and resource management of shared slices functions need to interact with the Mobility Management task since the user mobility and the selection of the mobility function may impact the management of shared resources.

5.2 Service Management

In the so-called ZOOM ("Zero-time Orchestration, Operations and Management") model, TM Forum introduces the resource-facing domain and the customer-facing domain in telecommunications network operations. While the resource-facing domain comprises the necessary models and objects required to deploy a telecommunication service in physical and virtualized network infrastructure (e.g., as utilized by network management and orchestration systems), the customer-facing domain comprises the models and objects required to describe, account, and charge for a telecommunication service towards the customer (e.g., as utilized in business support systems). Due to the different nature of these domains, the utilized models for describing telecommunication services look substantially different. With the advent of vertical sectors requesting dedicated telecommunication services using customer-facing domain models, the need for mapping them to resource-facing service descriptions becomes evident. In the past, MNOs executed this mapping in a manual manner, also due to the limited number of service (mainly MBB, voice calls, and SMS). The Service Management (SM) function of 5G NORMA is a first step towards automation of this task.

Accordingly, this subsection is split into three discussion parts (1) interfaces towards function of the Service Layer, (2) functionality of Service Management, and (3) interfaces towards other MANO Layer entities (network management/OSS and SDM-O).

Reference points with Service Layer functions

Service Management exposes one or several interfaces towards the Service Layer. Enterprise systems (e.g., Service Layer applications, BSS) or human operators from either the Mobile Network Operator (MNO) or the tenant shall use these interfaces. They allow the tenant to specify the SLA for a particular network slice. According SLA templates, containing metrics as exemplified in Table 3, allow the tenant to quantitatively and qualitatively describe the SLA requirements.

Table 3: Selection of SLA parameters to be specified by the tenant

e2e service metrics	Operation and Maintenance	Network performance metrics	Monitoring and accounting
Committed information rate (provided bandwidth)	Mean time between failures	Latency metrics (e.g., average round-trip network delay)	Service level reporting
Committed burst information rate (i.e., ability to extend the committed data rate)	Mean time to restore/recover	Packet loss	Subscriber-level reporting
QoS policies, traffic priority classes	Reliability and resilience	Call blocking and dropping rates	Penalties when not meeting the SLA specs
% availability (or outage) of telco service			

Functionality of Service Management

Customer-facing (CF) and resource-facing (RF) domain use specific modelling formats and data representation schemes, including, but not limited to, formal service descriptions, service-level agreements, as well as processes, such as, on-boarding of network slice blueprints, network slice deployment and instantiation requests, KPI monitoring policies, etc. These formats, schemes, and processes need to be mapped and translated between the two domains. For this purpose, Service Management holds the following functionality:

- Selection and initial configuration of network slice template to be deployed (including the mapping of data and models provided by the CF domain to according data and models of the RF domain). The selection decision is based on the input provided from the CF domain, in particular the specified SLA requirements. The template is selected from a repository of certified templates, i.e., blueprints that can be realized given the set of resources. For the purpose of automation, the Service Management function holds the mapping rules, i.e., for each valid combination of SLA parameters, the according template is specified. Generally, the templates contain both a high-level description of the supported services (e.g., massive MTC (mMTC)) as well as a detailed listing of included NFs (PNFs and VNFs, similar to ETSI NFV network service descriptions) as well as configuration details and the performance targets. An illustrative example of such further performance targets and configuration data is depicted in Table 4.
- The monitoring and/or computation of key quality indicators to be provisioned to requesting entities from the Service Layer according to the specification of the respective SLA. Key Quality Indicators (KQI) cover both high-level objectives (coverage, network sharing, customer satisfaction, interoperability in multi-vendor environments) and technical

objectives (general key performance indicators, such as handover failures, and QoE/QoS parameters);

- Support the definition and on-boarding of new network slice templates, including a listing of contained network functions, resulting interfaces, and further dependencies.
- Handling of selected Service Layer inputs in order to allow for tenant-driven management, orchestration, and control of a network slice during runtime, e.g., intra-slice QoS policy specification.
- Depending on the use case that need to be covered, service management can include further sub-functions that perform mapping between customer-facing and resource-facing domains.

Table 4: Exemplary output of Service Management for network slice properties for connectivity on a temporary construction site

	Radio	NFVI	SDN	UEs
Slice Lifetime	6 months	6 months	6 months	na
Capacity	3 carriers	1k sessions/h	10 Gb	1000
Coverage	10 cells	1 site	1 site	na
Speed	1 Gbps	na	1 Gbps	100 mbps
Latency	10 ms	10 ms	na	na
Robustness	medium	medium	medium	na
Security	high	high	high	high
Availability	99.9	99.99	99.99	na

Reference point with SDM-O

The interface with 5G NORMA SDM-O is of bi-directional nature. As a result of the mapping process defined above, Service Management provides a fully specified network slice template to the SDM-O, including further performance and configuration information as shown in the illustrative example in Table 4. The SDM-O in turn uses this template to initiate the deployment and instantiation of a new network slice and to trigger the according processes (such as, lifecycle management and function configuration [25] with other MANO layer functions (NMS, EM, VNFM, VIM, etc.). Further, the control instructions provided by a tenant during runtime are forwarded to the respective controllers (SDM-C/SDM-X).

In the other direction (northbound), SDM-O provides performance, fault, and configuration data about operating network slices according to the monitoring rules provided by the Service Management function. These data are used for performance reporting as well as accounting and charging towards the tenant.

5.3 Network Slice Brokering

The network slice-brokering concept relies on the ability of the infrastructure provider to easily and automatically negotiate with external tenants network slice requests based on the current resource availability. This directly opens new challenges on how to efficiently enhance the current architecture to build interfaces between the network management and tenant applications while requiring on-demand network slices. Differently to the Service Capability Exposure Function (SCEF), which exposes services [28], a proper network slice brokering facilitates on-the-fly resource allocation by reserving an indicated portion of network resources for a particular time window to a tenant. Proposed network slice brokering algorithms are deployed on the SDM-O which can facilitate on-demand resource allocation to external tenant applications and perform admission control based on traffic monitoring and forecasting including e.g., mobility based-on a global network view. Additionally, it might also instruct SDM-X controller to dynamically configure RAN schedulers in order to operate an inter-slice resource allocation while customizing scheduling on the allocated spectrum. This could be realized to guarantee slice resource isolation or even to configure policies in order to enable the selection of resource blocks from a shared pooled spectrum by taking into account service SLAs and the size of the network slice across the core network.

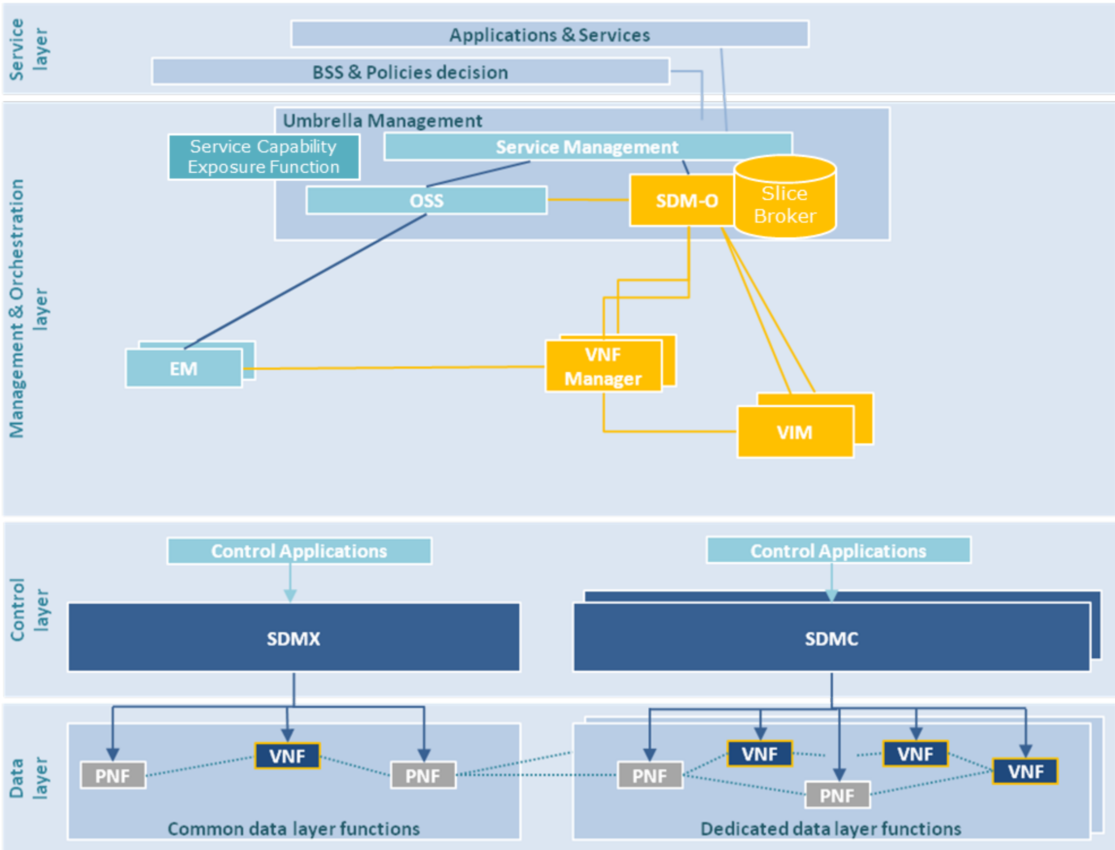

Figure 13: Network Slice Brokering within 5G NORMA Architecture

The network slice broker module must be co-located at the management and orchestration layer, which monitors and controls by means of SDM-X signalling the shared RAN elements (in case of shared spectrum) while interacting with the Sharing Operator Network Manager (SO-NM), as shown in Figure 13. In this way, it can gain access to network monitoring measurements such as load and different KPIs, e.g. mobility optimization, failures, SLA violations, etc. as well as obtain network infrastructure capabilities information. In addition, it can receive on-demand network resource requests from MVNOs, via the Type 5 interface, for allocating network slices based on SLAs. The network slice broker module upon performing the corresponding admission control decisions can take advantage of the 5G NORMA interfaces to grant the slice allocation to the Inter-slice Orchestrator functional block. In some case, the module can also interact with the SCEF to retrieve network slice requests. However, the interface of verticals or OTT providers towards the SCEF is under discussion. In this way the SCEF and the corresponding API is not only exposing information about devices, but can also provide control to tenants through the network slice broker module to allocate desired SLAs.

Interestingly, the proposed network slice brokering architecture supports on-demand resource allocation operations. This can be achieved by enhancing the existing interfaces. In particular, enhancements should differentiate tenants in order to handle the corresponding data traffic and provide performance monitoring information towards each participant operator. To enable this, a tenant identifier, e.g. PLMN-id, can be included in each data packet corresponding to different slices as well as in performance measurement reports to enable the MO-NM to provide feedback towards the corresponding SO-NM. Such performance feedback should involve only the allocated slice resources for privacy and competition reasons. For supporting generic tenants, the Itf-N ad Itf-B interfaces should also be enhanced to distinct the types of tenants by introducing a corresponding service identifier to each data packet and performance monitoring report. The Type 5 interface as well as tenant APIs should be extended to accommodate on-demand network slice requests with a particular SLA and timing requirements. The Itf-N and Itf-B interfaces should also be extended to carry out the configuration of network slices by introducing a new type of signaling considering MVNOs and vertical industries/OTT providers. Such interface enhancement and signaling should contain a set of additional information including:

- the amount of resources allocated to a network slice, e.g. physical resources or data rate;
- timing, e.g. starting time, duration or periodicity of a request, time window;
- the type of resources and QoS, e.g., the radio/core bearer type, prioritization, delay, jitter, loss;
- the size of file to be downloaded or data to be communicated to particular device/user or application server;
- service related information, e.g. mobility (stationary, low, medium, high), data offloading policies, service disruption tolerance.

Besides the service characteristics of a network slice, the set of cells which should accommodate the network slice request is an additional parameter that can be considered. Effectively, such a parameter can be either explicitly provided by the tenant or it can be determined by the infrastructure provider considering the location of the corresponding devices/users in combination with tailored service information provided by the SDM-O.

5.4 Slice VNF Allocation/Life-cycle management

One of the main challenges for 5G network operators will be the management of network services for diverse customer sectors and with different requirements (i.e. diverse vertical industries, mobile network operators etc.). Therefore, the 5G NORMA network, as a multi-tenancy mobile network, should provide a common network platform in which the mobile network infrastructure can be shared among several operators, enabling creation and dynamic life-cycle management of different network slices.

The management of different network slices with potentially very different requirements represents a big challenge for the 5G network operators, since they will need to deal with a high level of complexity to meet requirements from diverse customer segments (i.e. MBB, M2M, IoT applications, etc.) with very different requirements. In order to rise to this challenge our approach in 5G NORMA is to design a network with a high degree of automation. This approach will allow managing the available resources on-demand with enhanced flexibility and with no human intervention required. That way we provide a flexible, scalable and high performance means of selecting, controlling and deploying the necessary virtualized network functions from different operators on different network slices.

This section describes slice management operations considering slice VNF allocation and slice VNF life-cycle management. In a similar way as we allocate VMs in a cloud environment, VNFs forming a network slice in a 5G Network need to be provisioned, configured, monitored and decommissioned along with the lifecycle of the corresponding associated service. Virtualization capabilities (dynamic addition, removal, or updating of services, and dynamic mapping of different network resources to services) are used to achieve dynamic management of the deployed VNFs.

VNF allocation in the NFV infrastructure can be a complex task: many requirements and constraints may need to be met at the same time. Also, VNF allocation on telco networks adds higher complexity compared to the common IT resource allocation strategies. For instance, some VNFs requiring low latency or high bandwidth could be preferred to be physically allocated on Edge Cloud nodes, since traditional MBB resources should be kept in the Central

Network; this does not happen in common IT approach were it does not matter very much where a specific function is allocated. In addition, allocation and release of resources can be a very dynamic process, so frequent VNF allocations and releases may be needed along the VNF lifetime.

According to the principles described in Del. 3.1 [1] three main modules will be in charge of the VNFI orchestration and management: SDM-O, VNFM and VIM (see Figure 14 below).

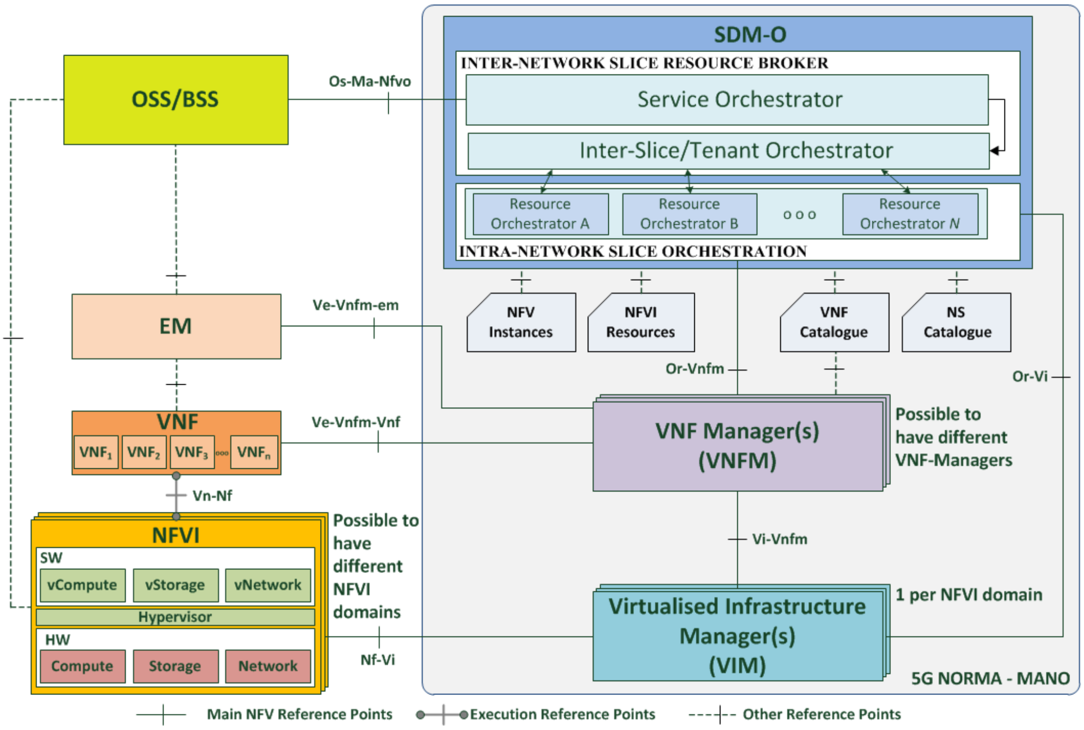

Figure 14: 5G NORMA Main Management and Orchestration Blocks

These three modules are the core part of the 5G NORMA VNF MANO architecture, and of course, they are located in the 5G NORMA Management and Orchestration layer. The role of these blocks is to manage the NFVI (including the network control components) and orchestrate the allocation of resources needed by the NSs and VNFs.

As illustrated in Figure 14, on one hand, we have the VIM and VNF Manager blocks, which are already defined in the ETSI NFV-MANO architecture [29]. On the other hand, we have the SDM-O (the 5G-NORMA orchestrator) which has been specifically defined for the 5G NORMA architecture. As seen from Figure 14, the SDM-O is internally composed by three different blocks:

- Service Orchestrator (SO), which is functionally equivalent to the NFVO defined by the ETSI NFV MANO specification.
- Resources Orchestrators, which are also equivalent to the Resource Orchestration function also in the ETSI specification (they provide an overall view of the NFVI resources in the administrative domain).
- Inter-Slice/Tenant Orchestrator, which is the orchestrator part specifically designed for the slices orchestration (see [1] for further details).

As we see in the figure, the WP3 “Inter-slice/Tenant Orchestrator + Service Orchestrator” modules correspond with our WP5 “Inter network slice resource broker”. In the same way, the “Resource Orchestration” modules from WP3 correspond with the WP5 “Intra-Network Slice Orchestration” block. Anyway, all these modules are internal blocks in the SDM-O; the remaining modules and interfaces are still functionally equivalent to what the ETSI NFV MANO specification describes.

According to the ETSI NFV MANO framework, the module more directly involved in VNF allocation & life-cycle management is (as its name suggest) the VNF Manager (VNFM). In short, we can tell that VNFM is to VNFs what the VIM is to the NFVI. Specifically, VNFM does the following:

- Manages VNF's life cycle. That is: it creates, maintains and terminates VNF instances (which are installed on the VMs, which the VIM creates and manages).
- It is responsible for the typical FCAPS functions for VNF's (i.e. Fault, Configuration, Accounting, Performance and Security Management of VNF's).
- It scales the infrastructure (up/down, by adding/removing additional VNF instances, or in/out, by adding/removing intra-VNF resources such as CPU or memory).

As we see in Figure 14, there could be multiple VNFMs in a typical deployment, each one managing its own set of VNFs (also, the VNFM delegates on the VIM, which typically manages NFVI resources in just one specific domain). This creates an additional challenge; the management and coordination of E2E services involving VNFs from different VNFMs domains.

This challenge is faced by the Orchestrator block (SDM-O) by using the Services Orchestration function (i.e., the ETSI NFVO equivalent). This function does this in the following way:

- Creates E2E services between different VNFs by coordinating directly with the respective VNFMs (i.e., it does not need to talk to each VNFs directly). An example could be to create a service between the base station VNFs from one slice and a VNF in the core network from another slice.
- Instantiating new VNFMs where it is applicable.
- Specifying the topology of the network services instances (i.e., the so-called VNF-FG).

Therefore, we could tell that the Services Orchestration module in the SDM-O is like "the glue" for VNFs, since it can bind together different functions to create E2E services in a sparse NFV environment.

But we are talking here about "*slice*" VNF allocation and life-cycle management; this is where the new 5G NORMA specific orchestration block came in scene: the Inter-Slice/Tenant Orchestrator (ISTO) block: the same way in the ETSI NFV MANO specification there is a single orchestrator (NFVO) to *glue* different VNF Managers, the Inter-Slice Orchestrator is used here to *glue* different slices.

More formally, the ISTO block can be used to handle the dynamic provisioning of different slices and to manage the resources sharing among them. That way, the ISTO will control the slices life-cycle and will coordinate the allocation of resources (e.g.: a tenant that would like to optimize the resources among all the slices could interface with the ISTO block) [1].

In summary, although VNF allocation and life-cycle management is directly performed by the VNF Manager (as the ETSI NFV MANO defines it), other blocks are also involved in the 5G NORMA architecture:

- The Inter-Network Slice Resource Broker to manage multiple slices (containing the Service Orchestrator (SO) and the Inter Slice/Tenant Orchestrator).
- The Intra-Network Slice Orchestrator, containing the Resource Orchestrators associated to each slice.

In the following section, we will see in more detail different processes typically involved in the slice VNF allocation and life-cycle management involving these elements.

5.4.1 Examples of Management Flows

This section includes a non-exhaustive collection of management flows related to VNF allocation and life-cycle management. All flows are informative, representing best practices for each operation, having the main objective of identifying information exchange between the different blocks in the management and orchestration architecture.
The following general principles are used for all the flows in this section:

- The Service Management block is the single point of access for all requests from the 5G NORMA Service Layer.
- The Inter Slice/Tenant Orchestrator (ISTO) orchestrates specific Network Slices.
- The VNF Manager handles VNF lifecycle.
- The SDMO, and specifically the SO, handles lifecycles of Network Service and VNF Forwarding Graphs.
- Hence, the SDMO has the E2E view of the resources being allocated across Network Services and VNFs by VNF Managers: all requests for resource allocation transit through, or are verified and granted by the SDMO.

5.4.1.1 VNF Package On-Boarding Flows

The deployment and operational behavior requirements of VNFs is captured in a deployment template, and stored during the VNF on-boarding process in a catalogue. Typical on-boarding operations are enabling, disabling, updating or deletion of VNF packages. As an example, this subsection describes the typical VNF package on-boarding flow together with the enabling and deletion of a VNF package.

On-board VNF Package flow

The following Figure 15 shows the process of on-boarding a VNF Package[2]:

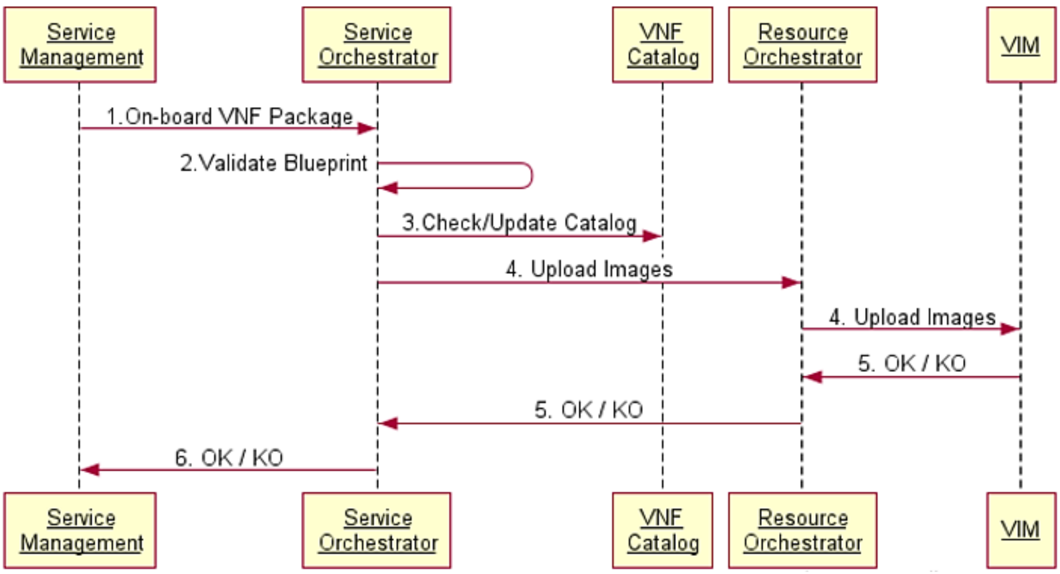

Figure 15: VNF Package On-boarding Process

The main steps for VNF Package on-boarding are:

[2] The concept of "VNF Package" is still not defined in the context of 5G Norma. In any case we can think about it generically, simply as a file containing other files (VNF descriptors, scripts, etc.) according a specific structure.

- A VNF Package is delivered to the SO in the SDM-O for on boarding the VNF descriptor. The request comes from the Service Management layer in the 5G NORMA architecture.
- The SO processes the VNF descriptor. This includes for example the verification of mandatory elements and the validation of authenticity and integrity of the provided descriptor. Also includes information that can be used to decide the slice where the VNF should be located (e.g.: a slice identification, or a way to get such slice-id).
- The SO checks and updates the VNF's catalogue (this is the same VNF catalog as the one defined in the ETSI NFV MANO specification [29]).
- The SO communicates the request to the RO.
- The RO makes VM images available to each applicable VIM considering the slice identification received from the Service Orchestrator. It is expected for the VIM to validate the integrity of VNF software images(s) as part of this operation.
- The VIM's acknowledge the successful/unsuccessful uploading of the image, which is back propagated towards the RO, SO and the Service Management modules.

Enable VNF Package flow

The following Figure 16 shows the process of enabling a VNF Package.

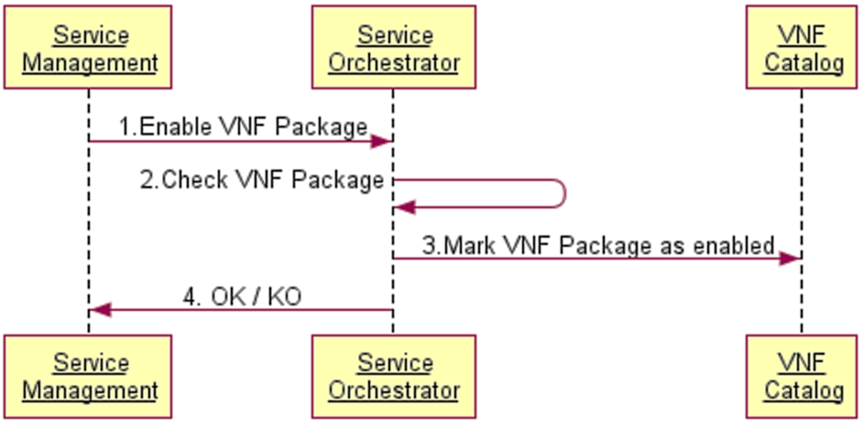

Figure 16: VNF Package Enabling Process

As we see, in this case the process of 'enabling' just takes effect on the VNF Catalog module. It just means that the VNF Package is ready to be allocated. The SO just verifies the provided VNF package checking things such as if the package already exists in the database or it is already disabled.

Delete VNF Package flow

The following Figure 17 shows the process of deleting a VNF package:

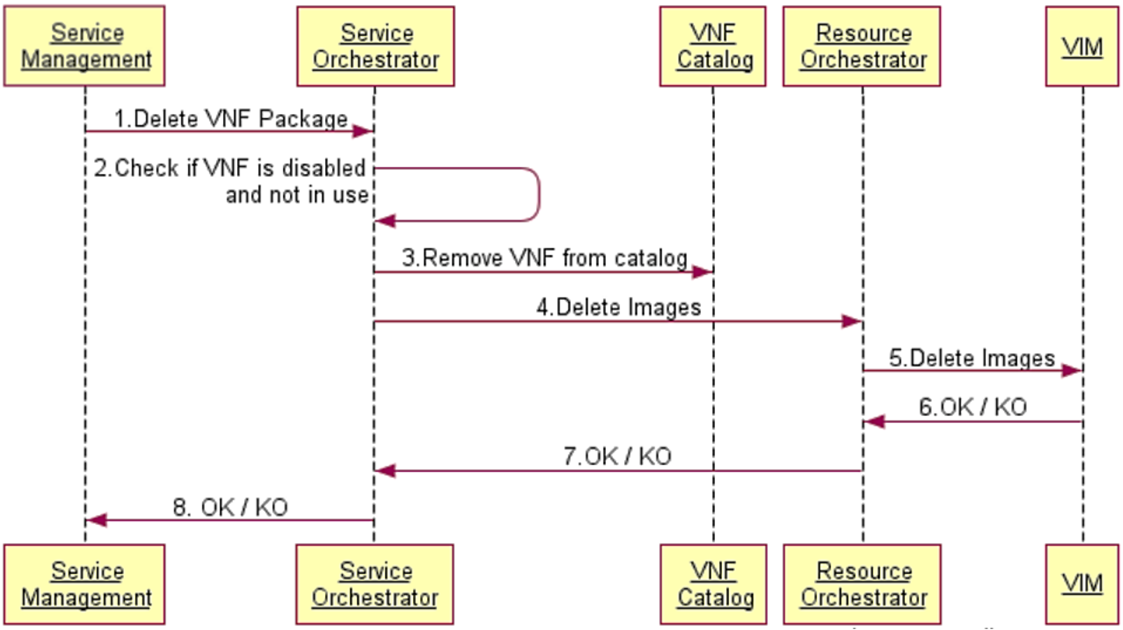

Figure 17: VNF Package Delete Process

As we see, this process is quite similar to the process of on-boarding a VNF package, but using the 'delete' operation instead. A general high-level condition for the deletion is to check if the VNF is already disabled and not in use. If that is not the case, the VNF Package cannot be deleted. Like for the on-boarding process, the SO module should inform the RO module about the slice which the VNF package belongs.

5.4.1.2 VNF Instantiation Flow

VNF instantiation refers to the process of identifying and reserving the virtualized resources required for a VNF, instantiating the VNF and starting the deployment unit associated with each VNF.

Figure 18 represents a proposal for the VNF instantiation flow with the resource allocation done from the SDM-O (i.e., using the SO and RO modules).

As we can see, the Services Orchestrator propagates the request towards the VNF Manager, which allocates the resources for a specific slice using the Resources Orchestrator, which talks directly with the VIM to allocate the network/compute and storage resources.

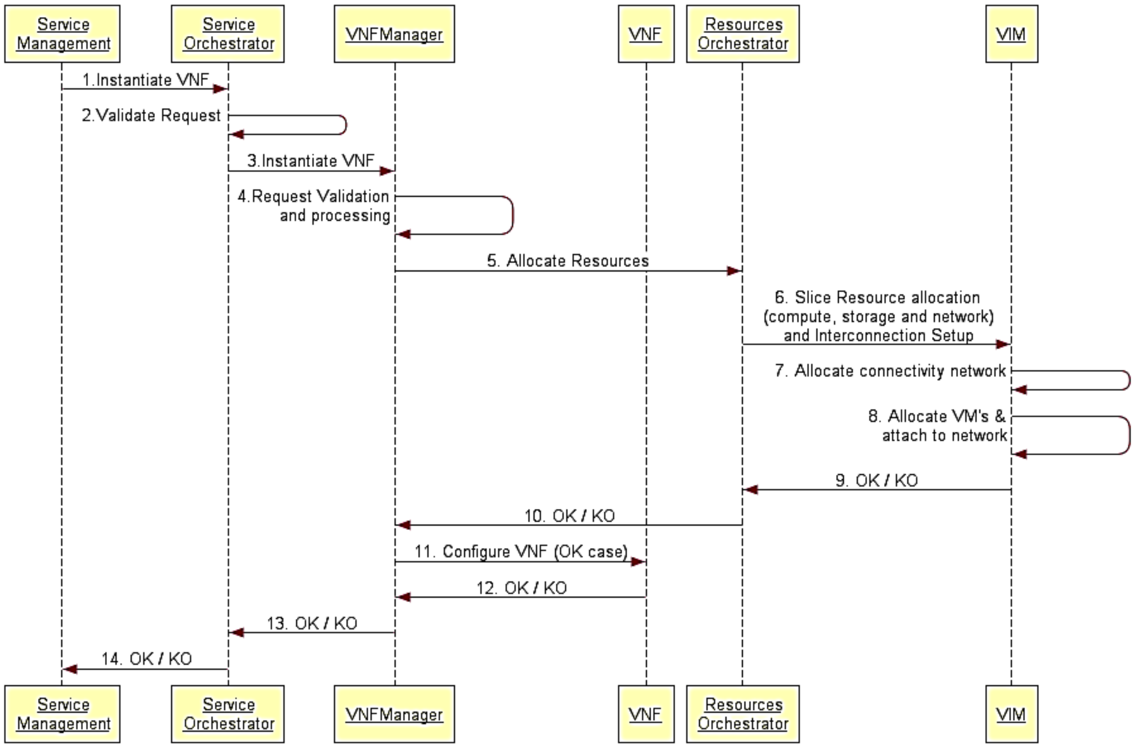

Figure 18: VNF Instantiation Process

5.4.1.3 VNF instance scaling

VNF instance scaling is generally the result of a QoS threshold being crossed (up or downwards), requiring expanding or contracting the availability of compute, storage or networking resources.

As a whole, managing scaling requires two things:

- Detecting the need to scale
- Determine scaling action

For the first thing the trigger could come from different sources; for example:

- A single VNF, when it embeds a monitoring and mapping function able to generate a notification (see Section 6.2 about QoS/QoE mapping).
- The VNF Manager (in this case then information on the event to monitor and the corresponding scaling action might be provided in the VNF Descriptor).
- The VIM (e.g., in case of network congestion, number of sessions, etc.). The VNF Manager will listen to those events and implement the decision about actions (the QoE/QoS events generated from the SDM-C (see Section 6) will be received this way, since the SDM-C, as part of the NFVI, is below, in the control layer).
- An EM, when the monitoring function/threshold crossing detection and event notification is not in the VNF, but in its specific EM. The decision about actions could be implemented in the EM itself, and/or forwarded to VNF Manager.
- The OSS/BSS block (e.g., due a management change in the capacity planning based on traffic projections).

Anyway, following the ETSI NFV MANO recommendations [29], all the scaling use cases could be grouped into three categories:

- ***Auto-scaling***. In this case, the VNFM monitors the state of a VNF instance and triggers the scaling operation when certain conditions are met. For monitoring VNF instances, it could subscribe to infrastructure-level events (generated from the VIM) and/or to VNF-level events (generated by the VNF itself or its associated EM if any).
- ***On-demand scaling***. Here a VNF instance or its associated EM monitors a VNF instance and trigger a scaling operation through an explicit request to the VNF Manager (i.e., the VNF or the EM *demands* to the VNF Manager to perform the scaling operation).
- ***Management-request scaling***. In this case, the requester will be the OSS/BSS or a human operator. The request will reach the VNF Manager via the SDM-O.

Regarding determining the scaling action (point 2 above), the type of required change could be:

- Configuration changes to the VM (scale up, e.g. adding CPU or memory)
- Release resources from existing instances (scale down)
- Add a new deployable unit instance (scale out)
- Shut down and remove instances (scale in)
- Network changes (i.e., increase bandwidth or available network capacity)

A major challenge here is that determining the scaling action may need to look beyond a single VNF instance (e.g.: solving a quality issue in VNF-1 may require changes to VNF-2).

In Figure 19 we present a possible simplified flow for automatic intra-slice VNF expansion (scale out) triggered by VNF performance measurement results:

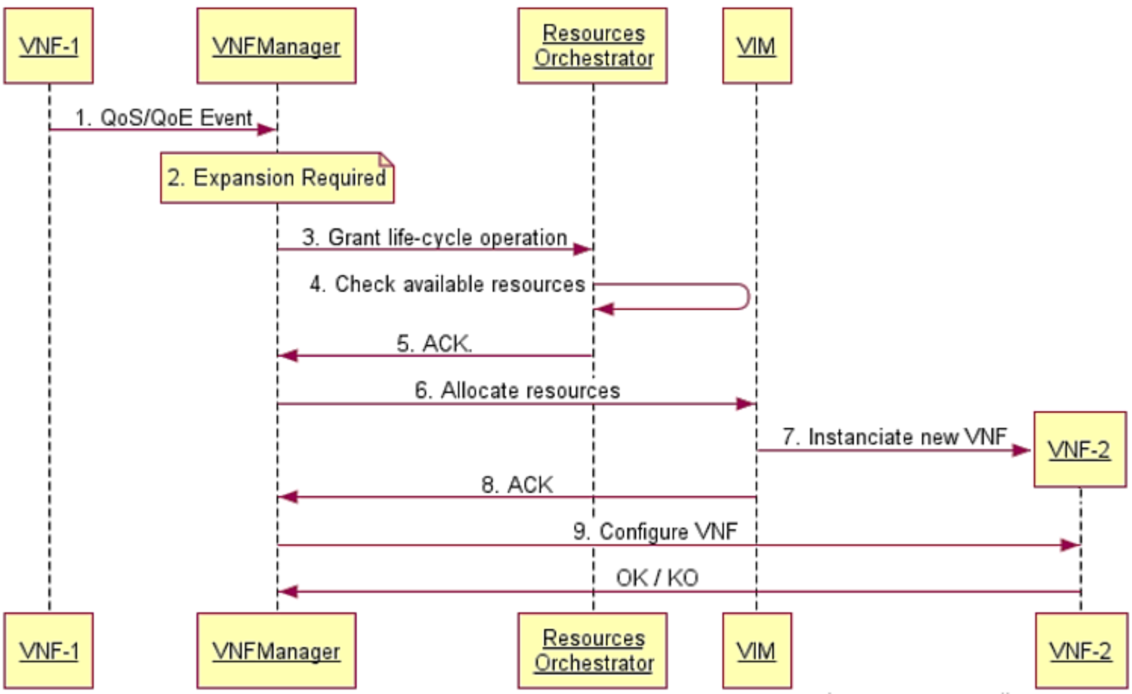

Figure 19: Automatic Intra-slice VNF Scale-out

As we see, the process starts with a QoS/QoE event generated by a specific VNF (VNF-1). As mentioned, it could be generated also from other elements in the control layer (i.e., the SDM-C block). That event is managed by the VNFM block, which, for this case, decides that an expansion is required. To allocate new resources, the VNFM sends a request to the RO module (inside the SDM-O); this module checks the resource type needed (CPU, Memory, IP, etc.) and checks for availability, sending feedback to the VNFM. Finally, the VNFM allocates the new VNF towards the VIM and configures the new VNF.

5.4.1.4 VNF instance termination

The VNF instance termination requests could be generated from the OSS/BSS system (i.e., as part of a decommissioning process) or from the VNF Manager when the need to terminate a VNF is detected (when VNFM detects the termination itself, or when it is notified from an EM). In any case, the termination request is processed by the SDM-O. Figure 20 illustrates a simplified view of the VNF instance termination process.

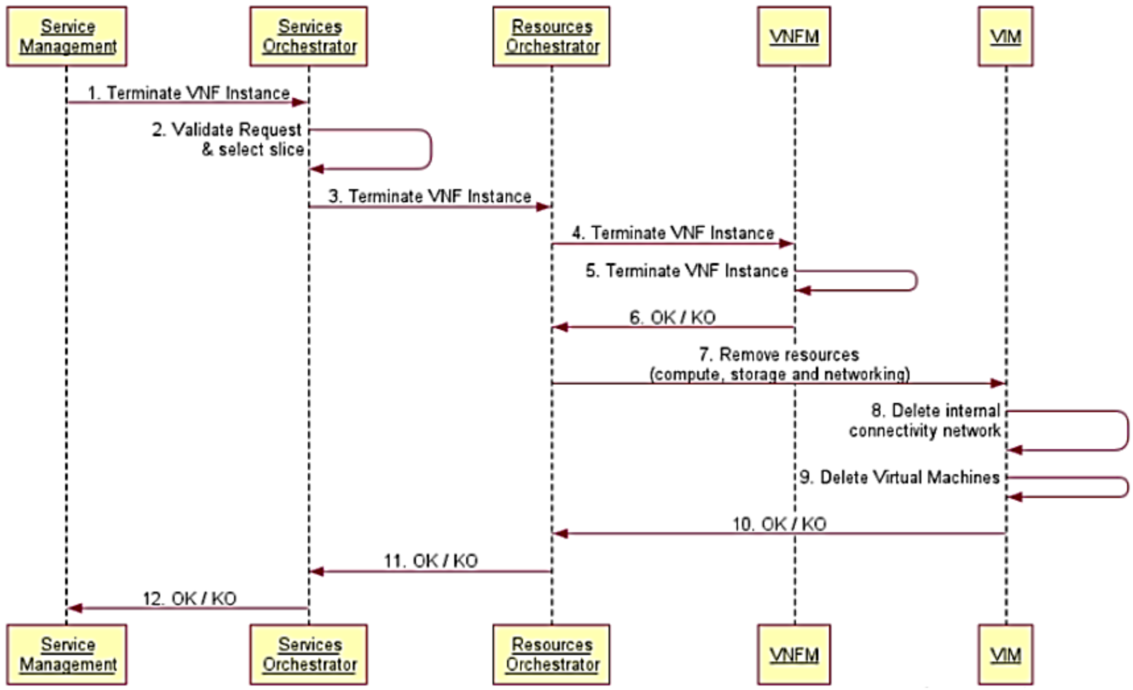

Figure 20: VNF Instance Termination Process

As can be seen, in this case the request is originated from the Service Management block. It arrives first to the Services Orchestrator block, which validates the request (i.e., check sender authorization and verifies if the VNF instance actually exists), deduces the slice identifier and send the request to the RO to remove the resources on the appropriate slice. The RO first terminates the VNF instance using the VNF Manager, and then de-allocates resources (memory, network and storage) sending the appropriate request towards the VIM.

5.4.1.5 NFV fault management

As with QoE/QoS measurements, fault events could be originated from different sources: physical infrastructure (i.e. physical compute, storage, and networking related faults), virtualised infrastructure (e.g. VM-related faults), and also, the VNF's application logic itself (i.e. VNF instance related faults). In addition, fault information could be originated from those different sources at the same time. That way, fault information should be correlated; that correlation could happen in multiple places: SDM-O, VNF Manager, EM and/or some OSS. Once a correlation point(s) is chosen, the other functional blocks are expected to forward the fault events to the targeted correlation point.

There could be multiple options, depending on the fault correlation point and the fault resolution point. Anyway, since multiple alternatives are possible, we will not try here to document all possible fault management operational flows. Figure 21 provides an example of NFV fault management in which the VIM and a VNF represent a double source of fault information:

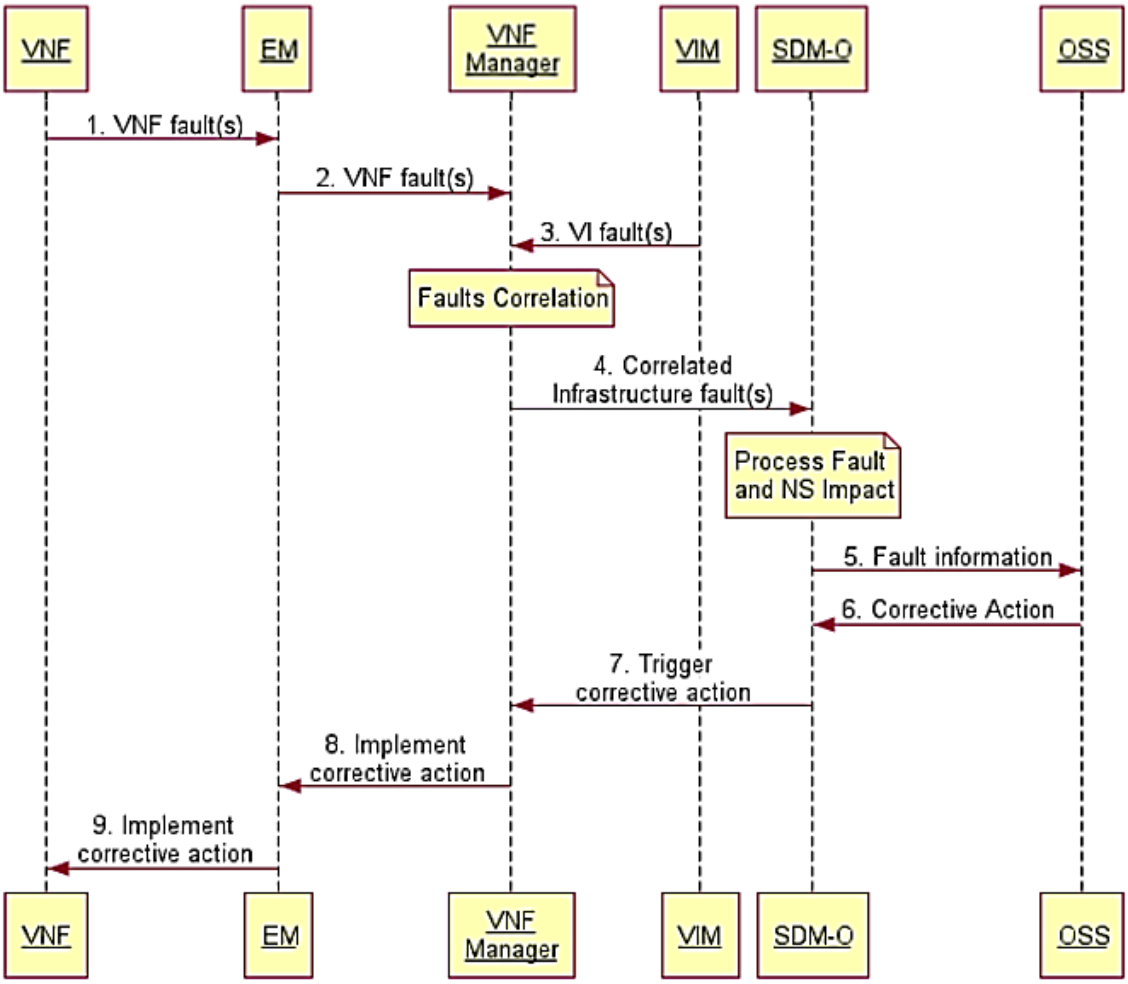

Figure 21: NFV Fault Management Process

As can be seen, in this case two blocks are detecting a fault condition: the VNF EM and the VIM; the fault information is correlated on the VNF Manager before triggering the SDM-O. After that, the OSS is notified and decides the fault corrective action, which is back-propagated to the VNF across the VNF Manager and the EM block.

5.5 VNF chaining location

The term "service-chaining" has been used to describe the deployment of topologically distributed VNF functions that via a specific configuration enable the creation of a service to the end users. The role of the orchestrator, in this case, is the process of specifying an ordered list of service functions that should be applied to a deterministic set of traffic flows. An overall logical architecture of the so-called VNF Management and Orchestration (MANO) architecture has been defined within ETSI [29] and the specific extensions as envisioned within 5G NORMA have been discussed in previous sections. Hereafter we focus on the chaining functionalities within the 5G NORMA NFV domain where lies the responsibility of both the SDM-C as well as the SDM-X in the case that a subset of the requested services relate to shared resources and therefore both controllers should coordinate to create the service. However, it is worth pointing out that one of the earliest related research works in the area is the one in [30] that can be deemed as an initial effort to provide a systematic unification model of middle-boxes, which can be considered as nodes that host VNF. The aim of that work was to provide a model where different middleboxes could be orchestrated, but without considering optimization models and/or efficient algorithms for the overall orchestration process. Further to that, the work in [31] propose the so-called *Stratos* framework, which can be considered as a network orchestration layer built on top of a Floodlight[3] controller. The role of *Stratos* orchestrator is estimate where to place various network functions in the network, to inform a VM manager (such as for example the virt-manager[4]) about this decision, and finally to instructs an OpenFlow[5] controller to distribute flows to the corresponding switches. Another effort on the control/orchestration is the OpenNF framework [32] that provide a design of the APIs to provide a joint control between network forwarding state and internal VNF state. The work in [33] can be deemed as another effort to provide orchestration between virtualized NFs especially focusing on issues such as VM migration and split/merging of flows.

The work in [34] provides an optimization problem for placing the chained VNF in a network taking into account as constraints various requirements of the tenants and the operator – but routing between and location of VNF is not explicitly taken into account. An overview of the challenges which emerge in virtual network function scheduling is presented in [35]. The authors explain the application of SDN and NFV technologies focusing in optical networks. The VNF problem is viewed analogous to the classical "*Job-Shop Problem*". For this reason, the authors use a mixed integer mathematical program outline to frame the scheduling problem. Within this framework results of the problem yields optimal results for small topologies. The authors in [36] address inefficiencies in resource and energy consumption in online virtual network embedding scenarios. The Energy Aware-Virtual Network Embedding-Node-Link Formulation (EA-VNE-NLF) is proposed to addresses these inefficiencies by considering two objective functions; the first to address resource usage and the second for energy consumption. The performance of the ILP formulation is compared to results obtained using a mobility aware location and chaining heuristic. The simulation results show gains in favor of the proposed minimization formulation compared to those of the heuristic. In [37] the authors provide a holistic treatment of VNF opportunities, emerging new architectures, and discussion for successful deployments. In [38] four different greedy heuristic algorithms are detailed for the problem of VNF chaining and a wide set of numerical investigations are presented providing an insight on the performance of the different heuristic algorithms. The work in [39] focus on delay requirements for VNF placement with application in 5G networks; an optimization problem is formulating resembling the resource constrained shortest path problem with the aims to minimize routing and latency and costs for flows requiring variable number of VNF.

The work in [35] give an overview of the challenges which emerge in virtual network function scheduling. The authors explain the application of SDN and NFV technologies over optical networks. The VNF orchestration problem is viewed analogous to the classical Job-Shop problem. For this reason, the authors use a mixed integer mathematical program outline to frame the scheduling problem. Within this framework results of the problem yields optimal results for small topologies. This paper extends the MILP argument posed with concentration on the orchestration and provisioning of VNF's over a mobile core network.

The authors in [40] address inefficiencies in resource and energy consumption in online virtual network embedding scenarios. The Energy Aware-Virtual Network Embedding-Node-Link Formulation (EA-VNE-NLF) is proposed to addresses these inefficiencies by considering two objective functions; the first to address resource usage and the second for energy consumption.

[3] www.projectfloodlight.org

[4] www.virt-manager.org

[5] www.opennetworking.org

The performance of the ILP formulation is compared to results obtained using a shortest distance path heuristic. The simulation results show gains in favor of the proposed minimization formulation compared to those of the heuristic.

An integer linear program is formulated in [41] to determine the optimal number of VNF and their placement to solve the virtual network embedding problem whilst considering node order placement requirement for function placement. Network costs described in the model include OPEX and resource fragmentation. OPEX costs include deployment of VNF, energy, traffic forwarding, and penalties for traffic violations where resource fragmentation costs are introduced through servers and links. Using a Veterbi based heuristic was used to compute per-node cumulative cost and compare results gathered from the ILP formulation. These results suggest that network OPEX can be reduced by a factor of 4 through the use of optimal VNF orchestration.

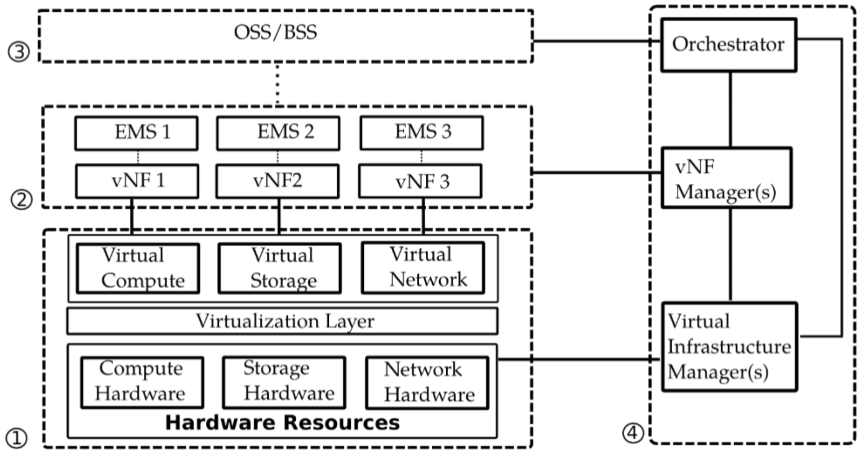

Figure 22: NFV logical architectural view as proposed by ETSI

As illustrated in Figure 22, the idea behind NFVI is essentially:

- To decouple software from hardware devices, and
- Convert them to their software counterparts where they may be managed for network efficiency.

The software equivalent of a physical network element is referred to as a VNF, which may fall under the category of network elements (VNF-NE) or network functions or middle-boxes (VNF-MB). A VNF network element consists of switching elements, mobile network nodes and signal control system elements[6]. A VNF-MB refers to network functions such as firewalls, network address translator, WAN optimization controllers, deep packet inspections and load balancers. The NFVI (element (1) in Figure 22) is a composite of three sub-components; the bottom physical components begin network, storage and compute layer, the second a hypervisor (virtual machine monitor) monitoring the physical substrate hardware. The third portion is the virtualized software implementations of the bottom layer, together creating the appropriate virtual environment for VNF deployment, teardown and lifecycle management. Element (2) in Figure 22 shows the virtual environment and VNF functions, which may include a combination of VNF-MB (middle-boxes) or VNF-NE (network elements). In element (3) of Figure 22 is the OSS/BSS (business support systems) dealing with configuration and management. The MANO

[6] Switching elements include routers and switches, broadband devices, remote access servers. Mobile network nodes include; HSS (Home Subscriber Server)/HLR (Home Location Register) and base station elements. The final category of elements is Signal Control Systems which include session boarder control elements.

Layer (element (4) in Figure 22) consists of the NFVO, VNFM(s) and VIM(s). The NFVO manages elements in (1) and (2) indirectly via the VNFM and VIM controllers respectively.

5.5.1 VNF Routing, Location and Chaining in Virtualized Network Infrastructures

The main motivation behind network virtualization is the sharing of a single physical infrastructure by multiple tenants. The procedure of the efficient mapping of virtual networks on the substrate network is called virtual network embedding and there has been significant research effort over the last few years in developing efficient algorithms to perform optimal and/or near optimal embedding of virtual networks. An example of embedding two virtual networks on a substrate network infrastructure is show in Figure 23 below.

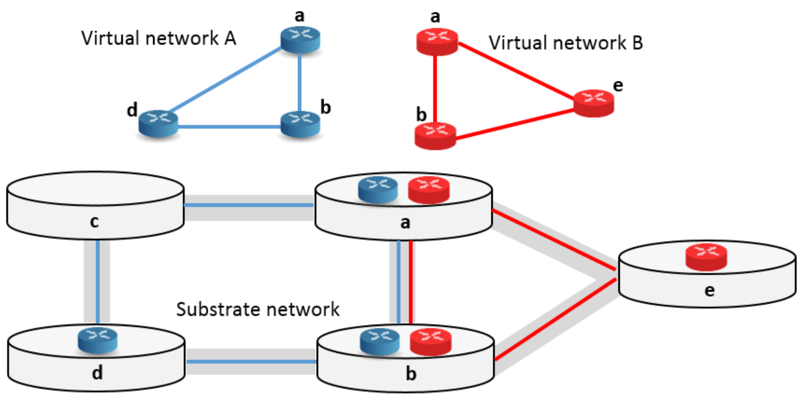

Figure 23: A toy example showing the embedding of two virtual networks in a substrate network infrastructure.

We, hereafter, assume that the network embedding is already in place when deciding about the location (hosting), ordering and routing of VNF requests. Theoretically, those two procedures could be jointly designed but might lead to very complex optimization problems that could have an interest only in terms on bounds on the performance since network embedding and VNF chaining take place in different time scales. Without loss of generality, we can assume that a set of nodes in the virtual network can be a candidate node to host VNFs (such as for example FWs, DPI, video format optimization, NAT services, etc.). Services will require a specific ordered chain of such VNFs and for a pre-defined number of service requests the problem is to find the optimal routing, location and chaining of VNF in the virtual network topology. This problem is highly combinatorial, and therefore requires advanced algorithms for optimizing overall network performance.

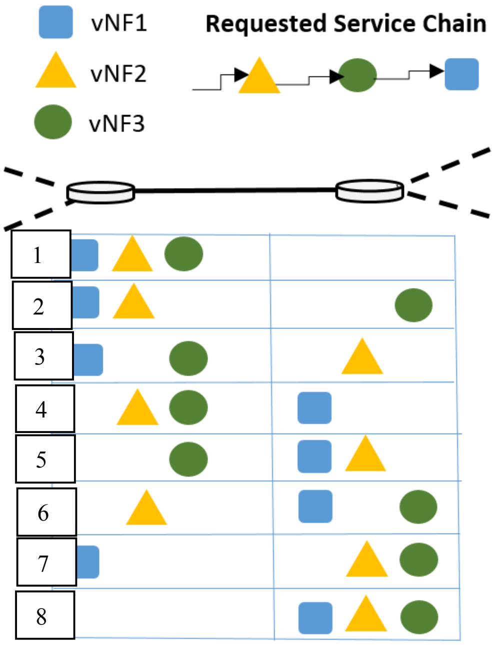

Figure 24: Possible locations of three VNFs in two network nodes that can host these functions

Figure 24 provides in an illustrative manner the issue of VNF location in different network nodes. As can be seen in Figure 26 for a service chain that requires in a specific order 3 different VNFs; there are 8 different possible allocations in two network nodes. Assuming a large number of such service requests and depending on the traffic characteristics and QoS requirements of the different flows the optimal allocation of VNFs in network nodes as well as the associated routing problems become a challenging issue in emerging SDN/VNF enabled networks.

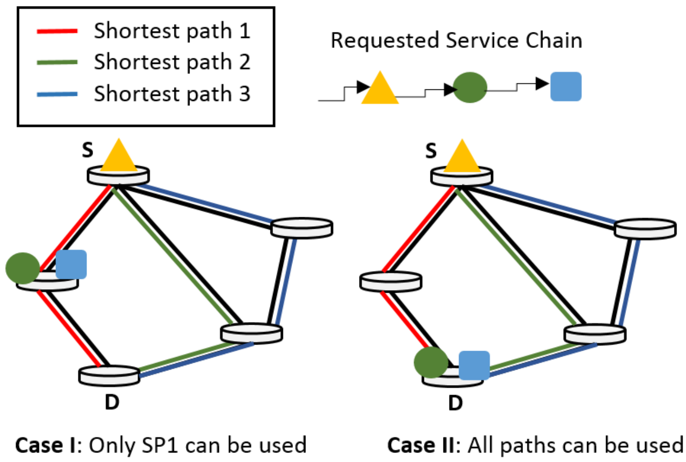

Figure 25: Effect of VNF location on the selection of available (shortest) paths in the network

We, hereafter, identify some key research areas targeted for contribution that received currently little research attention but with a significant potential to increase overall network efficiency; research contributions are tailored towards the areas detailed in the sequel.

5.5.2 Routing and VNF Placement

Figure 25 shows the effect of VNF hosting location on the overall path diversity and available path selection in the network. As shown in the figure, there are three alternative shortest paths between the source and the destination but the VNF allocation in Case I allow only exploring one of the shortest paths. On the contrary, the VNF allocation shown in Case II allows all three shortest paths to be utilized by the SDM-C and depending on overall aggregate traffic levels and individual QoS per service request the availability on selecting across various shortest paths can increase network efficiency. Shortest paths can be readily be available using OSPFv3[7], which is an open standard protocol, using Dijkstra's shortest path algorithm to find the shortest, best and optimum path to each and every destination node and/or network. At the same time it allows the support of multiple routes to same destination having equal cost for to make the routing process faster and balancing the load equally on various paths; extensions can also be utilized for more advanced routing decisions. Therefore, in order to allow a rich routing environment that does not adversely affected by the location of VNF in the network special attention should be placed on proposed optimization algorithms to allow full use of available (shortest) paths in the network.

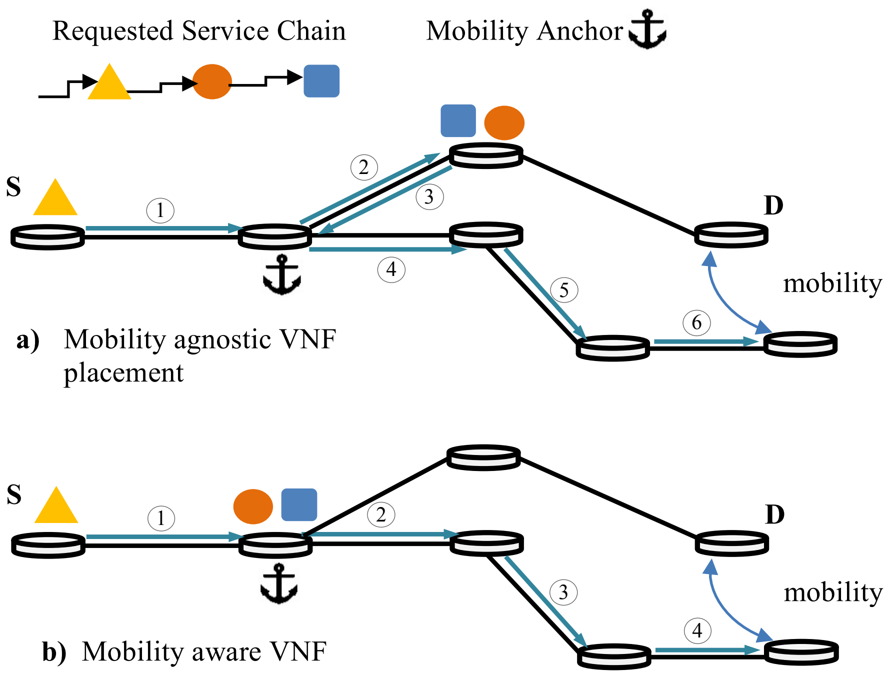

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Figure 26: The effect of mobility on the location of VNFs; a location that does not take into account mobility might lead to an increased routing cost.

5.5.3 Mobility and VNF Placement

Current proposed solutions for VNF placement and chaining assume a pre-defined fixed gateway to access router path, in other words that the routing path does not changing during the lifetime of the service. However, this may not be the case for mobile users with high mobility and/or with elephant sessions, which might entail a significant high probability of changing their

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[7] OSPF version 3 [RFC 5340] is in essence the same protocol as OSPF version 2 [RFC 2328] but equipped with the extensions of providing support for IPv6 routing prefixes and efficient use of the inherent larger available size of IPv6 addresses.

service access router. This operation might also affect the optimality of the selected VNF location and routing for the assumed requested service. This would be the case when the path between the node of the last-in-order VNF (to be visited) and the access router is changed due to user mobility. Moving to a new access router means that the above last routing path segment will be changed. The routing change also depends and on the mobility anchoring point for the session. An illustrative example of a possible detrimental effect of mobility on a VNF placement is shown in Figure 26. As shown in Figure 26 case (a); because of the location of the VNF and the location of the anchor point at the edge of the network the case of a mobility event that requires a change in the access router will result in having 6 hops, whereas as shown in Figure 26 case (b) a different location of the VNF will result in having 4 hops, which is a significant improvement. Even though this is a toy example illustrates the cross-issues between mobility decisions and VNF location. Therefore, a careful decision-making is required to take into account potential mobility episodes in the network and their effects in overall network performance. We note that the above shown example provides in an illustrative manner the effect of mobility on the VNF chaining, but depending how routing cost is used in the network the effects can be topology independent, when for example a specific QoS level needs to be supported.

To this end, we have developed mathematical programming formulations to achieve (i) Optimal Routing, Location and Chaining (ORLC) and (ii) a Mobility aware Optimal Routing, Location and Chaining (MaORLC).

5.5.4 Integer Linear Programming Formulations

In this section we define the Optimal Routing, Location and Chaining (ORLC) problem along with the supporting narrative for its construction. The ORLC model will serve as a base model that can be enhanced to support end user mobility. To proceed with a mathematical programming setting we define a binary decision variable $y^k_{r,\psi_r(l)}$ as shown in equation below which assign VNF of different order per service request to network nodes,

$$y^k_{r,\psi_r(l)} = \begin{cases} 1 \; if \; NF \; \psi_r(l) \; for \; request \; r \; located \; at \; node \; k \\ 0 \; otherwise \end{cases}$$

The next critical component to discuss is our cost matrix P which contains link/edge costs (known to the network provider). Given any two adjacent nodes k, m over an undirected graph we define the cost over an edge to be $p_{k,m}$. These edge costs are used to construct our shortest path matrix; a matrix containing the shortest paths from virtual nodes k to m. For model robustness we subdivide the cost matrix and identify three cost matrices; $\bar{P}_{s_r,k}$, $\hat{P}_{m,d_r}$ and $P_{s_r,k}$. Each matrix identifying with separate topological regions in the network. The first considers traffic from the gateway to the first network node (i.e. the VNF which is due to be visited first). The second holds the shortest paths from the last visited VNF to the access router (d_r). The final matrix identifies the shortest path costs along virtual edges excluding those edges used in in the latter two matrices.

The objective function construction requires we first identify the path from the gateway s_r to the first node i.e. the node hosting the VNF which is to be visited first. To this point, if a VNF is hosted on a virtual node, then the contributing cost would be the shortest path to the virtual node hosting the first VNF from it's current location. A more formal definition is as follows

$$\sum_{r \in R} \sum_{k=1}^{K} \bar{P}_{s_r,k} \, y^k_{r,\psi_r(l)} \; \forall \, r \in R, \forall \, k \in K$$

Using the decision variable defined previously and setting $l = 1$ in the order preserving function $\psi_r(l)$, we identify the node hosting the first VNF and thus accurately reveal the cost contributions of routing. Using the same technique with slight modifications an accurate account of the costs are revealed. The first minor adjustment is to the cost matrix to and from nodes - indicating we are moving from the node hosting the last VNF to the access router. The second adjustment is setting the binary decisions variable argument to the node hosting the final VNF (in the service request). Summing over all requests r and virtualized nodes k a formal definition takes the form,

$$\sum_{r\in R}\sum_{k=1}^{K}\hat{P}_{k,d_r}\, y^{k}_{r,\psi_r(l)}\ \forall\, r\ \in R, \forall\, k\in K$$

We account for the internal node costs by first, identifying the adjacent nodes whose VNF are to be visited as intended by the service request and secondly, multiplying this term by the edges costs connecting these adjacent nodes. This arrangement may be restated mathematically as shown below,

$$\sum_{r\in R}\sum_{l=1}^{L}\sum_{m=1}^{K}\sum_{k=1}^{K}P_{k,m}\, y^{k}_{r,\psi_r(l)}\, y^{m}_{r,\psi_r(l+1)}\ \forall\, r\ \in R, \forall\, k\in K$$

In addition to routing and VNF placement we have costs which are incurred by nodes in terms of consumed resources. Each VNF both has a required CPU cycle and buffer requirement (u_{f_i} and b_{f_i}). Switching perspectives, each node has a maximum available resource level which determines VNF placement. We introduce this into our model as $C^{k}_{\psi_r(l)}$where it's dependencies are VNF and node specific[8]. To capture per node costs incurred it is necessary to know if a VNF has been mapped to this node. What's more, to capture aggregate network costs, we do so by summing over all request, VNF and nodes, more concisely, this can be expressed as follows,

$$\sum_{r\in R}\sum_{l=1}^{L}\sum_{k=1}^{K}C^{k}_{\psi_r(l)}\, y^{k}_{r,\psi_r(l)}$$

With the addition of the VNF hosting cost in as well as the inclusion of the total routing contribution as detailed in the previous equations the joint routing and VNF placement optimization problem can be defined as follows,

$$\min\sum_{r\in R}\sum_{k=1}^{K}\bar{P}_{s_r,k}\, y^{k}_{r,\psi_r(1)}+\sum_{r\in R}\sum_{k=1}^{K}\hat{P}_{k,d_r} y^{k}_{r,\psi_r(L_r)}+$$

$$\sum_{r\in R}\sum_{l=1}^{L}\sum_{m=1}^{K}\sum_{k=1}^{K}P_{k,m}\, y^{k}_{r,\psi_r(l)}\, y^{m}_{r,\psi_r(l+1)}+\sum_{r\in R}\sum_{l=1}^{L}\sum_{k=1}^{K}C^{k}_{\psi_r(l)}\, y^{k}_{r,\psi_r(l)}$$

[8] Cost per VNF type are known by network providers before and are subject to change with advances in hardware CPU, RAM and storage capacities

$$subject\ to \sum_{r\in R}\sum_{l=1}^{L} b_{\psi_r(l)} y^k_{r,\psi_r(l)} \leq B_k, \quad \forall\, k \in \boldsymbol{K}$$

$$\sum_{r\in R}\sum_{l=1}^{L} u_{\psi_r(l)} y^k_{r,\psi_r(l)} \leq U_k, \quad \forall\, k \in \boldsymbol{K}$$

$$y^k_{1,\psi_1(\pi_1[1])} \oplus y^k_{2,\psi_2(\pi_2[1])} \oplus \dots \oplus y^k_{R,\psi_R(\pi_R[1])} +$$
$$y^k_{1,\psi_1(\pi_1[2])} \oplus y^k_{2,\psi_2(\pi_2[2])} \oplus \dots \oplus y^k_{R,\psi_R(\pi_R[2])} + \cdots +$$
$$y^k_{1,\psi_1(\pi_1[K])} \oplus y^k_{2,\psi_2(\pi_2[K])} \oplus \dots \oplus y^k_{R,\psi_R(\pi_R[K])} \leq |K|, \forall k \ \in \boldsymbol{K}$$

$$\sum_{k=1}^{K} y^k_{r,\psi_r(l)} = 1, \quad \forall\, r \in \boldsymbol{R}, l = 1 \dots R$$

$$y^k_{r,\psi_r(l)} \ \in \{0,1\}\ \forall k \ \in \boldsymbol{K}, \forall\, l \in \ \boldsymbol{L}, r = 1,..,R$$

The first two sets of constraints ensure that both CPU and buffer capacities at the nodes that will be hosting network functions are preserved. The next set of constraints ensures preserving the order of VNF to be visited and the last constraint ensures that the VNF will be hosted by a network node for each request. The fact that the decision variables are binary is shown in the last set of constraints.

5.5.5 Extensions

Among VNFs, it is expected that caching can be one of the potential key network functions in emerging networks; the plethora of caching applications especially on popular video streaming requires to pay special attention in terms of VNF chaining and location. This is because in the most general case, cached contents must be visited before other VNF can be applied and that the flow does need to reach a gateway node but can originate at the node that host the required cached content. 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 can reduce their utilization level. However, caching in mobile networks can be a more challenging issue since the optimality of cache locations might change with the movement/mobility of users. To significantly reduce access delays to highly popular contents diffusely caching contents close to the end user is expected to be a network technique of significant importance in emerging wireless/mobile networks. Since caching popular content closer to the end user might require more frequently changes of the cache location to keep providing the optimal performance, the caching location and the associated VNF chaining need to be jointly considered to avoid sub-optimal cases, hence improving overall network performance. Another issue of importance is energy consumption and VNF chaining for low latency services that might require efficient routing and therefore some form of prioritization compared to other flows in the network. In addition to the above it is also worth pointing out that also delay awareness and reliability consideration could be added to the VNF chaining and routing. In terms of delay, either strict delay requirements per service requests could be added as constraints in the above mathematical programming framework or, another objective function could be envisioned with the aim of minimizing overall delay when creating a VNF function. Furthermore, the multipath support which is already integrated in the above framework could be further explored to provide the desired reliability levels for different services. Minimizing overall delay and provision for high reliability might be crucial algorithmic functions to be supported by the MANO since it is envisioned that a plethora of future services will be delay sensitive especially those related to multimodal haptic/tactile applications that require ultra-low latencies as well as high reliability.

5.5.6 Final Remarks

The underlying premise of this section is that by enabling multi-path support and mobility awareness into the vNF routing, location and chaining problem it would be possible to achieve more efficient policies that increase the overall network performance. A number of illustrative examples have been outlined that explain the potential benefits in designing algorithms that do take from the outset into account mobility and multi-path diversity in the network. We have also detail an optimization problems to obtain optimal routing, location and chaining (ORLC) of vNF requests within a virtual network function infrastructure that can be considered as the base line to build more advanced features as well as providing a bound on the achievable performance.

5.6 Optimized Management of Network Slice Resources based on VNF profiles

After a network slice has been deployed (or embedded over the NFVI), configured and instantiated, it becomes necessary to ensure the provisioning of stable services while maintaining an E2E service integrity throughout the network slice lifetime. This means taking appropriate and necessary Lifecycle Management (LCM) decisions and actions whenever the QoS is compromised or at risk from being compromised. For example, one or more VNFs of a network slice being overloaded, and/or the virtual link(s) interconnecting VNFs become congested, and/or the allocated resources to the VNFs becomes increasingly utilized. In all such cases the 5G NORMA management system has to react at run-time to take timely LCM decisions/actions e.g., whether to scale or migrate one or more VNF instance that may prove to be the weakest link in the chain and hence responsible for compromising the E2E QoS.

Dynamic run-time management of active network slices is a very complex topic and has many implications that must be taken into account to ensure a stable service delivery. The main objective of this research challenge is to optimize the management decisions made by the Service Management and the SDM-O and/or SDM-C/X on active VNFs that are part of a Network Service represented by slice. Each time the slice orchestrator needs to perform a Life Cycle Management (LCM) action on one or more VNFs it will have impact on the performance of the service(s) that is being hosted by the slice. For example, if a constituent VNF of a network slice is being scaled or migrated; it will potentially result in service interruption or service degradation until the time the LCM operation has been successfully completed. In case of the non-optimum LCM decision, the Management & Orchestration Layer (SM, SDM-O) through the Control Layer (SDM-X/C) will execute a LCM action again thereby repeatedly affecting the underlying service(s). Thus repeated management decisions will not only affect the service quality but also result in the non-optimum utilization of the system resources. From the service continuity and quality point of view, it is important that the NORMA orchestrator (i.e., SDM-O) in cooperation with SDM-X shall make optimized management decisions. The optimality of management decisions is measured in terms of the number of times management decisions are made on a specific VNF and/or Network Service before it becomes stable. The resource efficiency is also a measure of the optimum performance of the management system. In other words the objective is to enhance the Quality of Decision (QoD) of the NORMA Management and Orchestration framework.

In the context of the above problem statement, a novel method has been proposed [42] [43] that correlates the resource utilization patterns of a VNF and based on that a functional and operational profile of the VNF is formed. The NORMA Management system is then able to derive management decisions that are in consistence with the operational needs of the VNF, rather than based on fixed/static resource profiles of a VNF as would normally be described by VNF Descriptor.

In this context we have proposed a Resource Aware VNF Agnostic (RAVA) method that can be utilized by the SDM-O inside the NORMA Management framework for making informed and optimum management decisions at run-time in view of changing workload conditions. The RAVA method was originally proposed in the context of MCN project [44] where a PoC setup was established in order to perform pilot tests in order to test its technology feasibility. The results have been very encouraging but based on simplistic assumptions and a small-scale emulated scenario. In this section, we would like to present the overall concept of RAVA in the context of SDM-O with some initial results.

Since this is work in progress, we also present the details on the work-in-progress

5.6.1 RAVA – Conceptual Overview

The conceptual details of RAVA has already been provided in [44], which is summarized in this section. The concept of affinity is central to the RAVA orchestration method, whereby the term affinity refers to the correlation between different Resource Units (RU). The affinity value, or affinity score, is a vector quantity that indicates the level or degree of dependence of one or more RUs on a Reference RU (RRU). This method derives and communicates information depicting the correlation, or affinity, between different RUs with reference to a specified RU under different workload conditions. This derived vector is referred to as Reference Resource Affinity Score (RRAS). RRAS provides an insight on how and by how much the utilization of an RRU will impact the utilization of other RUs. RRAS thus expresses the correlation, or the level of dependence, of an individual RU on the reference RU in terms of utilization. For example, the RRAS value of an I/O resource with reference to CPU indicates the degree of its utilization dependence on the CPU utilization. A high RRAS value would indicate a strong affinity, whereas a small value will indicate weaker affinity or dependence. The RRAS value computation is done by the cloud management and orchestrator entity, for example an NFVO, for all VMs deployed in an NFVI at runtime.

The RRAS values enables the NFVO server to make informed decisions in terms of optimum resource management during run-time under different workload conditions regardless of the type of VNF, hence resource aware and VNF agnostic.

As an example, assuming a linear relationship between the utilization of the two dependent RUs, we use the Pearson Product-Moment Correlation Coefficient (PPMCC) as a measure of linear correlation between the RU and the RRU. The Pearson coefficient (r) is calculated over the samples of average percentage utilization of the different RUs during a specified evaluation epoch $t_{eval} = n * t_{mon}$, where t_{mon} is the monitoring epoch during which the system monitors (x) samples of the absolute utilization (μ) of the different RUs, and calculates the average percentage utilization for the RUs as:

$$\bar{\mu} = \frac{\sum_{i=1}^{x} \mu_i}{x}$$

The values of n and x is a design choice. Thus over a single teval we will have n number of samples,where each sample is an average utilization of an RU during t_{mon}.

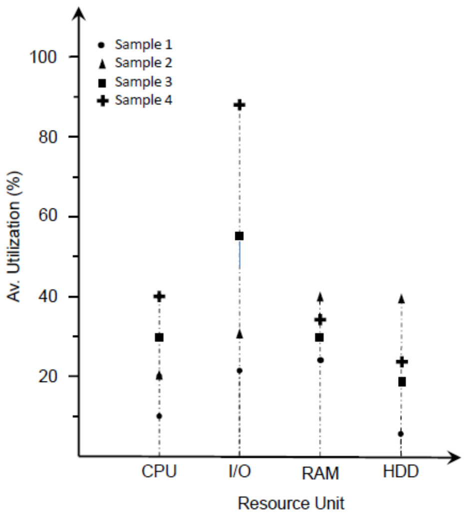


Figure 27: Resource Utilization samples for a specific VM.

A Pearson co-efficient (*r*) is then derived over these samples with reference to a RRU and the derived value of *r* is the RRAS. A conceptual notion of this can be explained from Figure 27 depicting samples ($\bar{\mu}$) for each of the respective RU for a VM during t_{mon}. The RRAS value, which is the Pearson co-efficient (*r*), is then computed for the different RUs with respect to the CPU, which is the RRU. Table 5 shows a single RRAS report instance corresponding to the example utilization values shown in Figure 27. The RRAS report depicts the RRAS for each RU with reference to a specific RRU based on the samples of average resource utilization.

Being vector quantities, the RRAS values show how much the utilization of an RRU is impacting the other RUs. A high positive or high negative RRAS value of a particular RU indicates a strong correlation of its utilization with reference to the RRU. On the other hand, a low positive or negative value indicates a weak correlation of a RU with an RRU. Moreover, a high positive RRAS indicates a "strong affinity" while a high negative RRAS indicates a "weak affinity". This will help enable the NFVO to precisely determine the influence of a RRU on the other RUs. For instance, with CPU as a RRU, it is observed from Table 5 that the I/O RU has a very strong correlation and thus a strong affinity with the CPU, while the correlation of Memory and HDD RU with the CPU is very weak. In other words, the I/O module will experience a higher degree of utilization than the storage with respect to CPU utilization. This could be indicative of a VNF that may perform packet forwarding and routing. In other words, the NFVO can determine the VNF's functional/operational profile by observing the RRAS values.

Table 5: RRAS Report Snapshot for a Specific VM

Reference Resource Unit	***Average Utilization (%) Samples***	***Reference Resource Affinity Score***			
		CPU	*I/O*	*RAM*	*HDD*
CPU	[10, 20, 30, 40]	-	0.98	0.4	0.05
I/O	[20, 35, 55, 90]	0.98	-	0.34	-0.01
RAM	[25, 40, 30, 35]	0.4	0.34	-	0.94
HDD	[17, 40, 20, 25]	0.05	-0.01	0.94	-

The NFVO maintains the past RRAS reports for a specific RU or a set of RUs. The period of history can range from minutes to hours or even days, depending on the policy. Such historical/past record of the RRAS report enables the NFVO to derive Affinity Signature (AS) of RU(s) with respect to a RRU.

An AS is a plot of the successive RRAS values for a RU, which can then be manipulated by deriving statistics such as affinity trend, as will be show later. The AS, and the affinity trend, provides the NFVO the information about the long-term affinity of a RU with a RRU for a VNF. This information will enable the NFVO to make informed and optimum management decisions, for example selecting the best possible PM to which a target-VNF should be migrated or scaled to. This will thus potentially improve NFVO's Quality of Decision (QoD). The notion of QoD is explained in next sub-section.

One issue that may occur with our stated approach is that linear regression will give a more precise trend if the moving average of our process is monotonically increasing or decreasing. Otherwise we need more complex models to assess the trends, stationarity and seasonality of the samples. Since this section presents the first results of the proof-of-concept, we are at present working towards developing more complex models and considering more elaborate scenarios.

5.6.2 Performance analysis

The initial performance results and analysis based on RAVA's PoC has been presented in [43] and in this section we will provide an overview of the analysis.

In general, RAVA method has been proposed to enhance the QoD of the SDM-O responsible for making life-cycle management decisions on the Network Services. The QoD is measured in terms of the following two mutually dependent criteria:

1. How resource efficient the management action is. The resource efficiency is in turn measured in terms of:
   a. Whether both the long term and short term resource requirements of the target-VM will be fulfilled in the target-PM.
   b. How non-intrusive a management action has been for other VMs that are already provisioned in the target-PM. That is, to what extent will the target-VM affect the performance of other VMs in the target-PM in terms of resource availability.
2. Number of times the management action has to be executed before the most-suitable PM is determined to live migrate/scale the target-VM to.

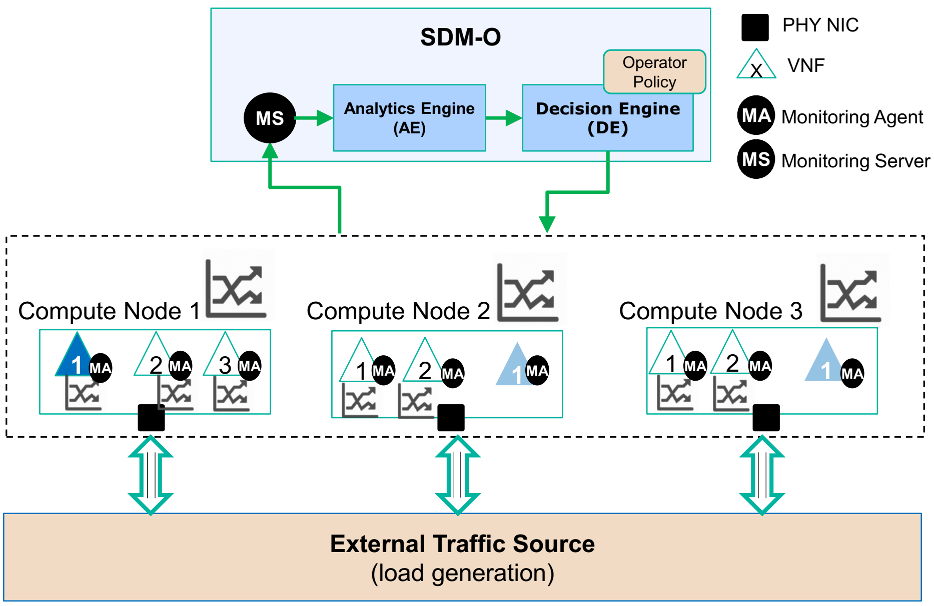


Figure 28 : PoC Testbed Overview

To analyze the QoD of RAVA based NS orchestration an experimental OpenStack [45] based test bed has been developed (see Figure 28) the details of which are provided in [43] . What is more important and relevant is to mention that the RAVA orchestration method has two main functional components namely the Analytics Engine (AE) and the Decision Engine (DE), which are proposed to be part of the SDM-O. The AE analyzes the RRAS reports for deriving AS and other necessary statistics, which are then fed to the DE. Based on the output of the AE and in view of the operator's policy, the DE makes relevant LCM decision for the VNF(s). These decisions are then translated into OpenStack commands and hence executed for the specified VNF(s).

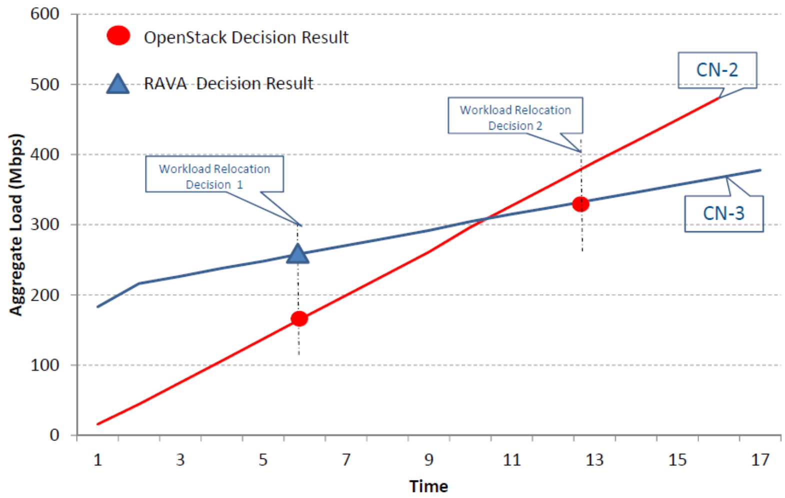
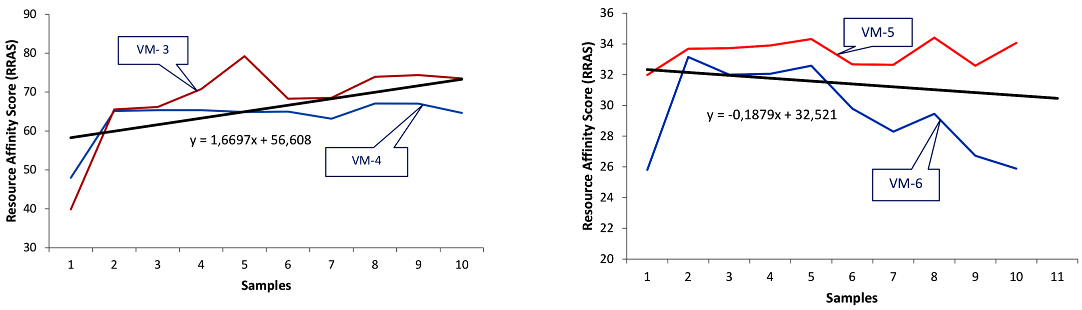


Figure 29: Load comparison between CN-2 and CN-3

In order to demonstrate RAVA capabilities, we emulated a scenario where a highly loaded I/O intensive VNF (target-VM) in compute node 1 (CN-1) is throttling the network I/O of existing VMs co-located in the same compute node (i.e., CN-1). The target-VM could be live migrated to one of the two available candidate compute nodes (i.e., CN-2 or CN-3) as both have the required I/O resources available to host the target-VM. At the time when the target-VM needs to be migrated, we observe the average network load on CN-2 is less than that on CN-3. This is depicted in Figure 29. However, at the time, the I/O utilization of VMs in CN-2 will have a strong correlation (or affinity) with the CPU utilization as opposed to the VMs in CN-3. Under normal scheduling policy rules employed in OpenStack, triggering a migration of target-VM will lead Nova Scheduler (OpenStack Computing scheduler component) to select CN-2 as node to migrate the target-VM to. Such decision is based on the assessment of the resource allocation ratio per compute node, dispatching the migration request to the less allocated compute node. This means the cloud controller overlooks the actual computational load posed by virtual resources, e.g., one or a set of VMs may be exhausting the network I/O capacity while still being within its allocated bandwidth limits. The cloud platform is not able to determine and predict the strong correlation of the I/O resource unit with the CPU resource unit for the VMs in CN-2. This will eventually overload the compute and network resources of CN-2. This is depicted in Figure 29 where the load utilization of CN-2 will increase beyond CN-3 soon afterwards. Thus, a default controller logic will be required to execute the migration of target-VM once more to CN-3. In other words, the QoD of the controller was not optimal.



(a) CN-2 (b) CN-3

Figure 30: Affinity Signature for the candidate compute nodes.

However, RAVA method will be able to determine and predict this strong correlation between the CPU utilization and the network I/O resource utilization of the VMs for the entire compute node pool. RAVA will also be able to determine that the VMs in CN-3 do not have such a strong affinity between CPU and I/O resource units. Thus, the controller will choose CN-3 over CN-2 as a host for the target-VM to live migrate to. This is illustrated in Figure 30, which shows the AS for the VMs in CN-2 (Figure 30(a)) and CN-3 (Figure 30(b)) respectively. As described before, the AS is a plot of the successive RRAS values, a RAVA metric that is utilized by the controller for making management decisions. The RAVA method will compute the linear regression expression for the average AS for both CN-2 and CN-3, which determines the degree of affinity between I/O and CPU RUs for the two candidate compute nodes based on the slope and y-intercept values. This is shown as a straight line in Figure 30 (a) and Figure 30 (b), depicting the straight-line equation. As noted, CN-2 has an increasing linear trend with a greater value of slope and y-intercept values when compared with CN-3. This indicates a very strong affinity of the I/O RU with the CPU, as opposed to CN-3, which has a slightly decreasing trend indicated by the negative slope and a smaller *y-intercept* value, thereby indicating a weaker affinity between the respective RUs. Thus, the controller will select CN-3 as a target-PM where to live migrate the target-VM because CN-3 will have resources available that will serve the resource requirements of target-VM on a long-term basis without any adverse impact on the performance of existing VMs in CN-3 (i.e., VM5 and VM6 respectively). This will ensure to keep the loads on CN-2 and CN-3 within preferred limits. Due to the strong correlation of I/O resource unit with CPU resource unit, the utilization of both I/O and CPU resource units of the VMs in CN-2 will continue to increase as opposed to CN-3 where it will remain almost constant after the target-VM has been migrated to CN-3. RAVA method thus clearly demonstrates enhancing the QoD of the SDM-O.

5.6.3 Next Steps

This work serves mainly as a high-level proof-of-concept on the potential impact of taking informed decisions on this context. The present model suffers some limitations (e.g., when Moving Average components of the signal does not increase/decrease monotonically) which will be tackled in the future work. As future work we propose to explore the time series analysis models [46] to properly assess the trends/seasonalities and the stationarity of the signal of correlated values, which are key to guarantee the robustness of our resource usage prediction schema (e.g., [47] [48]).

5.7 Shared Resource Management

This section proposes a method and processes to be executed between the building blocks SDM-O, SDM-X, and corresponding functions and entities related to SDM-C of a 5G NORMA architecture which are in charge of enabling efficient assignment of commonly available radio resources for multiple network slices.

The radio resource scheduler network function is separated into a VNF part controlled by the SDM-X (higher MAC scheduling, ICIC schemes) for asynchronous scheduling decisions and a V/P-NF part for synchronous scheduling decisions (lower MAC).

Radio resource scheduling for multiple network slices requires interaction between the SDM-X, SDM-O and the SDM-C based SLA/QoS Monitoring as proposed based on a message sequence chart illustrated in Figure 31:

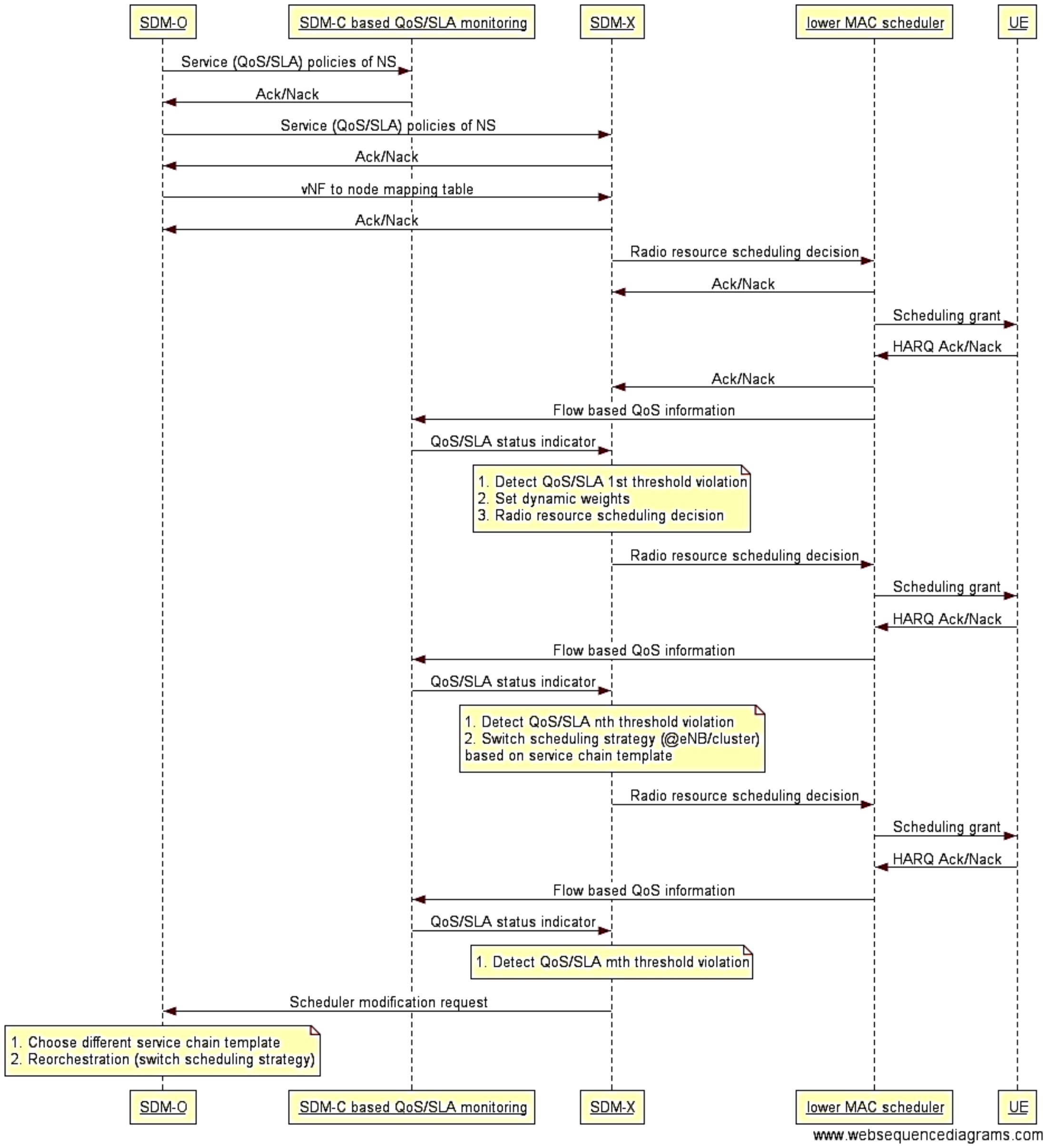


Figure 31: Radio resource scheduling process with the SDM-X

After the orchestrator (SDM-O) has set up at least one network slice on the physical infrastructure, service policies regarding QoS and SLA requirements for each logical network (slice) are transmitted to the SDM-C based monitoring entity as well as to the SDM-X. In addition, it is necessary to share additional information with the SDM-X, 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 de-/activate VNFs influencing the radio scheduling decision among shared resources.

The SDM-X is in charge of de-/activating ICIC schemes or asynchronous scheduling schemes based on the feedback of the slice specific SLA monitoring entity, which feedback an SLA status indicator per slice. Once multiple SLA indicators are received the SDM-X checks whether a threshold violation occurred based on previous scheduling decisions. Based on the analysis of slice specific threshold violation the SDM-X derives e.g., dynamic weights, which influence the upcoming scheduling decision on shared resources. This can be repeated several times to improve the SLA of a threated slice until a more critical threshold is violated. This triggers a mechanism which let the SDM-X switch the scheduling strategy based on the given service chain templates provided previously by the SDM-O. After adapting (de-/activating VNFs) e.g. the ICIC scheme or the scheduling metric, the SDM-X again derives an inter-slice scheduling decision which is considered by the lower MAC scheduler either in terms of dynamic QoS Class Identifiers (QCI) mapping or considering the SLA status indicator.

If the adaptation of the scheduling, ICIC scheme or the possible change of an e.g. eNB cluster does not result into an performance improvement for currently instantiated slices the SDM-X needs to send a modification request to the SDM-O which has to re-orchestrate the slices based on different service chain templates.

The most important characteristics of the proposed method are summarized again as follows:

- SDM-O provides V/P-NFs for lower and higher MAC scheduling and interference handling to the SDM-X (based on RRM data base with different flavored scheduling and ICIC strategies)
- SDM-X derives e.g. dynamic weights to influence the lower MAC scheduling decision based on monitoring results and occurring threshold violations within SDM-O arranged limitations
- Multi threshold based SLA monitoring to adapt scheduling/ICIC schemes, degrees of freedom based on service chain templates defined by the SDM-O and controlled by the SDM-X
- Indicate a necessary re-orchestration to the SDM-O before SLA violation occurs

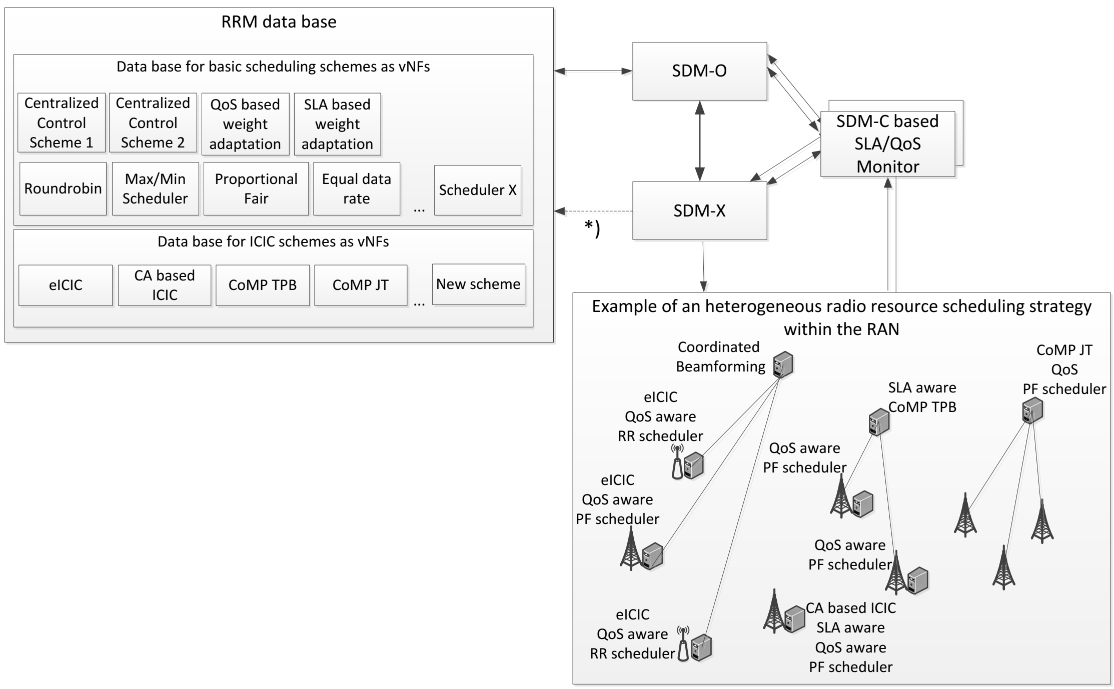


Figure 32: Example for an RRM database and a heterogeneous radio resource scheduling strategy

As described above the SDM-X is able to de-/activate VNFs to influence the scheduling scheme during the life cycle of a slice. In Figure 32 an example is shown how a heterogeneous scheduling strategy could look like within the RAN. Predefined complex service chain templates with RRM schemes based on a database the SDM-O sets up multiple slices while the SDM-X switches on/off parts of the template. The SDM-X might be even able to switch between scheduling strategies during the life cycle of several slices to improve the performance based on the monitoring entities' output.

However, the current investigations have left some open questions which will be further explored in the next phase of the project:

- The definition of possible SLA KPIs and SLA metrics (Mapping from SLA to QoS KPIs (e.g., QCI classes)).
    - A normalization of SLA metrics with different KPIs to monitor and fairly compare multiple slices is necessary.
- Two possible solutions to consider the SLA status within the MAC radio scheduler:
    - Introduce slice (SLA) status indicator to derive e.g., dynamic weights to prioritize scheduling decisions (e.g. for contradictory KPIs).
        - This will influence the communication with the lower MAC scheduler (Interface has to consider SLA indicator transmission to lower MAC scheduler).
    - Dynamic mapping to QCI classes based on SLA monitoring.
        - No communication with lower MAC scheduler necessary.
- Definition of complex service chain templates which need to support the possibility to activate/deactivate e.g. ICIC schemes by the SDM-X.
    - Will it be possible for the SDM-X to get access to the RRM database - w/o the SDM-O to react dynamically on changing requirements during life cycle (The assumption by now is, degrees of freedom given by service chain template, which is provided by the SDM-O)?
- Definition of the split between lower MAC scheduler (V/P-NF) and SDM-X controlled schemes based on time scale (synchronous and asynchronous P-/VNFs). How far can the radio resource scheduler be virtualized?
- Definition of the interface between SDM-X and lower MAC scheduler.

5.8 Constrained SFC sets

In this section the slice specific set-up of concatenated network functions (VNFs) as is orchestrated by SDM-O is addressed 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.

SFC issues detailed here cover the topic whether in a Multi-tenant scenario the end-to-end services described by SFCs/SFPs (including both VNFs and PNFs) the management shall be dynamically adapted (e.g. during session set-up) or pre-configured (e.g. during slice instantiation process). The latter approach would comprise a set of slice-specific SFCs/SFPs incl. service differentiation (e.g. eMBB slice with SFC for best effort internet access and constrained SFC / SFP for voice and audio-visual interactive communication with moderate latency and bandwidth constraints). Alternatively dedicated control protocols (adapted VNFs or SDM-C applications) will be involved when a new connection is established based on session context information. The proposed work shall extent the SFC SotA as described in section 9.12, also by enhancement of work addressed in the corresponding IETF WG.

The following describes SDM-O construction mechanisms for slice/service specific SFCs:

Chaining of PNFs and VNFs per service and network slice in an SFC aware way or via SFC proxies as specified in [49].

Comparing to the traditional cellular services above a typical 5G service or use case family with high service reliability or extreme low latency as required e.g. in Industry Control, Vehicular Communication and Real-time remote computing the definite demand for network slice adaptability is obvious with a view on the limited amount of (especially access and transport) resources. Then a constrained SFC or SFP has to be constructed considering the strict requirements. As specified in [49] the logical components of an SFC architecture comprise classifiers, Service Function Forwarders (SFFs), the Network or Service Functions (SFs) themselves, and SFC proxies. All these functionally distinct logical components are interconnected using the SFC encapsulation. A SFP is a mechanism used by service chaining to express the result of applying more granular policy and operational constraints to the abstract requirements of a SFC.

The orchestrated specific network function instantiation selection out of multiple locations for redundancy and/or low delay of transport and execution may have to be adapted dynamically in case of congestion/failure/or other situations due to which the originally selected path may no longer fulfill the request (or even be available).

In this case either a re-construction request to the SDM-O may be initiated by the SDM-C or the SFC App (as proposed e.g. by [50] with respect to the SDN Controller) or the SFC Control Plane (as proposed in [51]) conveys control information to the SF Forwarder for dynamic change of the path between the SFs. The decision on a usable path will be based on corresponding Metadata contained within the SFC Encapsulation header (NSH) which has to be pre-arranged during SFC construction.

Mapping and prioritization of SFs/NFs per characteristic and topology has to be provided for rapid look-up of an alternative SF/NF location in that case.

A potential visualization of such a chaining is derived from [52] where exemplarily support of edge computing is described on a high level. For provision of services over long distances in a cost-effective way, to reduce latency and reduce load on transport network the required functionality could be "deployed in flexible manner, leveraging also NFV".

The necessary functionalities (on both Control Plane (CP) and User Plane (UP) layer) to support such edge computing or ultra-low delay network slices include

- QoS
- Session/Mobility management
- Charging/Policy Control
- Optimisation (i.e. enabling selection and reselection of efficient UP paths / forwarding NFs)

The up to now agreed on (but not yet fully specified) reference points in a general architecture are shown in Figure 33 where CP and UP functions may consist of SFCs for control of issues as listed above and corresponding assurance/enforcement/anchoring of them on UP forwarding level.

As a first assumption, the Chaining of PNFs and VNFs is addressing UP only. For CP other principles may apply, e.g. publish/subscribe interface model for communication between them as also proposed in [53]. Such a dynamic asynchronous inter-component communication [54] allows various functional modules to interface by subscribing to messages submitted to a common network function. Such an NF may be e.g. the Message Routing and Forwarding Function (MRFF, as proposed in [52]) which is acting like an NF repository and eventually applying policy-driven load balancing.

As detailed above depending on slice/service performance requirements the SFC either specifies functional sequence only or decides on an SFP in detail with constrains to specific NF instantiations.

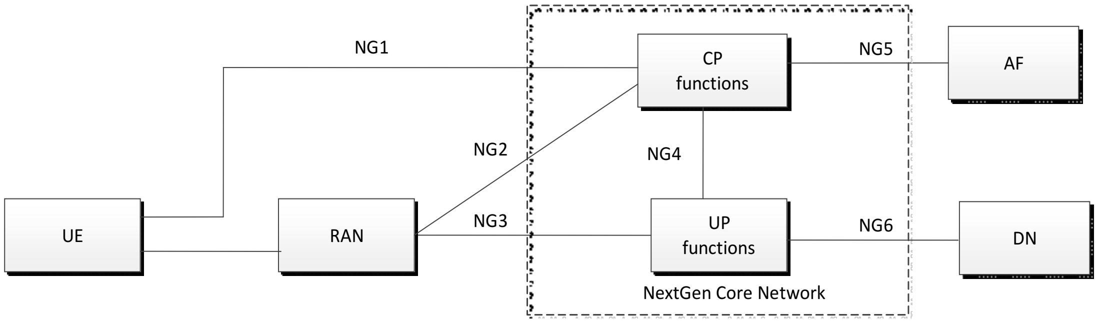


Figure 33: High level architecture and reference points for 3GPP next gen core network

Planned next steps are to evaluate expected performance difference of dynamic vs. pre-configured SFCs/SFPs construction (V/PNFs) for exemplary services. An individual IETF SFC draft (extension) is in progress which defines 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 [55]. 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 [56].

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 neighbored 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.

Those aspects as well as assessment of the potential of and detailed exemplary methods for dynamic SFC forwarding paths construction will be dealt with in the final version of this deliverable.

5.9 Slice hierarchical orchestration

5.9.1 4G toward 5G architecture evolution

New 5G services will require provision of extremely high throughput with ultra-low latency to users (e.g. to support 4K video streaming, Big Data), thus provide services as close as possible the user location may be a relevant solution. Mobile Edge Computing (MEC) proposed by ETSI presents the opportunity of dynamically instantiating services close to the end user in a edge cloud and imply massive and decentralized computing/storage/network resources, which will require processing and storage capabilities.

Moreover, the need of rapid adaptation of the networks to cope with changing demand coupled with the need to providing resource slices that aggregates computing, storage and network resources from operator(s) logical subdomains complete the 5G challenge.

In order to address these challenges the solution may be to leverage SDN and NFV as they purpose is to orchestrate VNFs on top of central cloud /edge cloud for the deployment of software functions. The figure below summarizes the evolution of actual 4G architecture toward potential 5G architecture

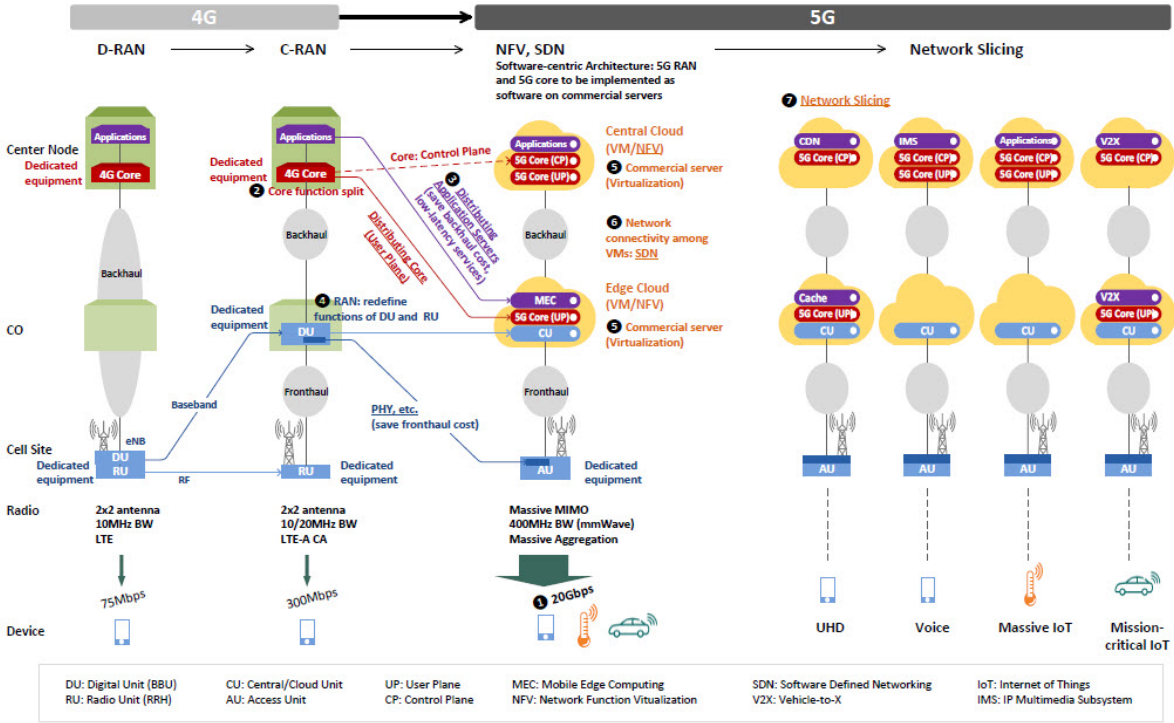


Figure 34: Network architecture evolution 4G toward 5G (source Netmanias)

5.9.2 Hierarchical VNF SDN orchestration for 5G networks

Today, 4G network is exploited through a centralized architecture. For 5G a cluster composed by compute, storage and networking resources managed by a orchestrator, VNFs will not be a self-contained in one cloud location system but relatively spread among central and edge cloud system in order to leverage MEC (see Figure 35).

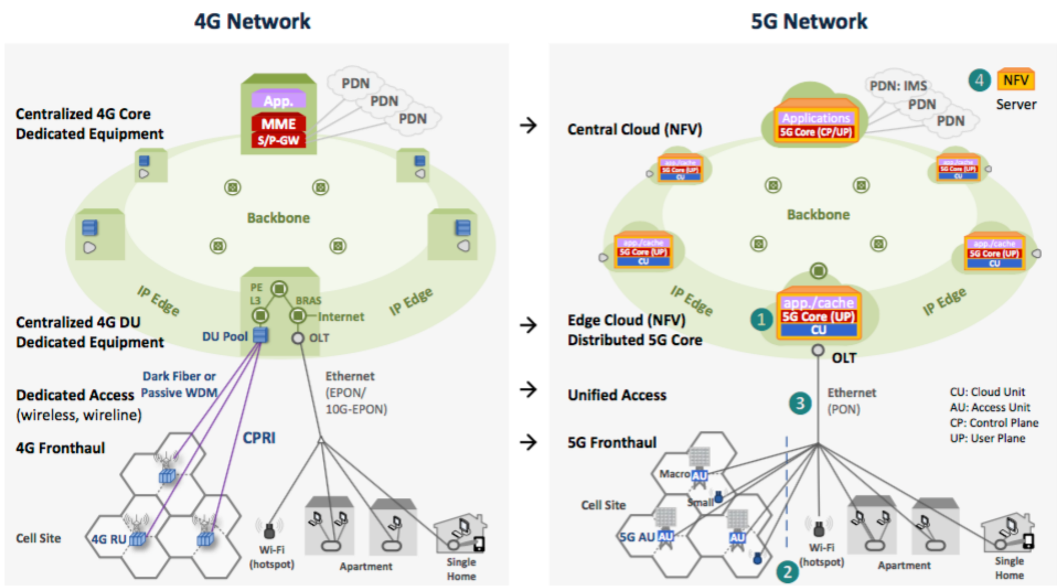


Figure 35: Potential 5G network topology (source Korea Telecom)

Cloud NFV management

Regarding NFV underlying cloud infrastructure that will enable MEC, which aimed supporting spread VNFs, can be identified by various architectural models, ranging from tightly coupled to highly dispersed ones:

- Multi-datacenter cluster with multiple, but tightly coupled data centers under control of the same provider.
- Loosely coupled multi-service cluster combine services from different cloud providers.
- Decentralized edge clusters utilize edge resources to provide data and compute resources in a highly dispersed manner.

For cloud NFV, this exhaustively regarding assets or constraints needed from cloud domains for 5G VNFs deployments (e.g. rightful location, resource availability, hardware/software specific features, pricing,..) will led to orchestrate VNFs with coordination through different clusters each managed by dedicated orchestrator:

- Need to automatically overflow workloads from local cluster to a remote cloud if the cluster run out of capacity
- Orchestrate/host privacy-sensitive services that must be run in a private local secured cluster
- Resiliency to private data center or cloud availability zone outage by spreading services across multiple zones and cloud providers.

SDN Network management

Regarding SDN, 5G services require the integration of all network segments (radio/fixed access, backhaul and core, see Figure 36) with heterogeneous wireless and optical technologies. A hierarchical control approach for scalability, modularity, and security purposes in multi-technology multi-domain heterogeneous wireless/optical networks can be relevant as in Figure 36)

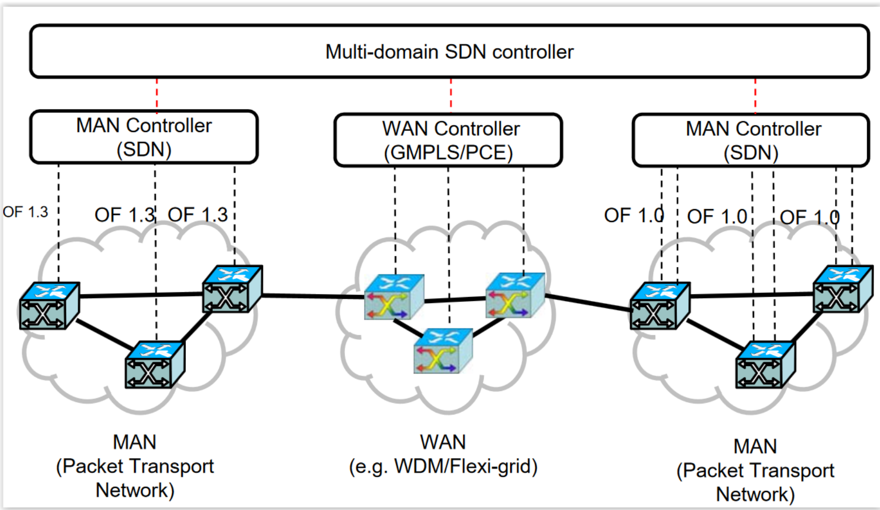


Figure 36: Multi-domain SDN orchestrator (source COMBO, 5G Xcrosshaul)

The cloud and network domains needed to fulfill 5G VNFs deployments/orchestration will be implemented on several clusters and SDN segments, where each of them managed by dedicated orchestrators. Management of this orchestration heterogeneity may be solved with a hierarchical orchestration that can guarantee orchestration consistency by applying federation among orchestrators (Figure 37)

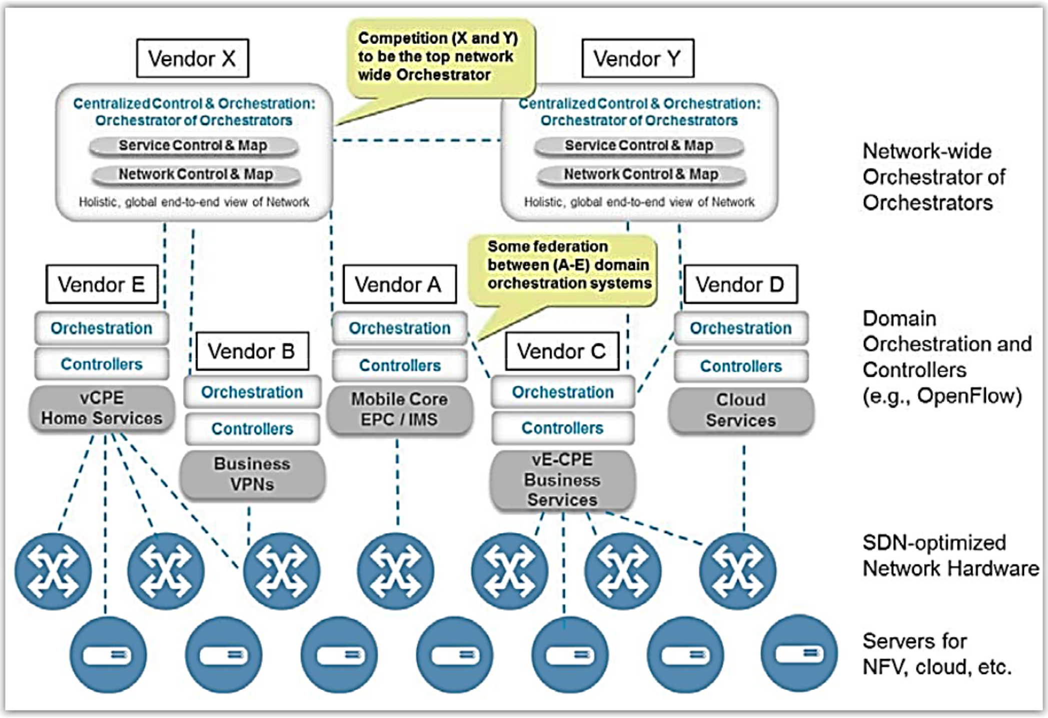


Figure 37: 2017–2020 Orchestration Evolution toward an Orchestrator of Orchestrators (source Infonetics)

5.10 Edge Cloud MANO

Some of the VNFs controlled by the 5G-NORMA defined hierarchy of controllers (SDM-C, SDM-X, SDM-O) will be deployed on an Edge Cloud infrastructure. However, definition of an NFV infrastructure layer tailored for the Edge Cloud has not been yet addressed by the industry. Equipment manufacturers are proposing for this purpose the same kind of datacenter architectures typically used for centralized cloud environments, assuming large numbers of servers, a very high footprint and an environment totally separate (physically and administratively) from the transport network used to connect the datacenters. As such, these datacenter architectures, shown in Figure 38, assume:

- an external hardware-based Provider Edge router (PE) (typically an MPLS PE) run by the transport operator
- a hardware-based Datacenter Gateway router (DC-GW) to connect the datacenters in an overlay fashion over the transport network, many times using the same technologies used in the transport network but transparently to it (e.g. L3 MPLS VPNs over GRE tunneling)
- a local leaf and spine switching architecture based on hardware
- the x86 compute nodes to run VNFs
- local x86 servers to run the VIM and SDN controller functions

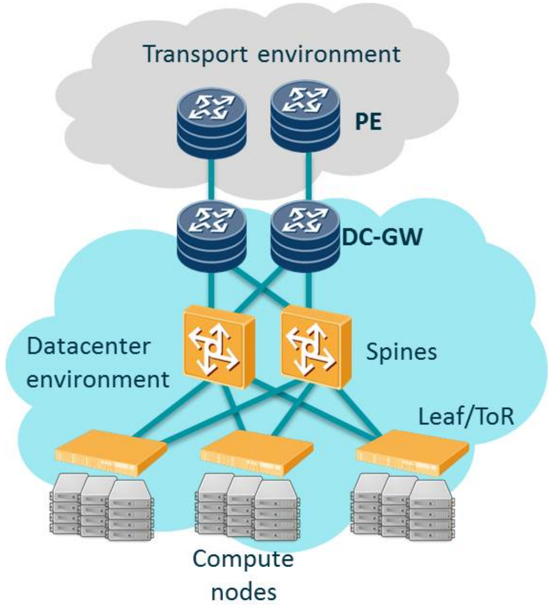


Figure 38: Typical datacenter reference architecture

It can be overkill in terms of costs and operations to consider this cloud reference architecture to deploy VNFs distributed to the network edge. It has to be taken into account that Edge Cloud deployment will not be from scratch, but it will very likely leverage on the existing network deployment of the operator. In that scenario for these edge locations, there will likely be already a PE and the need for compute nodes may be in line with the number of physical ports supported by this PE. Therefore, there might not be a real need (in terms of number of Ethernet ports or because of administrative demarcation) to force the inclusion of a DC-GW and a leaf-and-spine switching fabric in all the cases.

In order to allow for NFV deployments as distributed as the Mobile Station level, a more flexible network PoP reference architecture is required to cater for a more collapsed cloud architecture be possible, for instance considering as an option to have just the PE element as connectivity fabric core in an Edge Cloud PoP, as is shown in Figure 39.

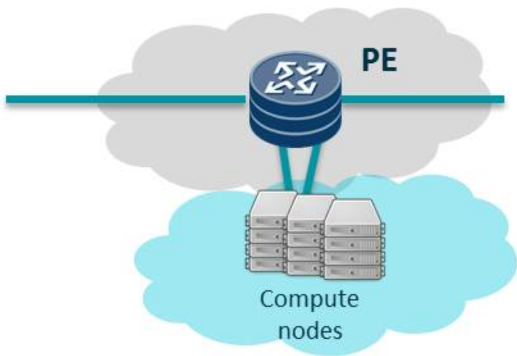


Figure 39: Collapsed edge cloud architecture

On the other hand, because of the performance required by data plane VNFs, they will typically use Single Root Input/Output Virtualization (SR-IOV) or PCI-Passthrough virtual interfaces to achieve the expected performance, instead of interfaces through the Virtual Switch (vSwitch) local to the hypervisor. However, most MANO implementations are limited to work with vSwitch interfaces and therefore the SDN controller solution packed with the MANO implementation is limited to the support of the underlay technologies supported by the vSwitch (e.g. VXLAN, VLAN, MPLSoGRE) and its configuration management interfaces (Openflow and Open vSwitch Database (OVSDB)). Integration of VNFs with SR-IOV and PCI-Passthrough interfaces at the MANO level is not widely supported but is a must requirement to address data plane VNFs. In addition to this, in the case of SR-IOV and PCI-Passthrough interfaces, the overlay technology imposed is VLAN based, but it has to be taken into account that in order to allow for a collapsed Edge Cloud PoP, the underlay used must also be in line with the technologies supported by the Edge Cloud PE (e.g. MPLS IP VPNs, VPLS or EVPN) and not be limited to the vSwitch networking technologies.

5.10.1 Edge Cloud Infrastructure High Level Requirements

Defining a complex and elaborate service orchestration framework, as the one proposed in 5G-NORMA, requires to have ready an Edge Cloud infrastructure layer, because otherwise 5G-NORMA innovations would never be possible to be deployed in the field because of economic and operational barriers. In order to account for a grow-as-you-need approach, and to match different levels of NFV compute needs at the different network levels (edge cloud vs. network cloud), 5G-NORMA architecture considers an NFV infrastructure and MANO layer to be used that meets the following design recommendations:

- Edge Cloud Point of Presence (Edge Cloud PoP) must count with an element (Edge Cloud PE), typically based on hardware with the current state of the art, that allows for acting as provider of Layer 2 and Layer 3 network services. These L2 and L3 services will provide connectivity to external legacy services, as it is done in the current network deployment, and also these services will be used as an underlay for the NFV infrastructure to connect VNFs intra-PoP (inside an Edge Cloud PoP) and inter-PoP (to another Edge Cloud PoP or to a Network Edge PoP). This Edge Cloud PE could consolidate other functions related to Layer 1 and 0 technologies applicable to the PoP location (IP-optical convergence, synchronization protocols support, etc.)
- It must be possible to connect the NFV servers directly to the Edge Cloud PE
- It must be also possible to connect NFV servers to the Edge Cloud PE through a typical datacenter architecture comprising a DC-GW layer and a leaf-and-spine switching layer. That way the MANO infrastructure can be shared between the cloud and network edge.
- It must be possible to automate the underlay interconnection of VNFs (intra and inter Edge Cloud PoP). As such the Edge Cloud PE must be programmable, favoring (official or de facto) standard data models to account for this programmability. The automation of the NFV undelay connections must be possible to be orchestrated with the automation of the overlay connections running on top of it and as part of a service chain creation.
- It must be possible to interconnect VNFs (intra and inter PoP) using virtio, SR-IOV and PCI passthrough virtual interfaces regardless of the kind of virtual interface on the other end.
- It must be possible to run the rest of the ETSI-NFV architecture elements (e.g. NFV MANO) centralized externally to the Edge Cloud PoP

Taking these requirements as a starting point, several implementation possibilities arise in terms of the networking protocols used to provide the underlay network services to the VNFs, taking into account on one hand its support in current (legacy) network equipment and on the other the evolution of networking protocols for achieving optimized datacenter interconnections. With this knowledge, it will be possible to have a prioritized list of the underlays that are required for an Edge Cloud MANO solution suitable for 5G-NORMA innovations.

The following technologies can be considered as underlay technologies of an Edge Cloud infrastructure layer:

- Candidate legacy technologies:
  - Layer 3 MPLS VPN over MPLS
  - Layer 3 MPLS VPN over GRE
  - Layer 2 VPLS VPN
  - EVPN over MPLS
  - VLAN switching

- Evolutionary technologies:
  - EVPN over VXLAN
  - VXLAN switching
  - Openflow switching

5.10.2 Edge Cloud Underlay Technologies Orchestration

In order for achieving the flexibility and dynamicity required by 5G-NORMA architecture, Edge Cloud NFV infrastructure resources must be orchestrated and the orchestration capabilities must be exposed to the rest of the modules of the 5G-NORMA architecture.

In order to have a prioritized list of the underlay technologies to be supported in the 5G-NORMA Edge Cloud MANO resource orchestration reference solution, the different underlay solutions must be assessed in terms of:

- Its capabilities for high availability and load balancing
- Ease of connection/interworking with legacy network environments
- Its support in existing vSwitches
- Existence of a standard (formal or de facto) data model for the underlay technology
- Existence of native management and monitoring protocols for the underlay technology
- Its support in existing SDN controllers
- Its support in existing VIMs
- Its support in existing resource orchestrators

5.10.3 VIM capabilities for VNF deployments

Effective network slice deployment in 5G NORMA architecture require an appropriate handling of data plane workloads, to guarantee end to end high and predictable performance at each slice.

Appropriate handling of workloads, require that VIM possesses a greater awareness of the capabilities of the platforms it controls. This awareness of the underlying infrastructure is referred to as Enhanced Platform Awareness (EPA) that aims to provide the VIM with all the required information, and control, to be able to take the adequate decisions in terms of VM placement and connectivity establishment.

Current SDN controllers provide all necessary support to NFV, but it is also required that at VIM level this support is required, so that SDN controller may be correctly instructed on the operations to execute

Among the different alternatives for Virtual Infrastructure Managers, Openstack has grown into one of the most solid candidates, due its open source nature and its wide support in the IT community.

Currently, there are several gaps in Openstack for NFV applications that prevent an effective deployment of high performance virtualized network functions. This section will center on those related to SDN connectivity, which need to be closed in order to build an effective orchestration by SDM-C and SDM-O.

Data plane Interface:

- Some VNFs, due to its role, might be expecting to manage VLANs (e.g. a PE router) or QinQ tags (e.g. BNG). Support for L2 services in 5G NORMA would require support of this type traffic at VIM level

Support for PCIE SR-IOV or PCI-Pass-through:

- SR-IOV and PCI- Pass-through are mechanisms to bypass hypervisor and S.O, layers and remove abstraction layers between VNF and the Network Interface Card (NIC), increasing bandwidth and latency performance and predictability. Current Openstack version neither provide support for SR-IOV nor for PCI-PT to provide fully automated connectivity from VMs virtualized I/O interfaces to underlay data-plane networks.

SR-IOV limitations

- Bandwidth scheduling. 5G NORMA data plane applications require, among other parameters, specifying bandwidth requirements, to be scheduled and enforced accordingly.
- In NFV applications, SR-IOV permits to multiplex a single physical interface into several virtual interfaces called Virtual Functions or SR-IOV interfaces. The traffic discrimination is done at the NIC based on the VLAN tag (one VLAN tag per Virtual Function). BW required for each interface is a requirement specified in the VNF descriptor. From the information contained in the VNF descriptor, SR-IOV will multiplex a single physical interface into several virtual interfaces called VFs or SR-IOV interfaces. The number of actually used VF in a physical interface depends on the actual BW reserved for each VF and the total bandwidth of the physical interface. When searching a host to deploy a VM, Nova scheduler should take into account the amount of bandwidth reserved by the previous VMs on each physical interface. Today, bandwidth is not taken into consideration.
- Enforcement (coupled to previous limitation):
- With today's NICs, it is possible to configure each VF in a NIC to limit the upstream and downstream bandwidth, thus avoiding that one VF saturates the whole physical interface. In order to avoid that one VF saturates other VFs in the same physical interface, it would be required that, when an instance is created, the NIC is configured appropriately to enforce the bandwidth required on the VF.
- Interface assignment: BW occupied on each physical interface is an important driver for host selection. It might make sense for nova to have some policy that permits to discriminate the host to deploy depending on the requirements from the orchestrator (i.e., deploying on a host whose physical interfaces have less available bandwidth in order to make a better use of the network resources, or deploying on a host with more available bandwidth to permit for future growth without the need to scale-out or re-deploy VM due to traffic growth).
- Dynamicity. Currently, bandwidth assigned to SR-IOV VFs are specified in the in the VNF descriptor, at creation time. There should be a mechanism to modify this bandwidth in run-time

Full support of connectivity types for underlay L2 connections:

- In NFV, it is required to connect through the underlay switching infrastructure any number of VMs using PF pass-through or SR-IOV interfaces. In addition, it is also required to connect in the same network any other external element such as a physical network node or a physical network (e.g. to connect a VM to the Metro Area Network. These physical network nodes or physical networks are expected to be attached to switch ports in the underlay switching infrastructure, through point-to-point (E-LINE) or multipoint (E-LAN) L2 networks
- Openstack integrates an Modular Layer 2 (ML2) plugin in neutron able to interwork with an SDN controller that automatically configures all connectivity. Today, ML2 plugin presents limitations, in the way that this connectivity is performed.
- Moreover, this connectivity should make an efficient consumption of forwarding rules sin the switching infrastructure (minimize MAC learning requirements), e.g. in a E-LAN point to multipoint network, one of the ports of the E-LAN networks can be configured as default upstream port so that any packet being sent to an unknown MAC address is forwarded through that port. This might alleviate the number of forwarding rules in the switching infrastructure. In the case of connection of external elements (physical network node, physical network), Openstack might require the definition of a neutron port bound to the specific switch port where the external element is attached.

6 QoS/QoE Service Control

6.1 Introduction

One of 5G NORMA ambitions is to design a framework to control end-to-end QoE/QoS. For that, a SDM-C building block is designed. The proposed approach resembles SDN in that we split mobile network functionality into *(i)* those functions that are being 'controlled'; and *(ii)* those functions that 'control' the overall network and are executed at the controller. However, our solution is specifically devised to control mobile network functionality, and "controlled" functions are not limited to data plane functions but also control plane functions, both of which can be placed arbitrarily in the edge cloud or the central cloud. It is essential to specify an interface between the controller and the functions that (i) is standardized and supported by all deployed equipment, and (ii) provides sufficient flexibility to obtain the desired behaviour of the network by reprogramming the behaviour of "control" functions only. This effectively provides network programmability capabilities allowing third parties, i.e. virtual operators and vertical market players such as OTT providers or Vehicle-to-Anything (V2X) operators, to request network resources on-demand.

Indeed, wireless networks comprise a mix of functions e.g. scheduling, power control, which have a stringent real time requirement (executed at 1ms level) and others functions e.g. pre-scheduling, Deep Packet Inspection... which are executed at much longer time scale e.g. ~seconds. These timing constraints are considered in the software defined approach design. Not all control functions in RAN domain could be executed as applications in the northbound of the controller due to real timing requirements like MCS selection, scheduling, etc except when the technology allows that e.g. accelerated controllers. The centralized control provides very important benefits for the operation of the mobile network in terms of re-programmability and supporting the required flexibility.

In this section, we describe how an efficient QoE/QoS control framework is built using the SDM-C concept. SDM-C will interact via dedicated plug-ins in the SBI with the VNFs to control their configuration and their resources. The control will rely on a couple of applications running in the NBI using the 5GNORMA-SDMC-Apps interface. Three applications are proposed. Two applications target to enhance the throughput of the RAN and the third one is related to selecting the best path to connect the different VNFs. This allows us to have a design of a controller able to span the network slice in an end-to-end way as it is targeted in 5G NORMA. Each network slice will have its SDM-C instance, which jointly with SDM-O work hand in hand to guarantee the SLA negotiated with the service layer. Mobility related applications are described in Section 7.

In order to optimize the network resource utilisation, continuous monitoring of the QoS and QoE levels for each service flow is required. Monitoring will be implemented at different processing points in the network collecting measurements related to the behaviour of the network or the service. These measurements are fed into a QoE model, responsible for modelling the QoE. Thanks to the latter mechanisms, 5G NORMA supports a fully dynamic, context aware QoE/QoS management that is able to detect the applications and their QoS/QoE requirements and adapt the end-to-end resource allocation and the data plane services accordingly, thus enabling good customer experience.

6.2 QoS/QoE mapping

6.2.1 Introduction.

5G systems are expected to support emerging use cases with specific and sometimes critical requirements. Examples of expected new services are: IoT (including mission critical), vehicle-to-vehicle/infrastructure (V2X) communication, tactile Internet, sensor networks and others with high end-user quality requirements. So, 5G Networks (5GN) should try to support context aware quality service management enabling a good EU experience. A way to get this is, of course, designing an efficient architecture and providing enough resources; another way is, somehow, to integrate information about users experience and use it to optimize the allocation of available resources. Besides, getting data about users experience is one of the main priorities for MNO's in order to avoid churn [57].

Regarding users experience two key concepts are usually referred: QoS and QoE. As a whole, QoS refers the degree of adequacy of the service to a number of physical measurable objective parameters (e.g.: latency, delay or jitter); QoE refers "the overall acceptability of an application or service, as perceived *subjectively* by the end-user" [58]. And that is the challenge: under same physical QoS factors different users could experience the service in different ways; or even the same user could perceive services differently under different mood or circumstances (i.e.: in noisy environments a service could be perceived in a different way even with the same physical QoS parameters).

The most evident way to overcome this is considering, not only QoS metrics, but the human influence factors also (mood, environment, terminal type…). However, measuring human perception is a complex task (just a probe in the users brain measuring their thoughts could give us that information, but this, beyond ethical considerations, is still several G's away from a strictly technical point of view). Although challenging, this difficulty can be overcome integrating the human influencing factors in a user-centric information system. So, although the direct measurement of QoE is not possible, it is something we can guess with some degree of accuracy by mapping a set of relevant QoS parameters and influence factors with an estimated QoE value. This is what we call "QoS/QoE mapping".

Since we are trying to guess the users subjective experience, QoS/QoE mapping is not an exact science, just a best engineering effort. Anyway, inferencing QoE can help providing a better user experience, and also, allowing MNO's to allocate resources in a more efficient way. The challenge is to keep users satisfied allocating the minimal resources for that purpose.

Considering this, two key questions should be addressed:

- How can we infer the user experience in a proper way?
- How to adapt the network to improve QoE without wasting excess resources?

1st question is more theoretical, and still an active research area. You can get an approach to this in Section 9.14 where we describe the basic concepts about QoS/QoE mapping and summarize the state of the art. The 2nd question is more technical, and for our purposes, the answer will be provided considering our 5GN architecture. This will be addressed in the following sections.

6.2.2 QoS/QoE Mapping in 5G NORMA

6.2.2.1 Introduction

Although correct, the general approach of getting QoE just by computing a mapping function from a set of input parameters, is quite simplistic when we must consider how to integrate this functionality from a practical viewpoint in the 5G NORMA architecture. When considering practical aspects this problem may require very different resources and capacities depending on the specific way the problem arises. For instance, it is quite different to get a QoE metric for a single VNF from just a couple of objective parameters (e.g., CPU occupancy and RAM usage), or getting QoE for a big set of individual end users in real-time considering a specific geofence and using a big set of objective and subjective parameters which can be difficult to monitor.

For the first case, a simple threshold function could be probably enough, while for the second one, we probably would require a complex infrastructure with DPI and Big Data Analytics capabilities. Of course, between these two bounds we could find a wide range of possibilities.

Some tenants using the 5GN infrastructure could require just QoS monitoring as it is performed in the current LTE architecture, while others could ask for more advanced approaches; so, if we want to address the problem from a general point of view we should consider how this wide range of possibilities could be supported on 5G NORMA.

On the other hand, as we can see in Section 9.14 , the issue of the QoS/QoE Mapping is still an active research area, different approaches to solve the problem exist (objective/subjective, intrusive/non-intrusive, different approaches to get the mapping functions, etc.). Besides, identification of service relevant QoE metrics and modelling of how these are affected by different QoS metrics is a key aspect, but this is application and service dependent: No general rule can be applied for this. QoE measurements could require a deep understanding of the specific KPI impacting on the user perception, but KPI's vary with the service type; for example: services like VoIP, Video streaming, On-line gaming or Internet browsing has unique performance indicators to measure. Other services, such traditional voice or messaging services have other specific KPI's. So, for 5GN we could select a set of relevant KPI's and a specific mapping function to compute QoE, but we would run the risk of delivering a too rigid architecture unable to manage certain tenants requirements or to include certain technical advances regarding QoS/QoE processing.

In summary, it is difficult to consider the specific QoS/QoE control requirements of all possible tenants and to think on all-network scalability on the medium term. For this reason, instead of defining a too specific solution, we consider a better approach to define an open framework, which can be adopted by different tenants in order to provide sufficient flexibility to obtain the desired behaviour by reprogramming the required functions. Therefore, instead of a specific mapping function and a specific set of strictly defined functional blocks, our objective here will be to provide 5GN with a flexible way to implement the necessary QoS/QoE Mapping functions using open interfaces and the flexible selection of functional blocks to integrate the specific requirements for each user. This effectively will provide network programmability capabilities allowing third parties (i.e. virtual operators and vertical market players) to set-up their specific QoS/QoE control strategies. Besides, this will also enables a path towards future approaches and strategies to focus the QoS/QoE mapping problem.

On this basis, we propose the following general requirements for the QoS/QoE mapping block:

- It must provide an open framework allowing the integration of different solutions in function of the specific requirements of each tenant (e.g., must allow both: monitor the individual user experience as well as objective network QoS parameters).
- It should be featured to use KPIs from different network elements (DPI nodes, mobile terminals, eNodeB or other network elements). The set of KPIs to use is not restricted; it should be possible to define them in an open way in the scope of each tenant SLA.
- It must be possible to integrate different mapping functions and execute them in parallel (i.e., each tenant may require a different function with different features & parameters).
- It should be based on open interfaces through which it should be possible to flexibly specify the parameters to monitor, the mapping function and the way the output (QoE) is delivered.
- In order to optimize the network resources usage, it should be possible (if required by a tenant) the continuous monitoring of the QoS and QoE levels for each service.

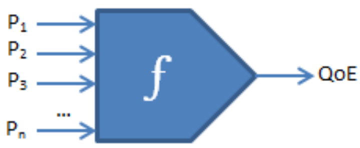


Figure 40: Basic Mapping Function

6.2.2.2 High Level approach

Said in a very general way our problem is how to integrate a basic QoS/QoE Mapping block in our specific 5GN architecture fulfilling the requirements described in the previous section.

A first high-level consideration is that we are not going to have just a single mapping function; we should be able to support the execution of different mapping functions in parallel. Therefore, a first evolution of the simplistic approach in Figure 40 above should be something like shown in Figure 41.

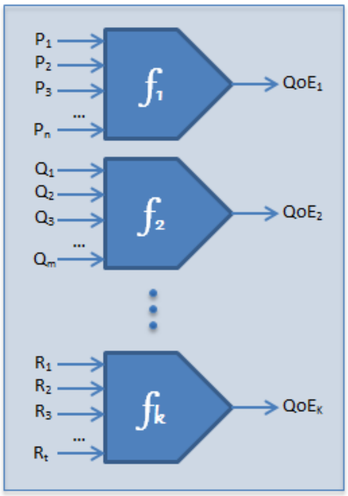


Figure 41: Mapping functions executed in parallel

That is, we should be able to process different mapping functions with a different input parameters set in parallel. Every function would provide a different QoE measurement.

Another high-level consideration is about input parameters. We could have input parameters from different sources and expressed in a very different way. For example, we could require to the same mapping function to process parameters such as the jitter expressed as a real number or the user mobile terminal type defined as a text string. Input parameters source can be diverse: radio stack parameters, profile users databases, billing information etc., and the parameters format can be different depending on specific encoding schemas. This makes necessary a normalization layer prior to the mapping function itself. So, a second step in these high-level considerations could be to add this normalization layer for each mapping function; also in a similar way, we should have the possibility to normalize the QoE output values using specific coding schemas (i.e., the resulting QoE could be needed according the legacy Mean Opinion Score (MOS) quantization scale, or using real numbers according a sigmoid function). Figure 42 below shows the addition of these elements for each mapping function; $N_1...N_k$ represent the input normalization functions, while $C_1...C_k$ are the output codification functions.

Another important point about integrating the QoS/QoE mapping functions into the 5GN architecture is the relationship with other functional blocks. Two blocks for which it is required a closer relationship are obviously the QoS/QoE Management and the QoS/QoE Monitoring blocks. The first one provides the definition of the QoS/QoE input parameters agreed in the SLA for a tenant, allowing also to configure the different parameters in our mapping module:

- Number and type of the different mapping functions. Depending on the specific function to be used (objective/subjective approach, etc.) the configuration will be different.
- The corresponding input parameters normalization functions.
- The output encoding functions
- The set of input parameters to which each mapping function should be bounded

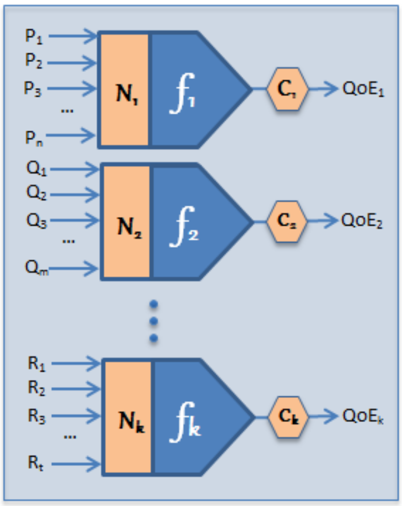


Figure 42: Normalization and Output Codecs

On the other hand, the QoS/QoE Monitoring function will be in charge of monitoring the selected input parameters. Specific configuration parameters should be provided in the SLA; for example: required sampling frequency or monitoring strategy (e.g., reactive, proactive, hybrid).

This block must be prepared to receive messages from our mapping module, and to execute the proper actions for each case (the SDM-C will receive these messages by its South-Bound Interface (SBI)). We understand these actions are basically to interact with the virtual infrastructure to request scaling operations for each single VNF or the forwarding graph update. Figure 43 shows the evolution of the high-level design considering these interfaces.

As shown, we can consider then that the QoS/QoE Mapping block has three main interfaces:

- A NBI to communicate with the QoS/QoE Management Module. It will be used to configure the mapping module parameters as previously said (specific functions to use, input parameters, etc.). It is assumed that the QoS/QoE Management module keeps also a close relationship with the QoS/QoE Monitoring module to configure the parameters to monitor and the way each parameter should be monitored (i.e., the monitoring module output and the mapping module input should be perfectly aligned). In addition, it is assumed that the QoS/QoE Management module will be part of the Management & Orchestration Layer in the 5G NORMA functional architecture.
- A West-Bound Interface (WBI) to receive data from the QoS/QoE Monitoring module. As we see, it is assumed the monitoring module gathers information from different sources in the network that can be relevant for the network itself or the service (e.g., user's terminal, RAN, different databases containing user's data or the virtual infrastructure among others). Continuous monitoring of the different parameters of interest will be required.
- An East-Bound Interface (EBI) to send relevant QoS/QoE Mapping events towards the SDM-C module. The SDM-C controls functions and resources for a specific slice, so the QoS/QoE mapping module will continuously analyse the status of a network slice according the SLA constraints, and will report about QoS/QoE relevant events towards the SDM-C. Based on those reports the SDM-C may adapt to the new situation in different ways:

    - By reconfiguring some of the VNF's it manages (i.e., changing the pre-scheduler, asking for a less aggressive Modulation and coding scheme (MCS)).
    - Notifying the QoS/QoE Management module when specific management operations are needed.
    - Reconfiguring some paths using a SDN-alike technique

- Asking for more resources to the orchestrator. In this case, network slice reshaping (i.e., scale in/out) or VNF relocation policies should be managed by the orchestrator.

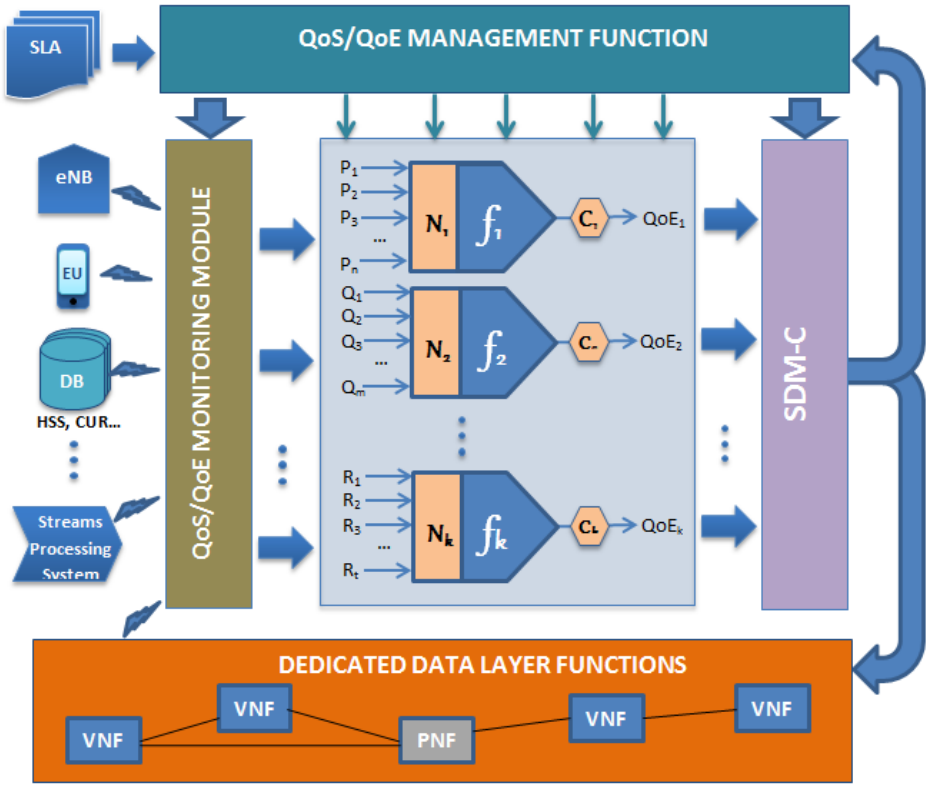


Figure 43: Interface with surrounding systems

Note that no direct connection between the QoS/QoE Mapping module and the underlying virtual (or physical) infrastructure is necessary. We assume the SDM-C will work as proxy for this. As we know, we have an SDM-C instance per network slice. The SDM-C will interact via dedicated plug-ins with the VNFs to control their configuration and resources.

6.2.2.3 QoS/QoE Mapping Module Building Blocks

Until now, we have provided a high-level description of the QoS/QoE Mapping module and the other blocks to which it has to communicate. The question now is; How could we design the interfaces to those other systems? The main problem regarding this is that, as we know, the QoS/QoE Mapping module function is intentionally not fully defined. As commented, we think that it is better to provide an open framework able to integrate different ways of implementing the required mapping functions. So, if the QoS/QoE Mapping function is something not clearly defined then how could we define a specific set of interfaces to it?

The different mapping functions we would like to integrate in the QoS/QoE Mapping module will be, after all, certain pieces of software code freely defined by the user (i.e, the tenant or the infrastructure manager). They could be something like simple threshold functions, or perhaps something more complex like a Multilayer Perceptron already trained with the corresponding weights matrix. However, they will be certain algorithms devised to compute the desired QoE value.

Hence, our problem here is related to *software deployment*. We need to *deploy* certain software functions (our QoS/QoE Mapping functions) which can be freely defined by users into our QoS/QoE Mapping system. As a whole, SW deployment is about all the activities that make a software system available for use; for us that “software system” is the mapping functions and the associated resources (normalization functions, input parameters, output encoders, etc.).

Focusing the problem as a software deployment issue, we can answer our original question: the way to design the interfaces to the other systems surrounding the QoS/QoE Module. The software industry already provides a well-known solution to deploy and integrate indeterminate (to a certain degree) pieces of code using well-defined interfaces. The key ideas are:

- To provide a common execution environment (or software container),
- Considering this execution environment, the user provides the piece of code to be executed and a set of descriptor files with additional information for the execution.

An example of this approach could be the EJB specification, a subset of the well-known JEE specification, which includes a container for web related software components (JSR 345). The software components (EJB's) are deployed on a runtime environment using standardized interfaces. Another example specially designed for telco applications is the JAIN SLEE specification (JSR 240) where certain pieces of code (i.e., Service Building Blocks and Resource Adaptors) are deployed on a software components container. Other examples are also the Java Servlets Technology (JSR 315) or even the JAR files used in the Java Language (besides the Java code, JAR files should contain certain standardized deployment descriptors to properly run in the runtime environment).

At this point we are not proposing to use EJB's, Servlets or whatever other specific technology for our QoS/QoE Mapping module. These are just examples. What we propose here is to use the same conceptual approach. In our case, the pieces of code will be mainly the specific QoS/QoE Mapping functions, which will be deployed on a common execution environment according certain fixed rules.

To be more specific, and to be aligned with the description in the previous Figure 43, we propose to have three different components to be deployed:

- ***QoS/QoE Mapping functions:*** This is the mapping algorithm to execute. It can be written in a general-purpose programming language according the user requirements.
- ***Input Adapters:*** This module will gather the parameter values from the QoS/QoE Monitoring System. It could include also the Normalization stage before the mapping function.
- ***Output Adapters***: This is the mapping function output interface. It will encode the QoE according the required protocol.

These three types of components will be deployed in a common execution environment using the corresponding deployment interface. Each component could be assigned to a specific slice or tenant. Figure 44 below illustrates this general idea.

The yellow U-shaped block represents the "Software Container" that works as execution environment for the three possible deployable components: Input Adapters, Mapping Functions and Output Adapters. As previously commented, we see also the three main interfaces:

- NBI (North Bound Interface or Management Interface) which is used to communicate with the QoS/QoE Management Module in the 5GN Management and Orchestration Layer (see Section 3)
- WBI (West Bound Interface or Monitoring Interface), to receive incoming parameters from the QoS/QoE Monitoring System.
- EBI (Est Bound Interface), the output interface to send QoS/QoE Mapping relevant events towards the SDM-C. It connects with the South-Bound Interface in the SDM-C module.

In the following subsections we provide a high-level approach to these interfaces. We are not going to enter here in a fine-grained details regarding implementation (specific technology, exact number of parameters, parameters type/range or other similar details), but as initial approach, we will attempt to provide the basic operations that should be supported.

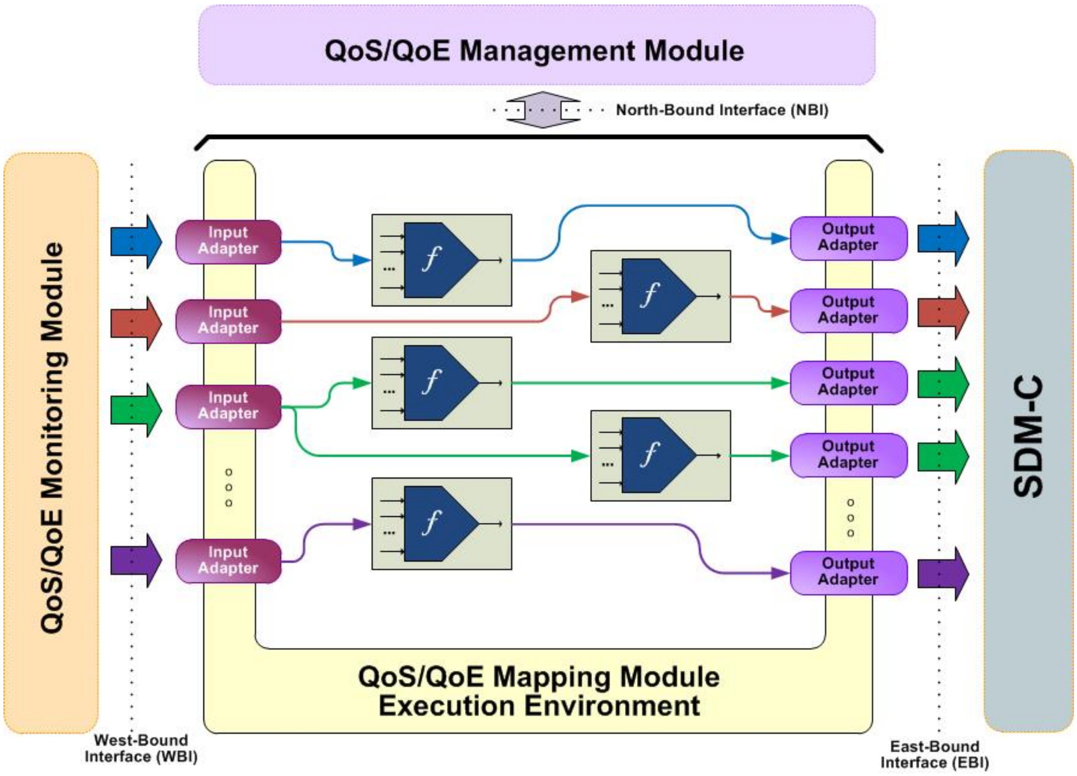


Figure 44: QoS/QoE Mapping Module Building Blocks

6.2.2.3.1 Management Interface

As mentioned, this interface is used for exchanges between the QoS/QoE Management block and our QoS/QoE Mapping block. The operations supported by this interfaces can be split in two groups: the specific operations for the Execution Environment and the operations for the Deployable Units. The following Table 6 and Table 7 show a list of possible operations for both:

Table 6: Operations for the Execution Environment

Operation Type	Description
`Configuration`	Get/Define the Execution Environment configuration. Explicit configuration parameters will depend on the underlying technology; they could be: – General purpose software configuration parameters (i.e. files location, hostnames, TCP/IP ports…), – Logging facilities configuration – Physical parameters (memory, CPU…) – Security parameters (i.e., access policy)
`Management`	Activate/Deactivate the execution environment itself.
`Licensing`	Install, remove and view the Execution Environment license(s).
`Query`	Query about status of the execution environment. This could include: – Current status (running, stopped, error) – List of already deployed units and their status – Usage statistics

Table 7: Operations for the Deployable Units

Operation Type	Description
`Deployment`	Deploy/un-deploy supported deployable units (i.e., Mapping Functions and Input/Output adapters).

`Management`	Activate/Deactivate already deployed building blocks.
`Configuration`	Operations to configure the deployable units. This could be: – Number and type of inputs for the Input Adapters – Encoding scheme for the Output Adapters – Logging
`Bounding`	Bound/Unbound the different building blocks among them. For example, to connect a specific Input Adapter to a Mapping Function, and that Mapping Function to the desired Output Adapter.
`Licensing`	Install, remove and view the components license (if any).
`Query`	Query the status of deployed units (some status could be: running, stopped, error…). Information about the configuration status can be also provided.

The following sequence diagram (see Figure 45) shows what could be a typical operation to activate the platform and deploy a simple set with just three components: a mapping function and the corresponding input/output adapters:

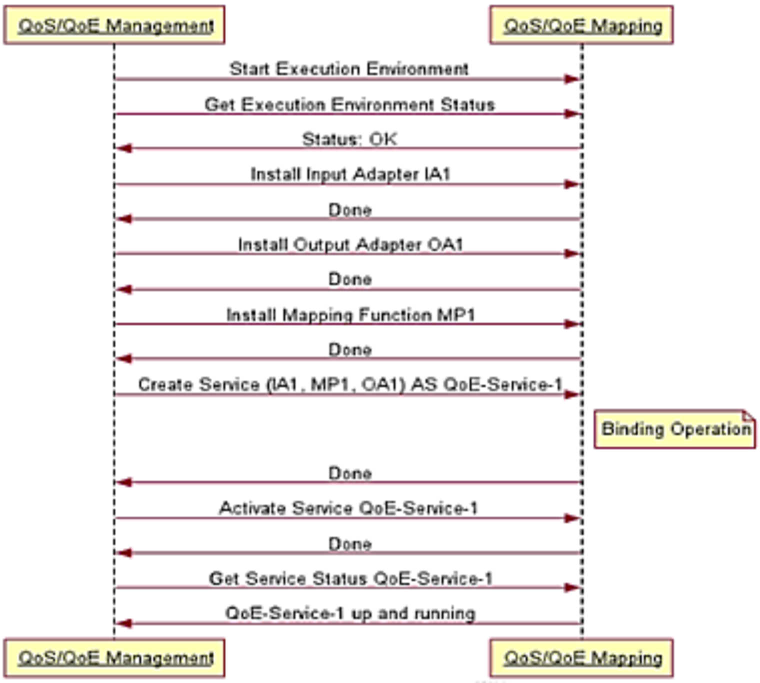


Figure 45: QoS/QoE Mapping/Management Modules Interface Example

Of course, for something like this to work it would be necessary for each deployable unit to be generated containing the corresponding descriptor files. Those descriptor files should describe the peculiarities of each component; for example, for the Input Adapters, the descriptor files will probably enumerate the different input they will receive from the monitoring system, the sample period for each parameter, ports and host to connect, encoding protocols, etc. Descriptor files could be encoded using broadly accepted languages such XML or JSON.

Figure 46 shows an example of what a descriptor file could look like using XML. This is just an example for a hypothetical mapping function (*VideoStreamingQoE_MappingFunction*) which is assumed to compute QoE from a set of relevant video streaming parameters. As shown, the mapping function is bound to an input adapter (*VideoStreamingInputAdaptor*) and an output adapter (*MosOutputAdaptor*) which seems to encode the output according the MOS scale.

```
<?xml version="1.0"?>
<mapping-function-jar>
  <mapping-function id="VideoStreamingQoE_mapping-function">
      <mapping-function-name>VideoStreamingQoE_MappingFunction</mapping-function-name>
      <mapping-function-vendor>5GNorma</mapping-function-vendor>
```

```
        <mapping-function-version>1.0</mapping-function-version>

        <input-params>
           <input-param type="float" min="0.0" max="1.0">Jitter</input-param>
           <input-param type="int" min="0.0" max="1e6">BitRate</input-param>
           <input-param type="String">ScreenSize</input-param>
           <input-param type="String">ScreenResolution</input-param>
           <input-param type="String" values="MPEG2, MPEG4">Encoding</input-param>
           <input-param type="float">Delay</input-param>
           <input-param type="int">PacketLoss</input-param>
        </input-params>

        <input-adaptor-binding>
         <input-adaptor-ref>
           <input-adaptor-name>VideoStreamingInputAdaptor</input-adaptor-name>
           <input-adaptor-version>2.1.1</input-adaptor-version>
         </input-adaptor-ref>
        </input-adaptor-binding>

        <output-adaptor-binding>
         <output-adaptor-ref>
           <output-adaptor-name>MosOutputAdaptor</output-adaptor-name>
           <output-adaptor-version>1.1</output-adaptor-version>
         </output-adaptor-ref>
        </output-adaptor-binding>
   </mapping-function>
 </mapping-function-jar>
```

Figure 46: Example of a XML based Descriptor file

Of course, we are not proposing here to use XML or this so specific format; this is just a conceptual example, but that could be close to a possible real implementation.

6.2.2.3.2 Output Interface

As reviewed in Section 9.14 (state of the art) the mapping function output encoding could be done in very different ways. This is why we have defined a general-purpose building block (the Output Adapter) to encode the output according the user requirements in a very flexible way. Anyway, this output has to be sent towards one of the main building blocks in the 5G-NORMA architecture: the SDM-C, so there must be a common agreement about how the Output Adapters can generate their output and how the SDM-C can process it.

To avoid losing generality our proposal for this is to use the well know event-driven software architecture (EDA); i.e., using a communication pattern based on events [59]. In this architecture, an event is simply defined as "a significant change in state". In our case, that change can be a change in the QoE Mapping Function which is relevant somehow. For example, the computed QoE could reach certain threshold, or we could have an Output Adapter programmed to work according the Weber-Fechner Law (see Section 9.14); in this case, an event could be generated when the program detects that, according the logarithmic law, it is necessary to increase resources to keep users satisfaction. From a practical point of view, this “change of state” is communicated by means of a (typically asynchronous) message: the “event notification”.

The event emitter will be the QoS/QoE Mapping System (using the Output Adaptors), while the events consumer will be the SDM-C. The mapping system will have the responsibility to detect and transfer events, while the SDM-C will have the responsibility of applying a reaction as soon as an event is received. For the communication to be possible, we also need *events channels*, which are the conduits in which events are transmitted from the Output Adaptors towards the SDM-C. The practical implementation of event channels could be based on traditional components such as message-oriented middleware or point-to-point communication.

To ensure communication, the semantic of event notifications will be decided by the Output Adapter designer, but following certain common rules to ensure that the SDM-C can understand and process the notification once received. Event messages could trigger the usual scaling operations in virtual environments (e.g., scale in/out) or the VM power up/down operations. This would allow implementing the typical elasticity operations from QoS/QoE measurements.

Event notifications will have the common structure normally used in Event-driven architectures; they are usually with two main parts: an "event-notification-header" and an "event-notification-body". The header should include the most relevant information to process the event (e.g., event name and type, timestamp). The event body can be used to provide more detailed information about the event. The following Table 8 could be an example of an event notification definition:

Table 8: Example of an Event Notification Definition

Header:	`EventName`	This is a free text agreed between the OutputAdapter and the SDM-C. A set of pre-defined event names could be defined, so the SDM-C could know what to do for each case according to that. Examples: – Change_in_MOS_Scale – 80_percent_threshold_reached
	`EventType`	Related to the event name, different types can be considered. Example: – Threshold – MOS
	`Priority`	Different priority levels could be defined (e.g. CRITICAL, MAJOR, LOW…).
	`TimeStamp`	It will be probably necessary to prioritize or track events.
Body:	`Description`	This can be an optional informational element (free text)
	`Subscriptor`	This is when the event is associated to a specific subscriptor. It can be identified by the MSISDN or IMSI.
	`Tenant`	Tenant identifier
	`Slice`	Slice Identifier
	`Source`	The OutputAdapter raising this event.
	`QoE Metric`	Distortion, blurring, freezing, noiseness, echo…
	`ContentType`	Voice, speech, music, video, 3D movie.
	`AppType`	Multimedia, gaming, augmented/virtual reality.
	`UserType`	VIP User / Regular User

6.2.2.3.3 Monitoring Interface

The monitoring interface specific implementation will be depending on each input adapter; i.e., we could have a monitoring interface compound by different interfaces: those needed by each input adapter. This is something we have to agree with the monitoring system (see Section 6.2).

6.2.2.4 QoS/QoE Mapping Block Deployment

Once we have more clarity (at least at high level) about the QoS/QoE Mapping building block and its main interface systems another important question arises: Where, in the 5G NORMA architecture, the QoS/QoE Mapping function should be located?

It is clear this function belongs to the 5GN control layer, but this is true only from the functional point of view. If we consider how the QoS/QoE Mapping function could be physically deployed things are not so straightforward. Depending on the QoS/QoE Mapping requirements (based on the, for example, slice, tenant, operator requests) the QoS/QoE Mapping module could have quite different aspects. Let us recall our two extreme examples previously mentioned:

- To compute an objective global QoE measurement from just a couple of physical parameters monitored inside a specific VNF (e.g., CPU and RAM usage).
- To compute real-time QoE measurements for a big set of individual end-users considering a big number of input parameters and using DPI and a Big Data Analytics infrastructure.

For the first case the requirements are not too demanding. Probably the mapping function (and even the monitoring) could be executed locally on each deployed NF. A simple threshold function executed on the NF could be used to raise an alarm towards the SDM-C module (or even some actions could be executed locally on the NF itself without involving other systems).

On the other hand, for the second case, it would be necessary to deploy a dedicated node (or even a set of nodes) to perform the DPI, BigData Analytics and real-time stream processing. Probably a CEP (Complex Events Processing) architecture would be necessary in order to trigger the events towards the SDM-C. Furthermore, the deployment of such complex set of nodes should be performed according the provider specifications; some nodes should be required to work in the central network, while others should be placed in the RAN to get the best performance figures.

Our approach is that 5GN should provide a general solution for this, not only a specific approach. Ideally, the three mentioned interfaces (north, east and west) should be implemented. However, to provide more generality, its implementation is not always mandatory; this depends on the implementation needs. The most evident case is the 1st case above, where the parameters monitoring is so simple that it can be performed in the NF itself, so no WBI is really necessary. Also, the mapping function management can be probably omitted, since the QoS/QoE Mapping block probably works as a stand-alone process with no special management functions required.

So, for the placement of the mapping functions we can consider the following options:

- Deploy the QoS/QoE Mapping function as a stand-alone process into the individual NF's (physical or virtual). The QoS/QoE Mapping function could be deployed on a single NF (even if the NFG comprises more than one), or redundantly, on each NF composing the NFG. In practice, this QoS/QoE mapping function would be probably devised as a specific algorithm able to generate by itself the QoS/QoE mapping events towards the SDM-C using the East-Bound-Interface. West Bound Interface should be implemented locally in the NF to receive the monitored parameters from the QoS/QoE Monitoring block (the monitoring function could be executed internally also; in that case the WBI is not used). Also, the NF could optionally implement the NBI to communicate to the QoS/QoE Management module (if not implemented, no management functions will be provided).
- Deploy the QoS/QoE Mapping module as a dedicated service in a specific separated node. The complexity of that service is variable, based on the customer requirements (it can be a single node or a more complex service with a distributed nodes set). Anyway, the basic idea is the same: that service should implement at least the WBI to communicate towards the SDM-C (est and nord interfaces are optional depending on the specific implementation).
- Implement the QoS/QoE Mapping module into the SDM-C block. In some cases it could be interesting to have a kind of "monolithic" SDM-C including QoS/QoE Mapping function capabilities. So, instead of using a specific NF for the QoS/QoE Mapping, this functionality is integrated inside the SDM-C. So, the QoS/QoE Module works as an internal SDM-C module, although preserving its functional independence. Generation of QoS/QoE Mapping events "towards" the SDM-C is internal, so even this interface is not mandatory here.
- Include the QoS/QoE Mapping module into the QoS/QoE Monitoring module. In some cases it could be interesting to have these two modules together, since in fact, they are in a very close functional relationship. Anyway, like in the previous case, the QoS/QoE Mapping module still keep its independence at functional level. The implementation of the WBI will not be probably necessary (an internal communication channel would be probably used), although EBI and NBI should be implemented in this case.

6.3 QoS/QoE enforcement and monitoring

The 5G NORMA aims to support fully dynamic, context aware QoE/QoS management that should be able to dynamically set QoS/QoE target based on detected application flows of the end users and adapt the end-to-end resource allocation and the data plane functions accordingly, thus enabling good user experience. Herein the study of the QoS/QoE enforcement and monitoring functions will focus on e.g. end user application detection and measurements to derive service/application specific QoE/QoS targets according to QoS/QoE policies and enforce the derived QoS/QoE targets by controlling the available resources among the competing user and application flows.

6.3.1 QoS/QoE Monitoring and target definition

QoS/QoE monitoring and detection functions should have the capability of autonomously detecting the conditions when all or part of the application flows of any end user requires specific treatment (i.e., different from the default) to enforce the QoS/QoE targets specified by or derived from the policies. The conditions may include events within the traffic of the managed application flows itself (e.g., an application with specific QoE requirements is started or the user changes the way of interaction with the application) or within the real time context or status of the resources serving the user's traffic (e.g., congestion occurs, or there is a change in other application flows competing for the same resources). Detection also includes the ability to identify the set of flows that are subject of a given policy and need to be enforced by specific QoS/QoE enforcement actions.

In order to determine the specific QoS/QoE enforcement action, the QoS/QoE targets for the identified set of application flows needs to be defined dynamically according to the detection/monitoring functions. The QoE targets define the set of QoE parameters/metrics on application session level (such as download time for web pages, the required bandwidth for video session, end-to-end latency per message transaction for V2X services etc.) and their corresponding target values/ranges that ensure good experience for the application/service vertical they apply to. The set of relevant parameters/metrics is specific to the type of traffic (e.g., the application type such as HTTP(S) Adaptive Streaming / YouTube for OTT or the service vertical itself such as M2M or V2X). The quantification of the target values is context based and specific to the attributes/content of the individual application session (e.g., the required bandwidth is derived from the detected/profiled media rate of the specific video file) as well as the context of the network and the resources (e.g., based on the available radio capacity and the flows competing for the same radio resources, see Section 6.3.2).

The high-level structure of policy and context based adaptive QoE target definition and QoS parameter mapping is depicted in Figure 47. This may be implemented as an application of SDM-C to (re-)configure QoS/QoE related VNF in order to achieve the defined QoE/QoS targets. The internal operation of the adaptive QoS/QoE definition function comprises the following steps:

- **Policy and contextual information evaluation:** First, the function evaluates if the policy requires QoE or QoS level management in the given context. For QoE management, QoE target definition and (optionally) QoE/QoS parameter mapping are performed whereas for QoS level policies only QoS parameters are defined (i.e., the QoE level is skipped). If no corresponding dedicated policy was defined for the application, there may still be policies that indicate how to handle such cases (e.g., try to maintain good QoE or just provide parameters for minimum/best effort service). If even no such policies exist, the function may operate according to internal or pre-configured defaults.
- **QoE target definition:** identify the QoE targets applicable to the application session and define the values for the parameters. The QoE parameters are adaptively defined based on the characteristics of the application session, the corresponding policy and the

local context. A limited number of QoS target groups have been introduced previously and each group has a common traffic characteristic and QoE influence factors. In case there is a QoE enforcement functions in the system that is able to take over and enforce such parameters, they are fed to the QoE enforcement functions. Otherwise the process proceeds to the next step.

- **QoE/QoS parameter mapping:** based on the QoE parameters and their values, a relevant set of QoS parameters are selected and their values are defined (see Section 6.3.1.2 for detailed information). Note that in case there is an QoE enforcement function in the system, this step is still implicitly performed by the QoE enforcement function itself within its internal enforcement mechanism. The scope of this step is to define a set of low-level parameters (e.g. the throughput/bitrate, delay etc.) that can be then used as scheduling/service targets by the QoS enforcement function such as radio/packet scheduler.
- **QoS parameter definition:** in certain cases (e.g., narrow service boundaries such as constant rate voice) the policies may indicate QoS targets directly (skipping the QoE level) as the selected QoS parameters are able to accurately describe the QoE requirement of the selected application regardless of the actual context. In these cases the QoS parameters are defined directly.

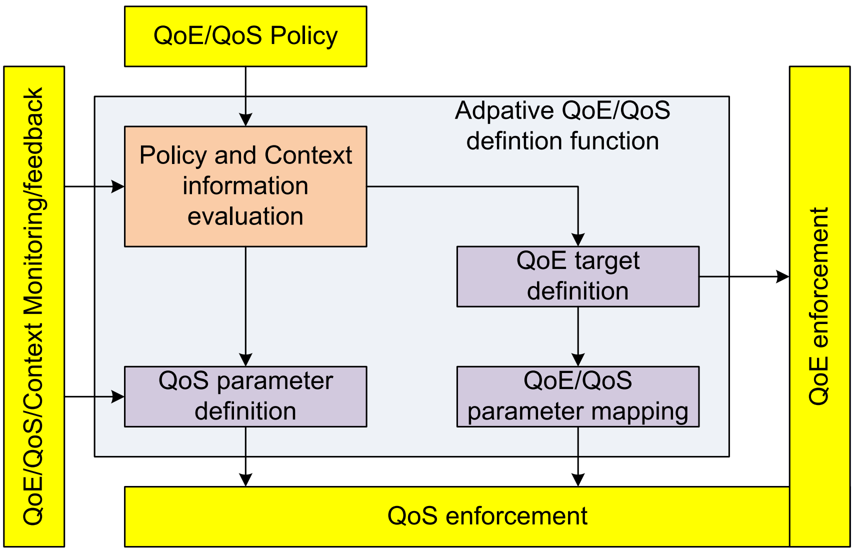


Figure 47: High level structure of adaptive QoE target definition and QoS mapping

As the context and the application behaviour is highly dynamic, the validity period of a given parameter value is limited and it requires re-evaluation whenever there is a change in any of the contextual information. Therefore, context changes should be detected (by an external entity) and fed back to the QoS/QoE definition function. This may result in actions such as to increase the bandwidth target due to the user switching to a higher data rate video or increase the download time target of interactive applications in case of congestion.

6.3.1.1 QoE targets definition

It is desirable to define commonly usable QoE targets to simplify the network design. However, a particular challenge addressed here is that due to the high number of different applications, it is not possible for a QoE management system to have dedicated metrics fit all applications. Instead, a small number of QoE targets are preferable that are generic enough to enable formulating the requirements of a large range of applications by classifying the applications into a limited number of groups. Each group has common characteristics with regards to the relevant QoE influence factors, i.e., what are the important parameters and attributes that have impact on the achieved QoE for a given application session. A valid classification scheme is outlined below, defining five groups with the common behaviour, general requirements, and examples:

Real time multimedia:

Transfers the audio/video frames of a live capture, i.e., content is disseminated at the same pace it is generated. Sensitive to jitter and discards (as they compromise the quality of the decoded content) and requires low delay (to maintain interactivity). Examples: Viber/Skype (voice/video calls), WhatsApp (voice calls).

Stored multimedia:

Delivers a multimedia file that is already available at the time of the request (often in different resolutions and formats). Requires short time to play (pre-buffering time), no stallings and decent resolution (matching the device capabilities). Examples: YouTube, Netflix.

Interactive data:

Generates demand (download/upload) in bursts with significant idle periods in between (mostly personalized content). Requires short download (or upload) time. Examples: web browsing, social sites (excluding video/voice parts), map views, cloud based productivity tools, Evernote.

Messaging/transactional:

Generates a few packets at a time (i.e., insignificant bandwidth requirement). Requires low latency (round-trip time) and no loss for high interactivity. Examples: chat, real time gaming.

Background:

Data transfer either running in the background (completely invisible to the user) or when the user is aware of its progress but does not have strict expectation about the completion time (i.e., no urgent waiting on the content like after requesting a web page). The user still needs to feel that the process is progressing and it is not stuck. Examples: pushed content (email, Snapchat message, where the user is only notified when the content is already downloaded in background), Dropbox, Box, SW updates.

The detection of which type a given application belongs to may be implemented via the following mechanisms:

- Detection of well-known applications: for a limited set of popular applications, specific detection logic may be implemented based on UP packet monitoring (e.g., by the correlation of IP addresses, DNS query/response messages, Transport Layer Security (TLS) handshake information, URLs, etc.). This may lead to the detection of a specific application (e.g., YouTube), which is known to belong to a specific application type due to its way of delivering multimedia data.
- Non-dedicated applications may be profiled based on the traffic pattern they generate (e.g., specific attributes of HTTP adaptive streaming, VoIP/video calls, messaging, etc. can be identified without knowing the exact identity of the application). Additionally, the application's behaviour may be matched to already profiled applications to identify that a new application generates the same kind of traffic as a known one thus it is likely that the similar characteristics apply.

The quantification of the QoE targets (e.g., download time, throughput/bitrate) may be based on pre-defined and/or on-the-fly detected attributes:

- For certain applications, the correlation between the user satisfaction (subjective experience) and the QoE targets may be studied and generally applicable values/ranges/limits may be synthetized (e.g., the download time for web pages that is usually accepted without causing frustration can be identified through crowdsourcing campaigns). Such targets may be configured in the policies.
- Certain QoE targets require the detection of session metadata, such as the media rate of the video in order to quantify the amount of bandwidth it requires for smooth playback.

This requires to obtain session establishment metadata by the network (e.g., from protocols such as Session Initiation Protocol (SIP) or Real Time Streaming Protocol (RTSP)), C-plane signalling (for native services), packet metadata (e.g., video data rate and codec information from manifests or from the metadata section of the video file being downloaded), or from any external source (such as signalling from the content provider or from the consumer application).

- Due to the increasing adoption of end-to-end encryption in the OTT domain, it may not be possible to access the required attributes directly by U-plane packet monitoring. Instead, real time traffic profiling mechanisms are needed that are coupled with enforcement actions. Such actions may temporarily provide the application with sufficient resources (referred to as incubation) so that the application exhibits traffic delivery patterns that are characteristic to the particular session. One example is the HTTP(S) streaming that is used by most of the stored multimedia services. These applications are downloading multimedia data at the pace it is consumed by the player, i.e., with a rate that is close to the playback rate in order to avoid pre-buffering excessive amount of data. Incubation enables the multimedia session to achieve a download rate that is comfortable for the specific content (i.e., matches the content characteristics), which can be measured during the incubation period and enforced later on.

6.3.1.2 QoS parameter definition

The QoE targets are converted or mapped to QoS parameters that are suitable for direct enforcement via e.g. radio/packet schedulers or other traffic management mechanisms. The QoS parameters are summarized in Table 9 for the traditional telecommunications services and the OTT vertical. Additional service verticals (V2X, M2M, IoT, etc.) are expected to at least partly reuse the same/similar QoS parameters, with possibility to introduce additional ones (such as reliability assurance for critical services) later according to the technology evolution.

Table 9: QoS parameters

	Parameter	Description / Comment
Telecommunications (e.g., native voice/video)	delay	e.g. target for voice: 100 ms (3GPP TS 23.203 QCI1 for conversational voice)
	jitter	e.g. target for voice: 0.5–1 ms
	packet loss	e.g. target for voice: 0–10^{-2} (3GPP TS 23.203 QCI1 for conversational voice)
	minimum throughput (capacity grant)	based on the codec parameters (e.g., AMR voice codec ~ 12.2 kb/s)
OTT	target throughput (capacity grant)	bandwidth required for good QoE (ideally this should be the service provided for the application)
	minimum throughput (capacity grant)	bandwidth required for acceptable QoE (below that the application is unusable so it is better not to serve it at all)
	scheduling delay budget (per packet)	amount of time after the packet must be scheduled for transmission (for real time streaming type of applications); may be even provided in each U-plane packet
	discard (yes/no)	discard sensitivity

	priority	relative priority (~ARP) to resolve conflicting situations when some application demands cannot be served
	urgency	a marking applied on a per-packet basis indicating that the service of the packet should be expedited (i.e., served out-of-order in a non-FIFO way)

For the OTT service, the values of the QoS parameters is not statically defined but calculated dynamically based on the context of the user's application and the network resource status. The consideration of mapping QoE targets to the QoS parameters for different traffic/application types is listed below:

- Real time multimedia
  - Minimum bandwidth corresponding to the content media rate (lower rate causes degradation through increased delay, dropped frames and decoding errors).
  - Bandwidth requirement is not subject to highly dynamic and abrupt changes.
  - Tight scheduling for steady throughput and low jitter (sensitive to jitters).
  - Low delay (in the range of conversational voice/video targets).
  - No loss (discards cause decoding errors and QoE degradation).
- Stored multimedia
  - Minimum bandwidth corresponding to the content media rate (lower rate causes degradation through stalling or switching to low resolution).
  - Occasionally higher target bandwidth to enable accurate demand profiling and to boost pre-buffering through incubation.
  - Bandwidth requirement is not subject to highly dynamic and abrupt changes.
  - Less tight scheduling than real time multimedia, throughput targets to be achieved over longer (at most end-to-end RTT) averages, not sensitive to jitter.
  - No loss (discards cause throughput degradation and potential QoE degradation via end-to-end transport layer actions).
- Interactive data
  - Highly dynamic target bandwidth depending on content size and target download time (application and user context specific).
  - May require no (or low) minimum bandwidth due to content elasticity (i.e., content may already be displayed to the user while downloading).
  - No loss (discards cause increased completion time and data starving at the application layer such as delay of specific objects).
- Messaging/transactional
  - Low latency (and high priority).
  - No loss (discards cause timeouts, delayed or even lost messages).
  - Urgency may be applied to important packets (application specific).
- Background
  - Best effort service (may have a minimum throughput requirement).
  - Service goal is to avoid flow level degradation such as TCP timeouts.

6.3.2 QoS/QoE enforcement

The main purpose of QoS/QoE enforcement is to manage resources for a dynamically identified traffic mix based on derived application specific QoE targets for good customer experience or autonomously defined network/packet level QoS parameters. The operation is dynamic and self-adaptive to handle the versatile application sessions and resource requirements based on actual traffic and network context. It also includes efficient Congestion Control (CC) mechanism to effectively solve the congestion problem by redistributing the available resources among the competing flows and applications according to their QoE requirements or the QoS principles selected by the policies. Therefore, the CC operation is incorporated into the QoS/QoE enforcement as an integrated capability.

As described in Section 6.3.1, the target throughput/bandwidth requirement of an individual application session that enables acceptable QoE depends on the application type and the attributes of the content being requested. Giving less bandwidth/resources to the session results in QoE degradations and possible termination of the session by the user. On the other hand, increased bandwidth/resource allocation beyond a level also has a diminishing marginal utility in terms of the achieved QoE. There is a certain (application and session specific) limit beyond which QoE could not be improved no matter how much more resources are given. For instance, multimedia applications (such as YouTube or Netflix), the minimum required amount resource/bandwidth is the media rate of the video/audio (plus protocol overheads). Giving more bandwidth, on the other hand, does not provide better multimedia experience once seamless playback is guaranteed (the extra bandwidth would be spent for accumulating more data in the playout buffer that has no added value for QoE as long as the buffer does not deplete). Therefore, multimedia application sessions have a narrow bandwidth profile around the data rate (or playback rate), meaning that increasing the bandwidth allocation above the media rate quickly stops delivering QoE improvement (having maximized the QoE already) whereas dropping just below the rate soon starts to cause problem as shown in Figure 48. Therefore, the goal of the QoE/QoS enforcement is to combine with resource management to arbitrate the resource allocations in a way that no application session gets under-allocated (causing compromised QoE) due to serving another session above their demand.

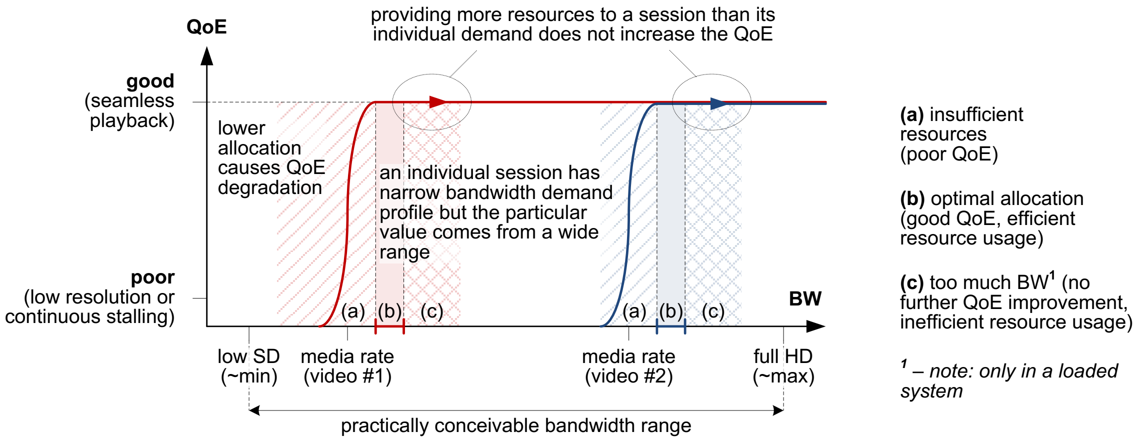


Figure 48: Illustration of the bandwidth allocation and QoE of video session

Figure 49 illustrates the system status, the QoE status and the corresponding QoS/QoE management and Congestion Control (CC) operation as the integrated QoE enforcement functions. The system status is characterized by the amount of traffic the physical network resources have to handle and it defines the CC actions. The objective of the CC actions is to readjust the amount of resources assigned by the QoE enforcement function to the amount of resources available in the system (i.e., keeping the control of the resource allocation but efficiently utilizing all available capacity). The QoE status indicates the relation of the application/flow demand to the available resources and it defines the QoS/QoE management actions to be executed.

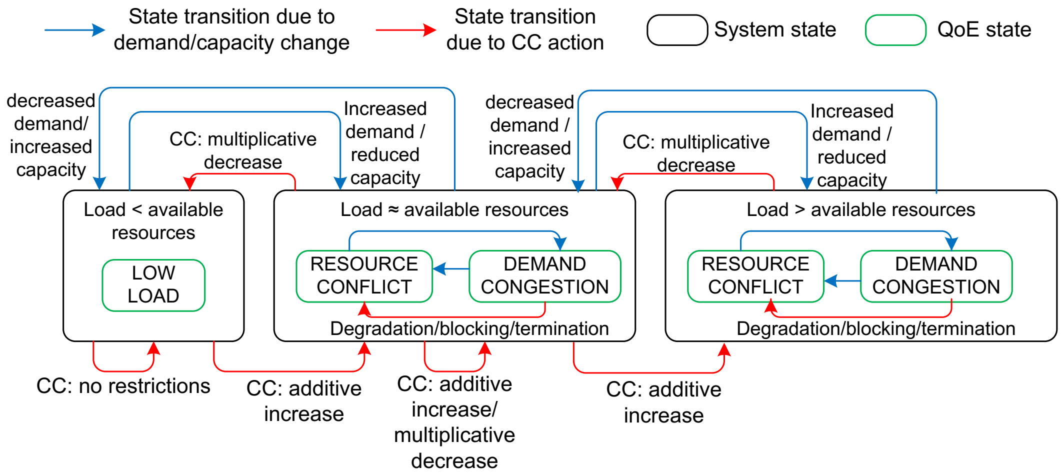


Figure 49: QoE enforcement and resource management operation

The details of the states are provided below:

- *Load < available resources* (system status): underutilized system, there are free physical resources (e.g., radio capacity or transport link capacity) after serving all application sessions/flows. The CC has no role in this state (i.e., should not limit the flows). In that case, the QoE status is LOW LOAD meaning that the desired QoS/QoE is provided natively by the system without the need of specific QoE enforcements on any applications/flows.
- *Load ≈ available resources* (system status): the bottleneck resources have become fully utilized, the application sessions/flows have to compete for the system resources. This is the point where QoE/QoS enforcement function has to start actively managing the QoS/QoE through its internal scheduler to enforce the desired targets. Also, this is the target system status the CC tries to maintain in case there is sufficient demand to load the system. The QoE status may be either RESOURCE CONFLICT or DEMAND CONGESTION:
  - RESOURCE CONFLICT: the cumulative resource demand of the applications/flows passing through the bottleneck resource fits into the available capacity. In that state, the QoS/QoE targets are enforced through redistribution (i.e., redistributing the bottleneck resource according to the QoS/QoE requirements). Note that redistribution is not relative prioritization but the enforcement of explicitly calculated individual per session resource (e.g., bandwidth) targets. This is the desired QoE status as it allows to fulfil the QoS/QoE targets of all applications/flows.
  - DEMAND CONGESTION: the cumulative demand of the application sessions/flows passing through a bottleneck is higher than the available bottleneck capacity due to either increased demand or reduced capacity. In that case, not all demands can be satisfied at the same time. Therefore, the QoE/QoS enforcement function needs not only to manage the QoS/QoE through redistribution but it also has to let specific sessions degrade (allowing them to receive less resources than what they need), or even terminate/block sessions. The criteria for selecting the degraded sessions are defined by the policies.
- Load > available resources (system status): the bottleneck resources are heavily overloaded, e.g. due to additive increase CC action. This is not a desired state from QoS/QoE management point of view, therefore it is only a transient state that is immediately resolved by the CC actions. In the meantime, the same QoE states and the corresponding QoS/QoE management actions apply as with the previous system state.

The transition between the states is triggered by three independent processes:

- First, the demand itself may change as users starting/stopping application sessions. This is detected by application detection function directly by observing the new application sessions/flows.
- Second, the available capacity may change (especially if the resource is a radio interface with varying channel conditions). This is followed by the enforcement function by algorithmically adjusting the amount of resources it distributes among the sessions.
- Third, the actions of the enforcement function itself change the system status by additive increase and multiplicative decrease CC actions or QoE status by degradation/blocking/termination.

The CC actions are further detailed as follows. Let *C(t)* denote the capacity of the resource as known at time instance *t*. . As the capacity of the resources may not be known beforehand, e.g. the radio resource capacity is variable and highly depends on the channel quality of each users, *C(t)* needs to be estimated by the enforcement function as introduced below. Let *T(t)* indicate the cumulative throughput as measured by enforcement function over all flows sharing the resource. Assuming that the system starts with low load, the *C(t)* is unknown and the enforcement function first only monitors the QoS/QoE without acting on the traffic. In case the demand increases or the capacity is reduced, the available resources in the system may become loaded. This is detected through the congestion detection capability. At that point, $C(t)=T(t)$, that is, the measured throughput over the congested resource equals its momentary capacity. The *C(t)* serves for the enforcement function as the starting point for the amount of resources that needs to be distributed through its scheduler functionality among the competing sessions. By scheduling the traffic internally, the enforcement function effectively decreases the load in the system. At the same time, *C(t)* and the amount of resources available in the system may become decoupled as the measured T(t) will be limited by the enforcement targets itself. Therefore, the AS needs to constantly probe for the resource availability in the system through its additive increase / multiplicative decrease CC actions as shown in Figure 48. Additive increase means to increase *C(t)* by a given Δ amount periodically, e.g. $C(t)=C(t-RTT)+\Delta$ where *RTT* is the measured round-trip time between enforcement point in the network and the UE. Multiplicative decrease means to reduce *C(t)* by an α factor so that $C(t)=C(t-RTT)*\alpha$.

- In case that the congestion has been resolved (the system load is decreased below the available resources) by its actions, the available system capacity should be higher than currently estimated *C(t)*. This case is illustrated by the yellow circle in Figure 48. In that case, the enforcement function additively increases *C(t)* until
  - o the system bottleneck becomes loaded again due to the increased traffic it has to process, at which point the measured T(t) throughput again becomes an accurate indicator of the amount of resources the enforcement function needs to redistribute (i.e., the system is kept at the Load ≈ available resources state); or
  - o the traffic sources become self-limited and they stop following the C(t) increase with an equal increase in their throughput (i.e., C(t) becomes greater than T(t)) and the system is not loaded; in that case, the system has actually transitioned to the Load < available resources state and all limitations may be lift off (i.e., the scheduler transits into bypass mode).
- In case the enforcement function detects that the QoS/QoE targets are not enforced due to the system loaded too much (*Load > available resources* state as illustrated by the purple circle in Figure 48), the *C(t)* is multiplicatively decreased until the resource re-distribution becomes effective.

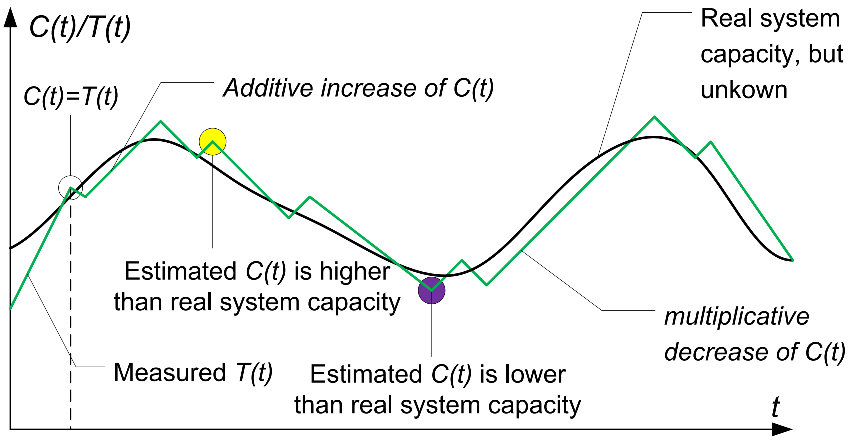


Figure 50: Illustration of additive increase and multiplicative decrease CC

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6.4 Video Pre-Scheduler

6.4.1 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 our 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 an application-aware scheduling for IP–based multimedia streams at the application layer atop SDN architecture, identified here as SDM-C, in a wireless system.

We consider a wireless shared channel scenario, where several streaming users share the common bandwidth and transmission power at the same time. In addition to the Layer2 scheduler, known as MAC scheduler, located at the eNodeB function which is in charge of assigning for each time instant channel resources to individual flows of users based on a particular scheduling policy. One of the targets of the video pre-scheduler is to enhance RAN resource allocation and take advantage of the SDN paradigm.

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 in this first step on:

- 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.
- Finally a video pre-scheduling strategy is investigated. The underlying mathematical model is proposed and the pre-scheduling algorithm is provided.

6.4.2 Video Pre-scheduling SDN 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 protocol is given. Finally, the scheduling approach is theoretically investigated and the resulting 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 duration 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.

Before the design of the solution can begin, it is necessary to determine which controller the solution should be implemented on. SDN controllers were discussed in Section 2.1.1. 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.

6.4.2.1 Architecture of the platform

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.

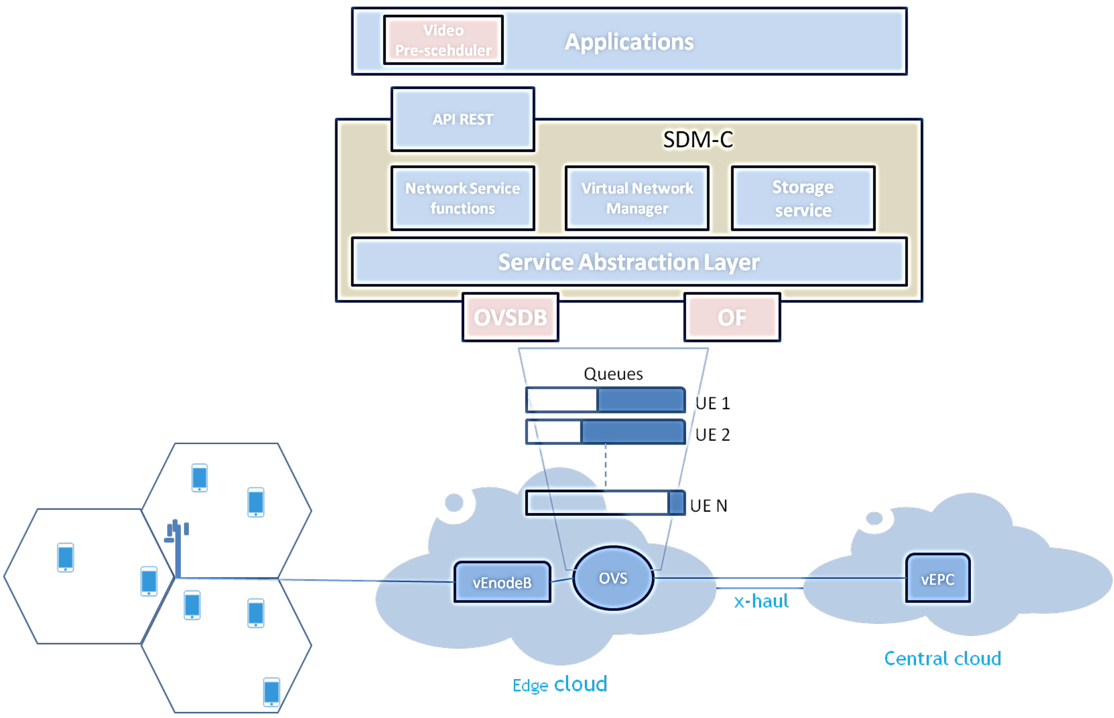

Figure 51: System architecture

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 OpenVswitch. 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 created, 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.
- **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 transmitted, 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 resources efficiently.

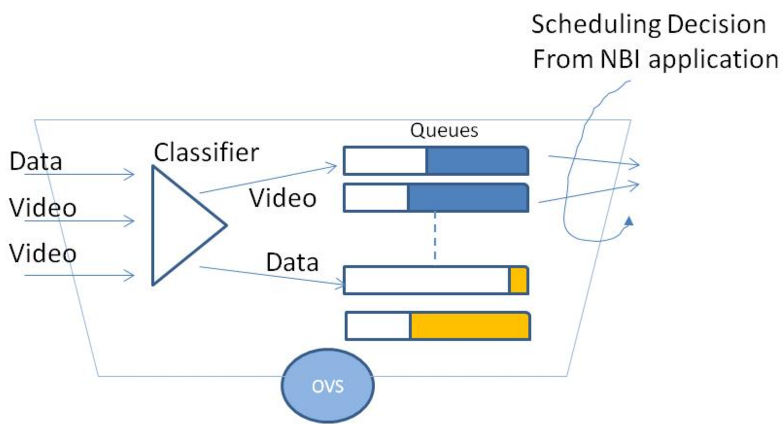

Figure 52: Synoptic of the Queuing system

6.4.2.2 Northbound APIs

They are used to communicate between the controller and applications. Northbound APIs are the most critical APIs in the SDN environment, since they have to support a wide variety of applications.
Our solution is an application that communicates with the controller and the underlying network via this API.

6.4.3 Link and buffer aware scheduling algorithm

We assume that several users in the serving area of a base station in a mobile system, as depicted in Figure 51, have requested to video stream from one or more streaming servers.
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.

6.4.3.1 Introductory example

To better understand the mechanism that we are proposing; let us consider two users X and Y with time varying channel. We suppose user X is in better radio conditions than user Y. Therefore, user X receives better average channel quality and rate. As shown in Figure 53, depending on the quality of the channel, user X channel varies between 8 Mbps and 6 Mbps and user Y channel varies between 4 Mbps and 2 Mbps.
If we consider that X was the only user in the system its rate will vary between 8 and 6 Mbps thus an average rate of 7 Mbps. If we consider now that Y was the only user in the system, its average rate would be of 3 Mbps. When both users are active at the same time then they will share the network proportionally resulting in an average rate of 5 Mbps, with X getting a rate of 3,5 Mbps and Y getting a rate of 1,5 Mbps.
Imagine that users are selected for data transfer depending on how much better their channel quality is compared to their average channel quality. In a first scenario, consider selecting only one user for data transfer in each time interval, namely the one that maximizes the ratio of their current rate to their average rate. X will be selected for data transfer in the first time interval while Y will do the transfer in the second time interval and so on. Therefore, only one user is active at a given time and when active, X will have a rate of 8Mbps while Y will get a rate of 4 Mbps. Since each user will only be active half the time, users X and Y will get an average rate of 4 and 2 Mbps respectively for an overall average rate of 6 Mbps. Hence, by prioritizing users with above average channel quality for data transfer not only each user gets higher rate but also the overall capacity of the network is enhanced.
However the prioritization of the users does not imply selecting only one user in each time interval. Now we consider a second scenario where a portion of the time interval is assigned to each user in proportion to their Current to Average Rate Ratios (CARR). Since X CARR is $\frac{8}{7}$ and Y CARR is $\frac{2}{3}$ they will get assigned fractions 0.63 and 0.36 of the first time interval respectively. Likewise X and Y will be assigned the fractions 0.39 and 0.60 of the second time interval respectively. Therefore, user X average rate over the two intervals will be $\frac{0.63x8+0.39x6}{2} = 7.38$ Mbps and user Y average rate over the two intervals will be $\frac{0.63x2+0.6x4}{2} = 3.12$ Mbps. We can see clearly the increase in users rate and the overall network capacity as well.

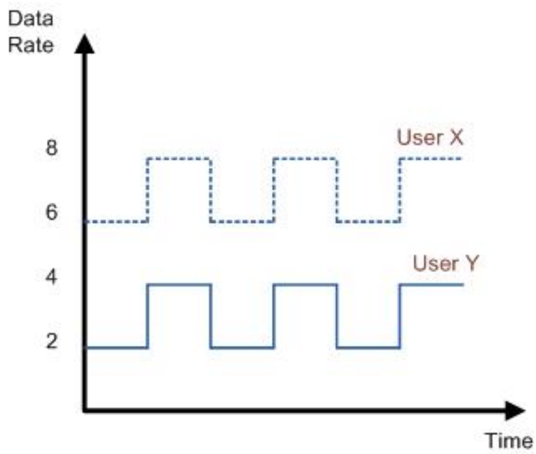

Figure 53: Exploiting time-channel variability

6.4.3.2 Mathematical model and Scheduling algorithm

Now let us take advantage of the SDN technology given that the SDN controller has an abstraction view of the wireless network. For that, we developed a module inside the SDN controller that can easily track information per streaming session such as flow rates, user playback buffer state and user position. This information is stored in rapid database (e.g., MangoDB, Redis, to name a few). The collected information can be used to determine the sessions in a given cell and, per time slot, rates and average rates. This can be used to calculate the schedule for the sessions. The concept of our proposed scheme is described in the following sub-section.

6.4.3.2.1 Mathematical Model

We suppose that the time is divided into equal intervals. Let $k = 1,2,3, \ldots$ be nonnegative integers that are assigned to intervals slot boundaries. Time interval *[k; k+1]* is called slot *k+1*. For each cell *C* and a time slot *k+1*, we consider *j* streaming users u=U_i;$1 \leq i \leq j$.

We denote by r_i^{k+1} the individual average rate of user U_i in time slot k+1. Averaging over the time slot is done to average out the impact of fast fading. "Individual" rate here means the rate that the user would get if it was the only user in the cell. Since there are j users, the

rate r_i^{k+1} would be j times the observed rate for user U_i in time slot *k + 1*.

We denote by R_i the average rate for user U_i computed based on the rates r_i^{k+1} over a sliding window of time slots.

Let $\delta_i^{k+1} = \frac{r_i^{k+1}}{R_i}$ be the ratio of the instantaneous to average rate for user U_i in time slot k + 1. Let α_i^{k+1} denote the buffer occupancy for user U_i at the beginning of time slot k + 1. α_i^{k+1}

is measured in units of time slots (of size k + 1). This means that the playback for user U_i can continue for $\alpha_i^{k+1} \times (k+1)$ seconds from its buffer alone.

Let ψ_i^{k+1} *be* defined as the buffer occupancy of user $U_i$at the beginning of time slot k + 1 divided by the sum of buffer occupancy of all j users in the cell at the same time slot:

$$\psi_i^{k+1} = \frac{\alpha_i^{k+1}}{\sum_j \alpha_j^{k+1}}$$

The principle of the algorithm is that at time slot k+1 user U_i will be served at rate:

$$\psi_i^{k+1} \times r_i^{k+1}$$

Figure 54 summarizes the proposed algorithm.

Algorithm : Scheduling Algorithm using user Average Rate

Input: Arriving flows
Result: Mapping flows to different users

Active ← TRUE
for *initialization of user buffer* **do**
    $R_i \leftarrow$ Average rate for U_i
foreach *time slot* $k+1$ **do**
    $1 \dots j \leftarrow$ Active
    if *Active* **then**
        $r_i^{k+1} \leftarrow$ Data rate of U_i in time slot $k+1$
        $\delta_i^{k+1} \leftarrow r_i^{k+1} / R_i$
        $\psi_i^{k+1} \leftarrow \frac{\alpha_i^{k+1}}{\sum_j \alpha_i^{k+1}}$
        Allocate ψ_i^{k+1} fraction of time slot $k+1$ to U_i
        $R_i \leftarrow R_i(1 - \frac{1}{n}) + \delta_i^{k+1} \times \frac{1}{n})$

Figure 54: Proposed scheduling algorithm

6.5 QoE aware eICIC

6.5.1 Introduction

In 5G NORMA architecture, the link between the QoE manager component and the SDM-C that brings QoE intelligence deeply into the mobile network allows a direct access to QoE awareness to all NBI applications interfaced with the controller. The Self Organizing Network (SON) functions can also benefit efficiently from QoE intelligence to meet users QoE requirements. Indeed, we argue that exploiting the QoE knowledge will give a clearer picture to SON algorithms of user's satisfaction and enables to perform the network optimization/configuration for the benefit of users.

We will concentrate on the specific case of 3GPP SON function that is the SON interference management mechanism, known as eICIC that was introduced to mitigate inter-cell interference.

3GPP eICIC mitigates interference occurring in DownLink (DL) transmission by time-sharing the radio resources between macro and pico access nodes. This can be obtained with the insertion for macros of certain silent periods during their transmission periods, named Almost Blank SubFrames (ABS), during which pico nodes can transmit at reduced interference. During ABSF, the pico nodes are allowed to announce a signal strength that is artificially increased by a margin called CIO so as to "force" UEs to associate with those pico nodes. Conventionally, eICIC computes optimal pairs (ABS, CIO) on each cell pair (macro, pico) of the controlled network. The cell radio configuration features, ABS and CIO, are jointly optimized to maximize a network utility, such that in turn it results in a global coordination scheme of inter-cell interference between macro and pico nodes. As an overall network utility, the sum of logarithmic user rate utilities, which refers to network Quality of Service (QoS) metric, is mainly considered by QoS-based optimization methods.

Mobile Network operators see user satisfaction, namely QoE, as an essential commercial challenge. Indeed, controlling or managing QoE provides operators, on one hand, a sustainable industrial competitive advantage, and enables them, on the other hand, maximizing and securing the degree of customer satisfaction and finally reduces customers' churn. To manage QoE, prior work has largely investigated the idea of bringing service or application awareness into the network [61]. Indeed, QoS enhancement through a fair distribution of the user radio throughput does not guarantee a homogeneous satisfaction level among users. To solve this problem, a twofold approach is proposed to apply to eICIC algorithm: on one hand, the experience of a user e.g. watching a video is controlled by a QoE metric measured directly from the application layer; on second hand, a fairness criterion is applied directly on QoE in addition to a fairness criterion on the users. Indeed, the received video quality is unfair when homogeneous user rate especially when the transmitted videos have different content characteristics. The method integrates a direct measurement of user satisfaction - namely QoE - in the utility function used within a LTE framework performing a dynamic eICIC optimization in HetNets presented in [62] and [63].

The goal is to provide a fair video quality to different video flows.

A major outcome of our work is that for video applications use case, the performance of QoE-eICIC is analysed to illustrate the benefit brought by the QoE awareness to both optimizing the inter-cell interference coordination and ensuring user satisfaction over HetNet:

- in term of network KPIs (cell edge and median throughput, respectively 5th and 50th percentile) and,
- in term of QoE KPI that is the number of QoE-based satisfied users per cell or km2.

The QoE-aware eICIC mechanism is designed as an application from the SDM-C, running in the northbound which role is to control within eMBB slice (part of network control of SDMC) via the configuration of the RAN such as inter-cell interference coordination scheme favours resource allocation that provides a fair video quality to different video flows.

6.5.2 Quality of Experience as a video utility

Quality of Experience w.r.t. Structural SIMilarity (SSIM)

SSIM is a popular metric of image/video quality among video experts and operators since it has the advantage of being both objective, low complexity and accurate. From the human eye perspective, it improves the representation of the perceived video quality compared to traditional metrics such as PSNR and MSE. Therefore, SSIM has been largely adopted as an indicator of user's satisfaction level assuming that higher the value provided by this indicator is, higher the user satisfaction is and as an enabler of online user QoE assessment. SSIM generates extremely high absolute Pearson correlation [64] that highlights the high level of correlation between the values delivered by SSIM and the video quality state.

Based on its properties of high correlation and low complexity, SSIM is adopted as quality metric for video application and is used preferably to assess user QoE online for video services.

SSIM is a pure mathematical fidelity metric of a video content quality as seen by the human eyes based on a Full Reference (FR) model. It measures image degradation in terms of perceived structural information change [65]. SSIM measures the similarity of the two signals (the original and the distorted signal) by comparing the luminance, the contrast and the structure. This evaluation is done by using some low level structural information such as statistical metrics (mean, variance and covariance) of intensity values of pixels in local patches.

SSIM is computed within a square window of size $N \times N$, which moves pixel-by-pixel over the entire image as:

$$SSSM(x,y) = \frac{(2\mu_x\mu_y + C_1)(2\sigma_x\sigma_y + C_2)(2cov_{xy} + C_3)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)(\sigma_x^2\sigma_y^2 + C_3)}$$

with μ and σ denoting the mean and the variance of the luminance value in the corresponding window, cov_{xy} denoting the covariance of x and y, C_1, C_2 and C_3 being variables to stabilize the division with weak denominator.

The range of the SSIM index goes from *0* to *1*, which represents the extreme cases of totally different or perfectly identical frames, respectively. SSIM is associated to the subjective metric MOS scale, which assesses subjectively the perceived video quality on a scale of 5 values, from 1 (bad) to 5 (excellent), as reported in [66].

Table 6: Mapping SSIM to MEAN OPINION SCORE SCALE

SSIM	MOS	Quality	Impairment
≥ 0.99	5	Excellent	Imperceptible
(0.95,0.99)	4	Good	Perceptible but not annoying
(0.88,0.95)	3	Fair	Slightly annoying
(0.5,0.88)	2	Poor	Annoying
< 0.5	1	Bad	Very annoying

However, SSIM captures the spatial differences between two representations of the same frame and, hence, is particularly suitable to express the perceived quality of a static image when coded at different levels of compression. Consequently, it does not consider the effect of the temporal correlation between consecutive frames in a video. But, prior work has shown that the average SSIM computed over a sequence of frames of a video clip is generally a good QoE index for the video as well. Therefore, for video sequences, a Video SSIM (VSSIM) metric has been defined to measure the quality of the distorted video in three levels, namely the local region level, the frame level, and the sequence level.

Structural SIMilarity (SSIM) as a video utility

The evolution of SSIM as a function of the encoding rate R has been validated in [61] with the following parametric rate-distortion model:

$$SSIM(R,q) = q_1.log(q_2.R + q_3) \qquad (1)$$

where R is defined in the interval of interest $[R_{min} ; R_{max}]$ and $q = [q_1, q_2, q_3] \in Q \subset \mathcal{R}^3$. The time-varying and content-dependent vector q reflects the spatial and temporal complexity of the video content S. For all values of q belonging to the set of admissible values Q, equation (1) describes a continuous, invertible and strictly increasing function of R.

The model of dependency between SSIM and the encoding rate of equation (1) presents an almost perfect correlation with Pearson coefficient always higher than 0.99 [61]. On this basis, we adopt *SSIM* as a video utility to create a QoE-based utility. The objective of our quality-based approach is to favour the rate allocation which allows maximizing the overall video quality under quality fairness constraint and according to UEs channel condition.

Figure 55 depicts curves of rate-distortion for the different video programs. It illustrates the monotonous increase in video quality with the encoding rate R. When R goes above a given limit, the progression of *SSIM* slows drastically down until converging to the maximal value $SSIM_{max} = 1$. Above the limit, R needs to augment hugely to generate a perceivable enhancement of SSIM.

Additionally, we observe that heterogeneous *SSIM* measurements related to the various programs are measured for a given encoding rate. This means that when identical applicative data rate is also assumed, users experiment an unfair quality according to the content complexity. It is also important to note that the increase in encoding rate does not always correspond to an equivalent increase in the quality of experience for the end user. Figure 55 suggests that the quality experienced by a user (and hence, the *SSIM*) is strongly related to the content of a specific video. The assessment of a “good,” “acceptable” or “bad” quality is heavily depending on the video content.

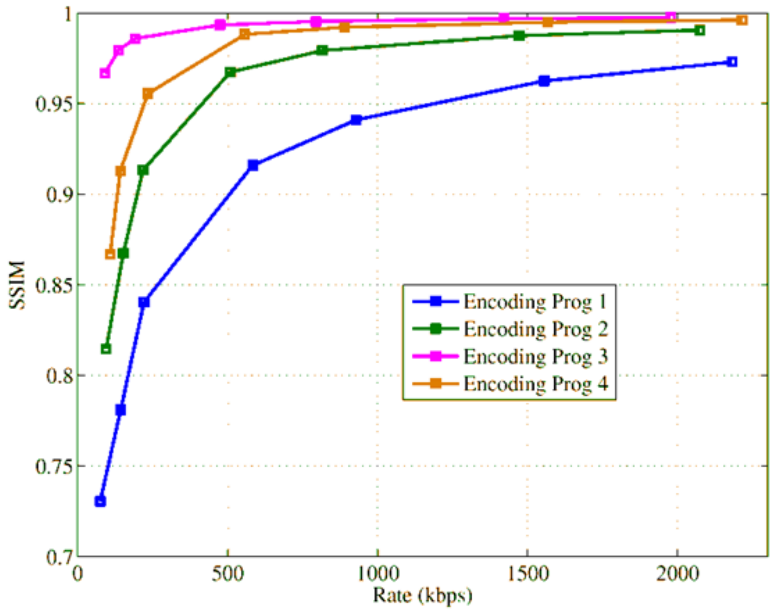

Figure 55: SSIM as a function the encoding rate and content

6.5.3 HetNet Inter-Cell Interference Coordination piloting by QoE for heterogeneous networks

Optimization settings: Cell Individual Offset and Almost Blanked Sub-frame

3GPP eICIC involves ABS patterns to protect preferably users located at small cells edge that are severely disturbed by interfering macro cells (LTE Release 10). The protection is achieved with a time-based repartition of the Physical Resource Blocks (PRBs) distributed into "regular" time slots where macro cells will transmit data traffic and a number of particular some time slots where macro cells will mute and do not transmit any data traffic. ABSs correspond to the subframes during which the macro cell does not activate any traffic channels but only certain control channels which are transmitted with reduced power. This pattern is signalled in the form of bitmap of length 40 sub-frames lasting 40 ms. As shown in Figure 56, during ABS, UEs connected to a pico cell can receive or send data and avoid interference from the macro cell and thus considerably reducing the level of interference experienced on the downlink (DL) channel. At the same time, in order to favour user association to pico cells against macro cells, 3GPP eICIC defines non-negative CIO in dB for each eNodeB of pico cell to force some macro users to be attached to pico cells which are initially not tagged as their best serving cells as shown in Figure 56. The possible CIO values between each two neighbouring cells range from (0 dB) to (24dB) but reasonable values are in the 10dB range [62]. This phenomenon is called Cell Range Extension.

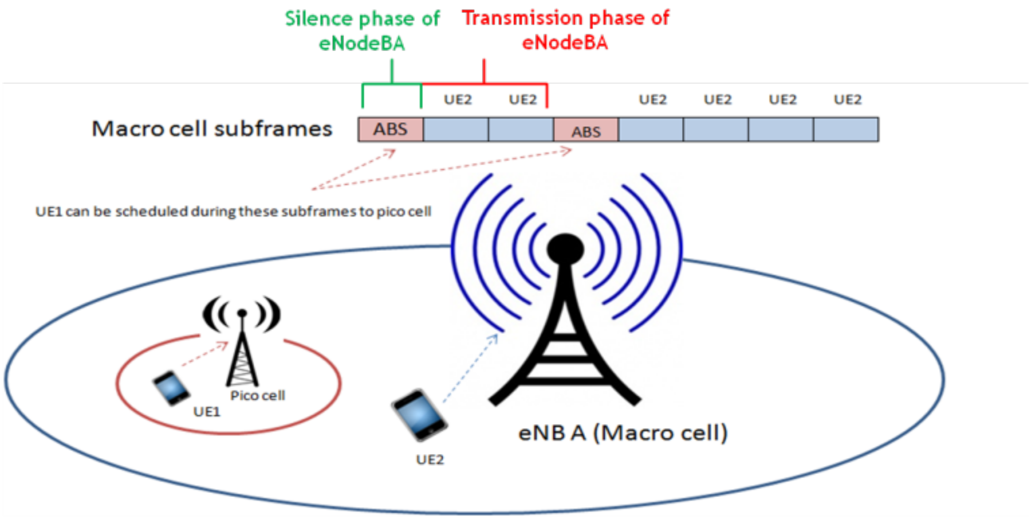

Figure 56: 3GPP Interference Mitigation Mechanism

Dynamic enhanced Inter Cell Interference Coordination driving by QoE

The dynamic QoE-aware eICIC mechanism is in charge to derive the optimal radio settings ABSF and CIO for all eNodeBs of HetNets. As a SDM-C application running in the northbound the interference coordination mechanism consists in two-tier model that comprises an optimizer and a centralized coordinator/control located in SDM-C. SDM-C has the role of the control decision entity among the eNBs that send/receive periodically (eg. via X2 interface [67]) updated derivation of optimal radio settings (ABS and CIO) or updated measurements. Based on a game theoretic iterative algorithm considering the state of the whole network, the entity optimizer derives optimal radio settings that are sent to the eNodeBs and to be used by the local eNodeB schedulers for transmissions. This global inter-cell interference optimization result in best radio settings (ABS,CIO) for each cell as demonstrated in [62] and [63].

The QoE-aware eICIC optimization framework is depicted in Figure 57.

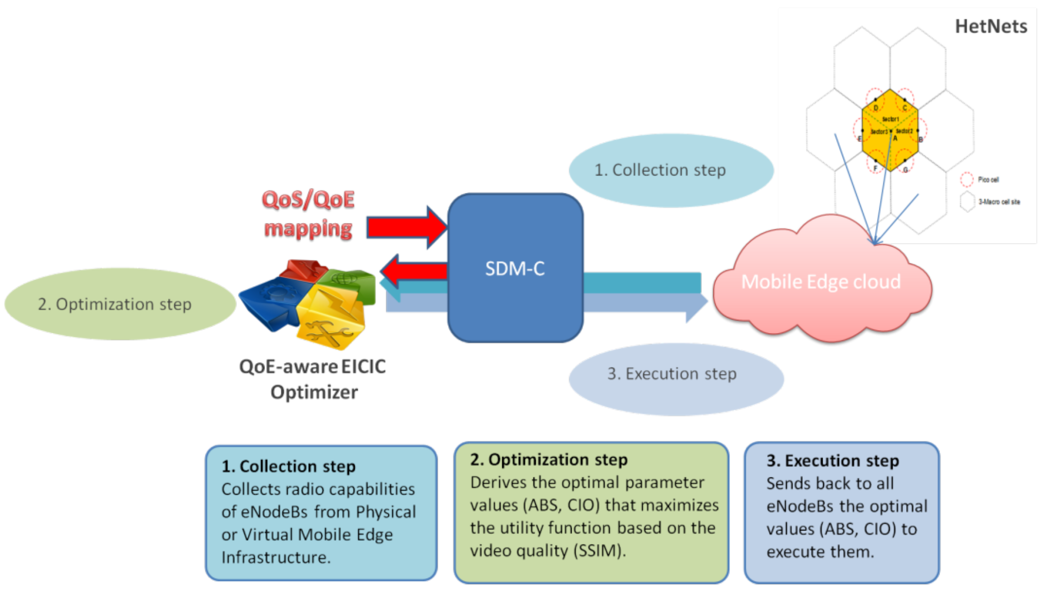

Figure 57 : QoE-aware eICIC optimization framework / operation description

Since the settings (ABS,CIO) determine the time slots of signal transmission between eNodeBs and attached users within cells, they have an impact on the SINR distribution or repartition over the Hetnet deployment zone and are responsible to manage the Inter-Cell Interference. However, given the SINR distribution within a cell among others radio metrics, the eNodeB L2 radio scheduler according its policy decides how to allocate the available resource per user attached. Therefore, eICIC via the derivation of the optimal pairs of (ABS,CIO) impacts, in one hand, the resource allocations among users decided by L2 radio scheduler and in second hand, favours the SINR distribution that would maximize an aggregated network utility representing either the targeted QoS or QoE metric.

Thus, the idea is to integrate a service-aware direct measurement of QoE in the optimisation function utility of the dynamic eICIC mechanism. The global inter-cell interference optimization piloting by QoE would therefore permit to limit the interference experienced by the mobile users in cell edge while improving the QoE over the network.

In next steps, simulations will be performed in the framework of 3GPP LTE with a MATLAB-based LTE simulator that performs a dynamic eICIC optimization in a HetNet. We extend the LTE framework performing a dynamic eICIC optimization in HetNets by including users requested heterogeneous HTTP adaptive streaming (HAS) video services via the implementation of an application layer in addition to the radio layer. We implement in the eICIC optimizer the derivation of ABS and CIO through the maximization of the utility function based either on the user radio throughput (SLR mode) or either on the video quality SSIM (QoE mode). The simulator is then used to test the optimization method for each utility in various scenarios and permits to measure the performance with different metrics. They are Key Performance Indicators (KPIs), which were selected to illustrate HetNet performance at the network point of view in term of radio rate and at the user point of view in term of satisfaction level including QoE and MOS.

6.6 QoE based routing

As we move from the current 4G generation to 5G networks, Quality of Experience has become more prominent. How to provide the best QoE to the end-user in the dynamic and heterogeneous environment of 5G becomes then a worthwhile challenge. This challenge should be tackled in multiple fronts and at multiple levels. Software-defined mobile networks are defined by the separation between the routing control and data forwarding, so in this section we focused on adding QoE considerations to the 5G NORMA's architecture routing control. In a previous section, a QoS/QoE monitoring and mapping functionality was detailed, showing how to use multiple and diverse parameter to determine QoE and QoS.

5G NORMA aims to control the end-to-end QoE, so the usual SDN routing control needs to start considering the user's experience. In the proposed architecture, this translates to the SDM-C modifying its control of the data forwarding in order to improve QoE. A northbound application will use the information available at the controller to dynamic determine the optimal route for a flow to take, based on users' QoE feedback. Remember that the controller has a global perspective on the network. When the route is fully determined, the application can send it to the controller, which will then enforce this route by commanding the forwarding elements at its disposal.

Exploring all conceivable routes and their relationship with QoE would be a complex and time-consuming task: there are too many factors to consider, and it is not always clear how changes in the route will influence QoE. Since the user's feedback can be dynamically retrieved, instead of a static solution for optimal route determination, the goal should be to have an adaptable and reactive system that gradually modifies its configuration towards improving QoE. The approach taken here is to use reinforcement learning (more specifically, Q-learning).

Here is a breakdown of the basic process of using Q-learning for routing control:

- All nodes have a table with values (called Q-values) that indicate the quality of the link to each of their neighbours
- In our case, the estimated QoE if the flow is directed through that link
    - So, when a data provider sends a packet to the end-user

- Each node in the route selects the next node using its Q-value table
- When the packet reaches the end-user, he sends a QoE feedback that travels back through the routing path
- Each node uses this feedback to update its Q-value table accordingly.

The whole process (selection, evaluation and learning) represents an adaptive, dynamic and evolving routing system focused on improving QoE.

For the QoE value, the SDM-C should calculate some form of numerical value (in the literature, Mean Opinion Score is commonly used [68]). As mentioned before, Section 6.3 proposes a QoS/QoE monitoring & mapping functions that could provide this value to the routing scheme described here.

QoE-based routing in mobile networks is a current and not fully explored area of research, with some work on wireless mesh networks [68]. Reinforcement learning for routing has been explored in other areas (mobile ad-hoc networks, for instance), and shown to be a good approach. Combining reinforcement learning with QoE seems a promising step in the right direction. An overview of the current state of the art on QoE-based routing can be found in Section 9.7.

When looking at the basic process outlined above, some questions arise, and some decisions have to be made:

- How to select which neighbour to route the flow? In the most straightforward way, the maximum Q-value could be used. This is not ideal. All the different links should be explored to reliably assess their impact on QoE. On the other hand, the selection process must converge in a timely manner.
- How reactive should the system be?
    - How quickly old information is replaced?
    - How much should change in the QoE affect the system?
    - Which initial values shall be inserted in the Q-tables?

Proposed Algorithm

Now that we have an idea of the general process and the motivation behind this work, let us describe a new algorithm for QoE-based routing for the 5G NORMA architecture.

First, this is how a node ***x*** updates its Q-table, when it receives the feedback from the node ***y*** ahead on the flow:

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

- $\mathrm{QoE_{xy}}$ means the estimated QoE value in node *x's* Q-table when directing the flow through node *y*
- $\mathrm{QoE_y}$ means the user's feedback (QoE value) received by 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
- The values $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ represent the learning rate and the discount factor.
- Learning rate ($\boldsymbol{\alpha}$): determines to what extent the new information will override the old information
    - $\boldsymbol{\alpha = 0}$ means disregard any new information
    - $\boldsymbol{\alpha = 1}$ means considering only the most recent information.
- Discount factor ($\boldsymbol{\beta}$): determines how important future rewards are for the system.
    - $\boldsymbol{\beta = 0}$ means only consider the current rewards
    - $\boldsymbol{\beta = 1}$ means look for long-term high rewards

Next, this is how node $\boldsymbol{x}$ calculates the probability of neighbor $\boldsymbol{y}$ being selected as the next hop, when the data is going from the data provider to the user.

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

- Probability of choosing link $\boldsymbol{xy}$ is the exponential of the current calculated QoE between node $\boldsymbol{x}$ and node $\boldsymbol{y}$ 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 $\boldsymbol{x}$
- The temperature variable controls how much exploration and exploitation will be done. Exploration here means trying many different links in order to understand fully how they react. Exploitation here means repeatedly using the links with good estimated QoE value. High temperature value means exploration. Low temperature value means more exploitation. Ideally, the system should start exploring a lot, and then eventually exploit the good links it founds.
- This temperature value should decay with time. Initially, the value should be high, then gradually decrease
    - Every time a selection is made, reduce temperature value by a certain percentage

This principle of promoting exploration applies to the initial conditions the system will operate with: all nodes will start by assuming high QoE values for all their neighbors. In the beginning, exploration should be maximized.

Future work

Simulations using network simulations (most likely ns-3) will be conducted. There are three goals to be achieved with these planned simulations:

- Find out optimal values for the learning rate and discount factor, values that make the system react appropriately to changes in QoE feedback
- Discover exactly how reactive the system is after these optimal values are discovered
- Compare the proposed system with Shortest Path Routing and Weighted Shortest Path Routing.

There are two possible extensions to the process proposed here. First, backwards exploration could be employed. Backwards exploration means that when a node receives a packet, it also receives information about the route taken by the flow so far. The best route going from the data provider and the user, as well as the best route going form the user to the data provider can then be determined. Second, dynamic ways of determining the learning rate and the discount factor should be explored.

6.7 QoE assessment through vehicular simulator

Vehicular communications are a kind of traffic that may need additional consideration in 5G networks. Flows initiated by vehicles (from both human and vehicles) may span over several kilometres, stressing hence the MME with a possible high number of handovers. Studying the impact that this class of flows on the cellular deployment and, hence, on the SDM-C is paramount to understand and correctly dimension the network infrastructure and the algorithms needed to ensure the optimized operation of the network. Also, the study of this kind of mobility patterns is an introductory step for the enforcements of vehicular-tailored QoE/QoS policies.

Flows assigned the vehicular category are then monitored, eventually enabling new traffic classes if there is the need to meet new QoE/QoS requirements. Road Side Units (RSUs) and short range Vehicle-to-Vehicle communications will play a fundamental role for this purpose, enabling both the continuous flow monitoring and the possible offloading to the Dedicated Short-range Communication (DSRC) Network.

Finally, the information of how the vehicular traffic affects the network can be used to both dimension the cellular network deployment (including DSRC based small-cells) and the infrastructure on the edge and central clouds.

Before going to a fully-fledged implementation, simulation is often a valid technique to initially assess the impact of vehicular movement on the network. In the clear majority of vehicular networking studies, the design and performance evaluation of solutions partially or fully relies on synthetic models of road traffic. Indeed, experimental evaluations would require large-scale testbeds comprising hundreds of vehicles, leading to overwhelming costs and organization complexity. Unfortunately, the correctness of this approach heavily depends on the selected tools. Therefore, an initial assessment on how to evaluate the impact of a highly demanding environment such as vehicular communications has on the cellular network is certainly a paramount step to perform.

As reviewed in Section 9 there are already plethora of networking simulations for vehicular networks. However, part of the problem stems from the fact that there is currently a lack of a clear understanding of which level of realism in road traffic modelling is actually sufficient and necessary to the simulation of the networking impact of vehicular movement patterns. Some efforts have been made to answer this question. However, either lacks of technical deepness or focuses on shot range wireless communications.

To provide a thorough evaluation of the impact of vehicular movements on a cellular network and hence use it to classify and enforce QoS metric for vehicular flows, some incremental steps need to be performed:

- To provide a consistent definition of the level of road traffic realism needed for the simulation of vehicular networks in a mixed urban/highway environment.
- Identify a set of metrics that, despite being necessarily circumscribed, covers a vast portion of the many and varied vehicular networking use cases. The selected metrics should be particularly meaningful for the classification of vehicular traffic and useful to identify the load introduced in the network by vehicular related service flows.
- Design an assessment algorithm that, leveraging on the best simulation engine and the set of retrieved metrics, can be used to improve the network configuration to better support this class of services.

The above points are summarized in Figure 58, describing the role of each sub block into the 5G NORMA vehicular evaluation platform.

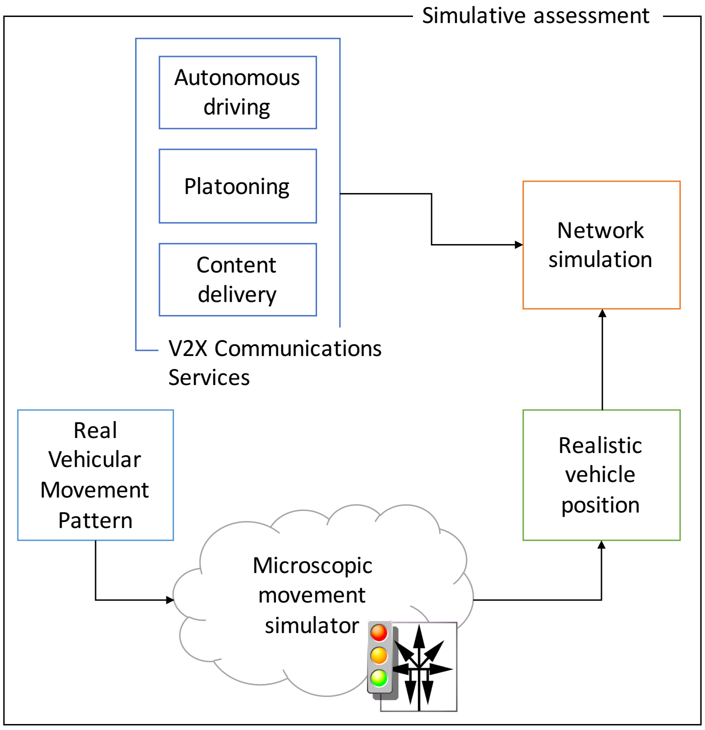

Figure 58: Assessment of the 5G NORMA architecture through vehicular network simulation

6.7.1 Methodology

As reviewed in section 9.8 there are already plethora of networking simulations for vehicular networks. However, part of the problem stems from the fact that there is currently a lack of a clear understanding of which level of realism in road traffic modelling is actually sufficient and necessary to the simulation of the networking impact of vehicular movement patterns. Some efforts have been made to answer this question. However, either lacks of technical deepness or focuses on shot range wireless communications.

In order to achieve the objectives declared previously, a realistic simulation environment should be set up. It must provide the following tools and data sources:

- **Digital Map:** a very critical component is a comprehensive representation of the physical infrastructure. This is not limited to the street layout and the interconnection among different road segments, but it also includes information about the telecommunication infrastructure. Two useful data sources for gathering this kind of information are OpenStreetMaps (OSM) for the road infrastructure and OpenSignal (OSG) for the cell position and coverages.
- **Microscopic Mobility Models:** The second element is represented by validated models of the driver's behavior, which describe, at a microscopic level, his decisions in terms of acceleration, deceleration, lane changing, and, generally, his reactions to the surrounding environment. This provides the precise location of vehicles at each moment throughout the simulation.
- **Macroscopic Traffic Flows:** the resulting mobility patterns should be realistic not only under a microscopic perspective, but from a macroscopic perspective as well. That is, the simulated vehicular aggregate flows should mimic the real values measured within the simulated area. This implies gathering information about the traffic demands between origins and destination in the simulated area (e.g., the so-called O-D matrix) and correctly assign those flows to the different available paths.

- **Cellular network simulator:** the aforementioned items are needed for obtaining the most precise and realistic position of vehicles with a very fine time granularity. This information is then used to emulate cellular network connectivity using a LTE simulator. The digital map is also used to infer the interference caused by buildings. The LTE simulator is a a multi-cell, multi- user LTE-advanced system- level simulator with real-time simulation capabilities developed by Nomor Research, that was also used for one of the preliminary 5G NORMA demonstrator [69]. The simulator incorporates LTE protocol stack model for the user plane. The protocol functionalities have been simplified to the main functionalities, in order to enable real-time performance. Particular focus has been laid on Medium Access Control (MAC) layer, in terms of functional accuracy. The physical layer (PHY) is emulated in its effect by using off-line link- level simulation results. This modeling also caters for the channel estimation, channel coding, modulation schemes, and receiver equalization. The simulator runs at Transmission Time Interval (TTI) level granularity along time and Physical Resource Block (PRB) level along frequency axis. This makes the simulations accurate and detailed enough to produce realistic results for analysis. The scenario used for carrying out the LTE network simulations comprises of multiple eNodeBs and users communicating over the radio interface, with 2GHz as the center frequency, 10MHz system bandwidth, and with TTI of one millisecond. Simulation parameters are presented in Table 10.

Table 10: Simulation Parameters

Parameter	Value
Center Frequency	2 GHz
Bandwidth	10 MHz
Fast Fading Model	Urban Macro (Uma)
eNodeB Tx Power	43 dBm
eNodeB Height	25m
Scheduler	Proportional Fair
Pathloss Model	WINNER+ [70]

All such components need to be integrated via a federated software suite which, i) can provide the requirements 1-3 with the maximum reliability and very high granularity (order of milliseconds), and ii) can be easily coupled with a state of the art network simulator.
This work is based on a seminal article [71] that provided a reliable simulating framework obtained by a refined OSM digital Map of the city of Bologna and a reliable O-D Matrix of the city. Moreover, we used SUMO [72], the state of the art tool for microscopic vehicular simulation. Finally, the Network Simulation is carried out using the emulator developed by NOMOR [69]. Finally we get the cell tower locations from OSG, filtering 210 Cell Towers

belonging to the 4 operators available in the Italian market.

Figure 59: Segment Popularity of the scenario (darker links mean higher loads)

Figure 59 represents the analysed scenario, whose characteristics are:

- Three hours' simulation of around 20,000 vehicles
- Peak occupation: 4000 vehicles
- Average trip time: from 10 to 15 minutes

The data regarding operators and cell towers were gathered from OpenSignal. The total of 210 towers is divided as follows: 63 of Operator 1, 60 for Operator 2, 53 for Operator 3 and 34 for Operator 4. Finally, vehicles are assigned to Operators according to their penetration rate: 34.43%, 32.16%, 23.13% and 10.28% respectively.

6.7.2 LTE performance assessment with vehicular use cases

The goal of this work is to provide some initial assessment of the impact of vehicular communications on a state of the art LTE deployment. Therefore, we simulated, using the input vehicular mobility described above, a collision avoidance system: one of the most typical applications of future vehicular networks.

Collision avoidance algorithm

Collision avoidance systems are used to early warn vehicles in the surrounding about abrupt decelerations or obstacles. This information is also useful for vehicle platooning purposes. Therefore, we implemented a Vehicle to Infrastructure (V2I) algorithm that sends a warning messages (2 Kbytes of data payload) to a centralized server that sends back the information to all the surrounding vehicles (the ones in a 200m radius) every time the headway vehicle is closer than 10m from the sender. All cars check for warning state at regular intervals of 2.5 seconds.

Scalability considerations

In order to overcome some of the physical limitation of the simulator, we reduced the simulation area to a 2 square km area, with 12 eNodeB managing 1500 vehicles. We claim that this subset is a valid representation of a small-scale scenario of the entire simulation. The eNodeB placement is detailed in Figure 60.

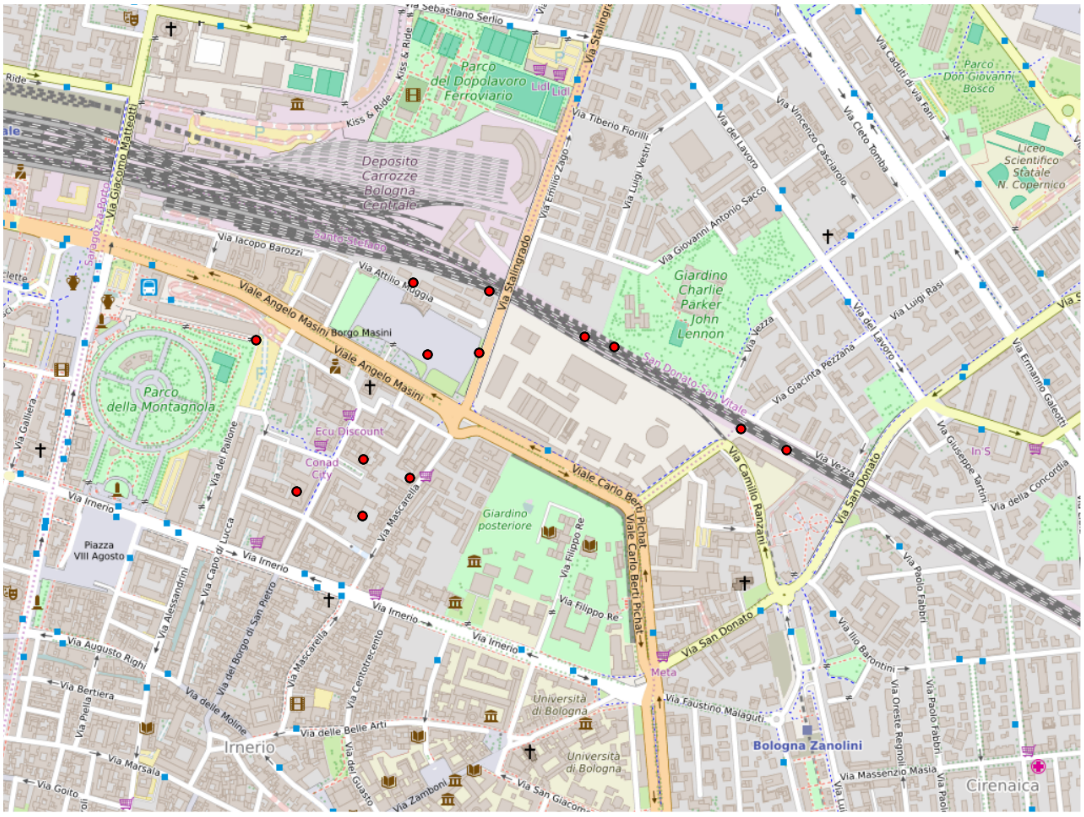

Figure 60: eNodeB placement in the simulated scenario

Preliminary results

We collect some preliminary results in the following. The first metric we consider is the uplink delay, that represents the total time that a packet takes to travel from one car to the central infrastructure. This also involves the LTE's inherent extra delays required for scheduling, uplink grant access and Hybrid Automatic Repeat Request (HARQ).

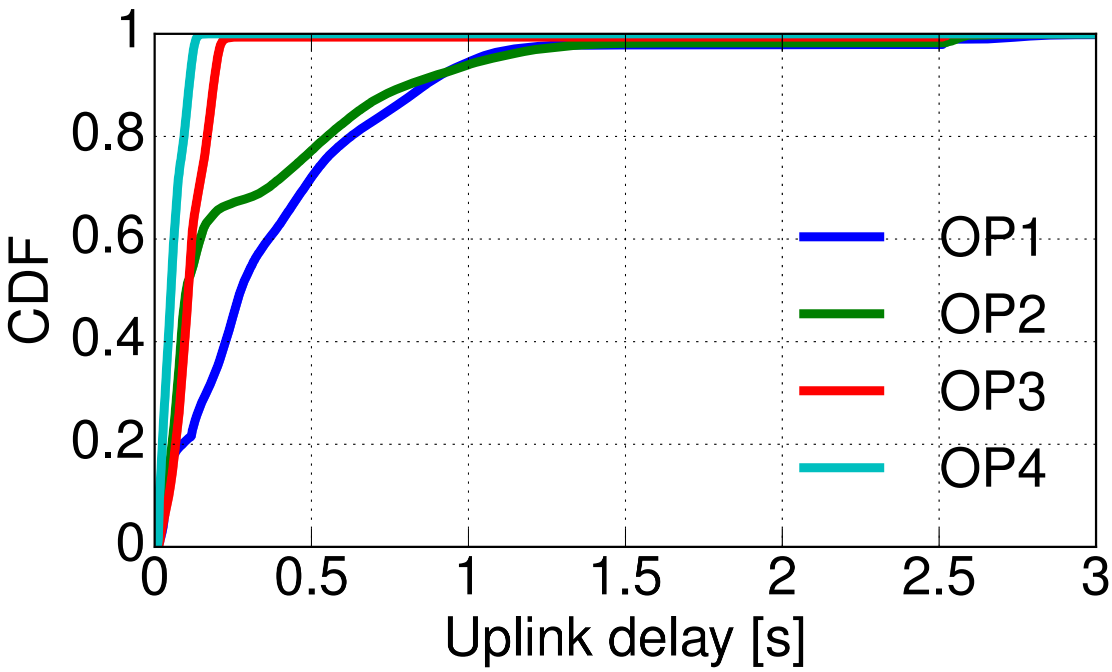

Figure 61: Uplink delay CDF

The CDF shown in Figure 61, detailed by each operator, show how the obtained values are well above the 100ms threshold usually considered as highest value for end to end vehicular communications [73] [74], values due to the congestion caused by the simultaneous access of many UE after possible temporary congestion for the red light cycles at intersections. This behaviour is also reflected by the time series of the delay values shown in Figure 62.

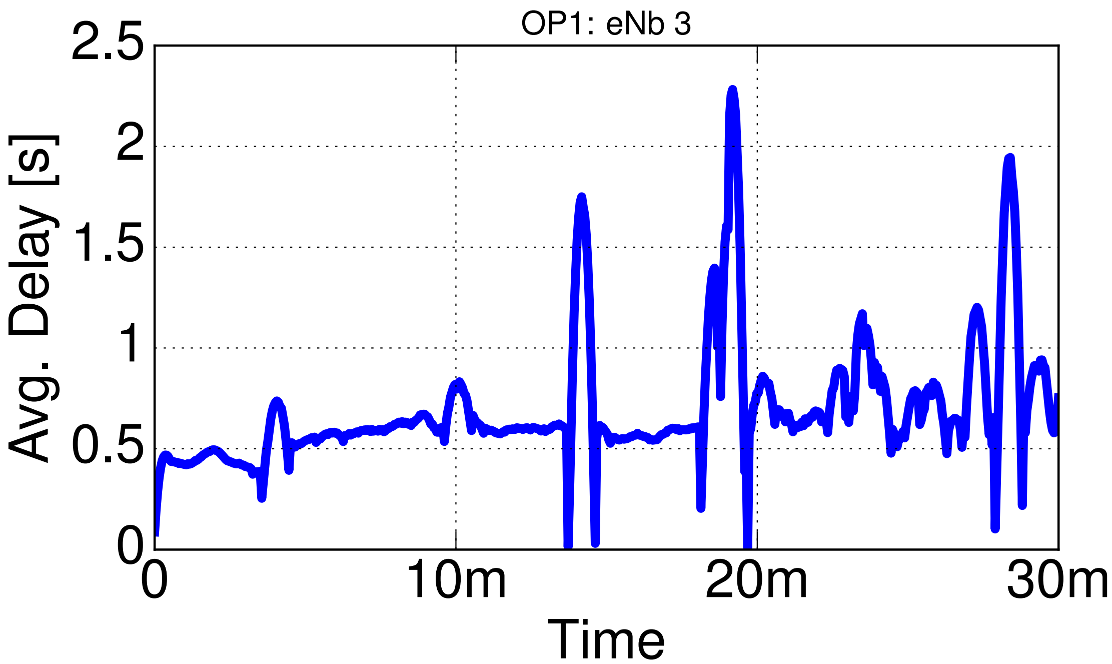

Figure 62: Time series of the average delay for an eNodeB

Besides the unconstrained delay problem, another issue that arises from introducing V2I traffic into the cellular infrastructure is the suboptimal utilization of the PRB, which may be used to obtain much higher throughput values.

6.7.3 Future work

We will extend the current extent of the simulation framework to cover:

- More heterogeneous scenarios, by isolating different areas of the digital map, showing how different vehicular traffic characteristics impacts on the obtained KPIs.
- An extended set of KPIs that will cover, for instance, throughput metrics.

Possibly different vehicular applications.

7 Mobility Management

7.1 Introduction

The challenging requirements in terms of mobility support in a future 5G system are less related to the increased data volume but more governed by end device and applications' variety. The expected amount of different terminal types covers beside handhelds and smartphones many different new machine-type devices and a broad range of services with mobility demands which range from support for zero or nomadic mobility only to that for high speed (e.g., vehicular) terminals.

While the connection characteristics change during movement across multiple cells and points of attachment, the session has to continue either coping with an endpoint address change or requiring fixed addresses. Also seamlessness with respect to the user or application experience may differ, demanding for minimal disruption without loss of information or being able to cope with “break before make" where a higher layer protocol cares for data completeness.

Mobility management here focuses on connection continuation and other mobility related procedures, like location tracking or paging are seen as assistant tools not dealt in detail here.

An efficient solution for serving all varying requests cannot be a single universally applicable mobility function, but has to follow a modular approach to adapt the network configuration according to the respective service or slice demands (i.e., the so-called mobility on-demand [75]). The challenge is to identify the actual demand as precisely as possible and select the best fitting solution depending on the overall scenario. Several criteria can be taken into account in the selection process, including the characteristics of the terminal and its environment (e.g., smartphone or sensor device in a pedestrian movement or attached to a car) as well as the network conditions (e.g., load of neighbouring cells and radio technology or specific parameters such as bandwidth and latency). On the other hand, also performance requirements of the application (e.g., in terms of connection reliability and session continuity) have to be considered.

Potential solutions may be based on the Distributed Mobility Management (DMM) approach as discussed at IETF (Internet Engineering Task Force) where a split of control and user plane functions and basic modular logical entities for anchoring, location and forwarding management are proposed. A contribution to the IETF, describing the DMM extension for flow mobility was addressed in this framework [27].

Special consideration has to be given to potential bundling of multiple links to enhance throughput and reliability. Such a multi-path connectivity is already available as carrier aggregation (e.g., bundling different frequencies within LTE technology) and known as off-load or local break-out when a cellular device with multiple interfaces connects (e.g., to home WLAN to access the Internet). A commonly managed standardized solution without need for customer interaction and covering heterogeneous access domains has still to be developed.

To provide extremely low delay connectivity (e.g., as demanded by tactile Internet applications) the content and processing resources have to be provided near the edge of the access link. Such distributed functionality in the Mobile Edge Cloud (MEC) has to be migrated efficiently in case of session endpoint movement but also due to load balancing reasons in case of resources shared between multiple slices. To keep latency and jitter in required limits demands for new mechanisms when taking the movement decision.

The major demands to the new mobility management protocol are, besides providing a high flexibility, also to grant high availability and reliability (e.g., by avoiding a single point of failure). Furthermore, they should contribute to achieve high resource efficiency (e.g., low signalling overhead, avoiding too much tunnelling, minimum redundancy in case of error retransmissions) and not increase the operational burden (e.g., in terms of deployment and network management effort).

In the framework of the 5G NORMA WP5, we split this thorough problem into two big areas (Mobility Management scheme selection and Mobility Management scheme design) and two targeted innovative approaches Multipath and Edge Functions Mobility. The functional architecture is depicted in Figure 63,

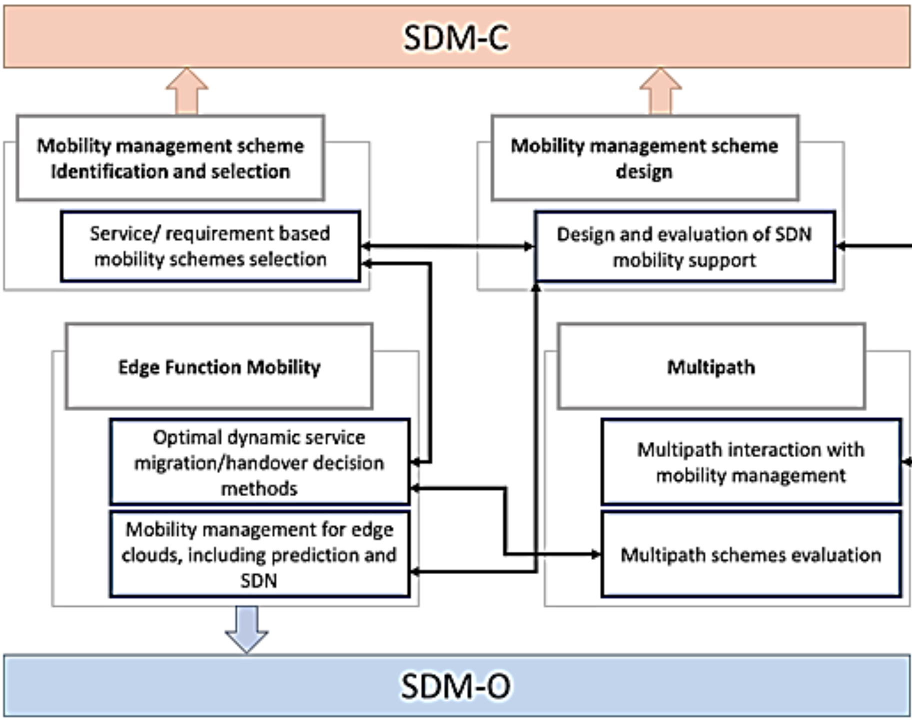

Figure 63: Organisation of Mobility Management Task in WP5

Figure 63 shows the needed interfaces among the different blocks of the Mobility Management entity and their integration with other elements of the architecture such as SDM-C and SDM-O.

- **Mobility Management scheme identification and selection**: This function takes the information about the mobility requirements of terminals attached to each network slice to select the most suitable mobility management scheme to be used. For example, an IoT slice do not need any specific mobility management scheme, while a Vehicular Network one may need an especially tailored mobility management scheme. The specific Mobility Management scheme is finally implemented in the framework of the Mobility Management scheme design function.
- **Mobility Management scheme design**: this function includes the actual design of the mobility management scheme using the SDM-C. By following the SDN spirit, the logic of the mobility management scheme is implemented as a Mobility Application that process high level primitives through the SDM-C 5GNORMA-SDMC-Apps Interface that control the underlying resources.

- **Edge Function Mobility**: When dealing with mobility, the movement patterns of users may involve the migration or re-instantiation of VNFs to a different edge cloud. This will involve the Mobility Management scheme to reshape the data plane from the access to the core and the Orchestrator to possibly re-allocate new resources in the edge cloud.
- **Multipath**: it has been proven that exploiting path diversity both in the access and in the core of the network provides advantages in terms of performance and reliability. However, the application of this kind of approach in the framework of Mobility Management has still to be assessed, by first integrating it into the mobility management and then by assessing the obtained performance.

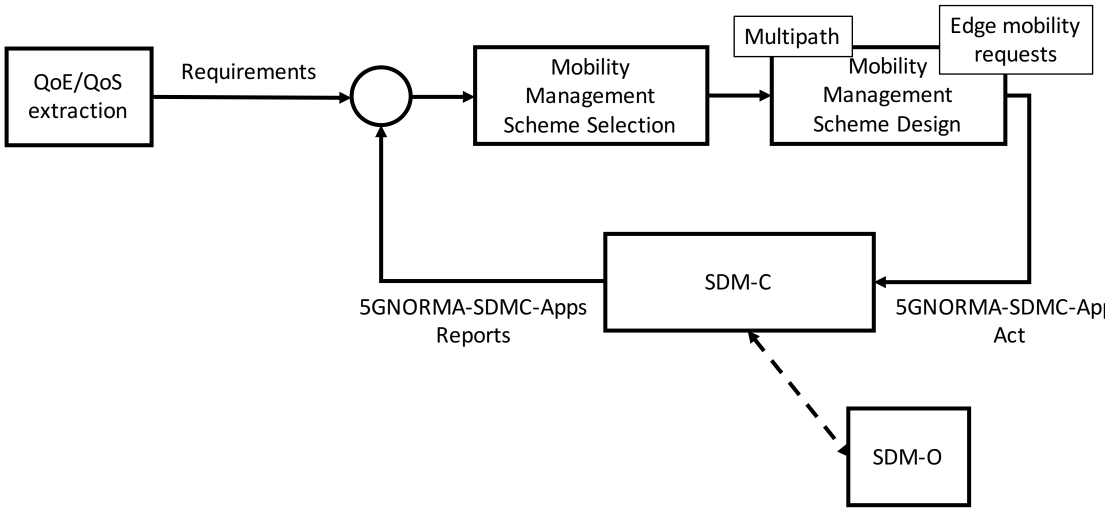

Figure 64: Interaction of Mobility management task with others

Mobility Management Lifecycle:

Figure 64 provides another view of the Mobility Management task: its control loop. Mobility management is applied on a per-slice basis, although it can be easily extended to control more than one slice simultaneously by using the SDM-X concept. First, QoE/QoS requirements are extracted from the service and they are provided to the Mobility Management module as reference. Based on this, the best mobility management scheme is selected according to the slice characteristic. Among the selection that the Mobility Management scheme may perform there are the possible use of multipath and the request for Edge Function Mobility: all of them are delivered to the SDM-C through its NBI. The SDM-C actually performs the control of the network slice by acting on the data path or by issuing new resources requests to the SDM-O. Finally, it reports back to the Mobility Management scheme the status of the network. This information is used to change the selected mobility management scheme, if needed, or for taking other mobility decisions.

7.2 Selection of Mobility Management scheme

The mobility management of current mobile networks has been initially designed to provide "one fits all" mobility management scheme, which enables lossless handover to all services. Such an approach is inefficient, as lossless handover might not be needed for all services, thus might unnecessarily introduce additional jitter in the data path. Given the variety of services that 5G networks can include, a more flexible mechanism for selection of mobility management schemes is required. In other words, in 5G networks, the mobility management scheme cannot remain fixed as in today's networks, but it needs to be selected flexibly according to the context of the service or a network slice. Envisaged 5G services and slices exhibit different demands for mobility support in terms of e.g., terminal speed, session continuation requirements, and of stability of the endpoint address.

7.2.1 Binding of Mobility Management scheme to Network Slices

In order to address the need for more service tailored Mobility Management (MM) support we aim at designing a network slice which includes specific network functions enabling a dedicated set of mobility functions inside this network slice. A way to realize this is to maintain specific flavours of network function and/or specific configuration of network functions and instantiate them according to the context of the network slice. The selection of appropriate mobility management scheme needs to be provided through a dedicated functionality, i.e. *binding functionality*. The binding functionality provides the mapping between the mobility related context of the slice, i.e. mobility management requirements and the mobility management scheme that supports the mobility requirements in the most suitable way. In particular, the binding function chooses a specific MM scheme for each network slice for a specified amount of time. The binding functionality takes into account not only the network slice context but also the predetermined policies in order to select a suitable mobility management scheme. Mobility management schemes can differ in many ways, e.g., requiring special handover policies and settings in the RAN, flexible mobility anchoring, adaptive gateway relocation rules, or customized network elements (e.g., local gateways or gateways with specific mobility support functionality). The selected mobility scheme determines the behavior of the BS and GW functions of a mobile network.

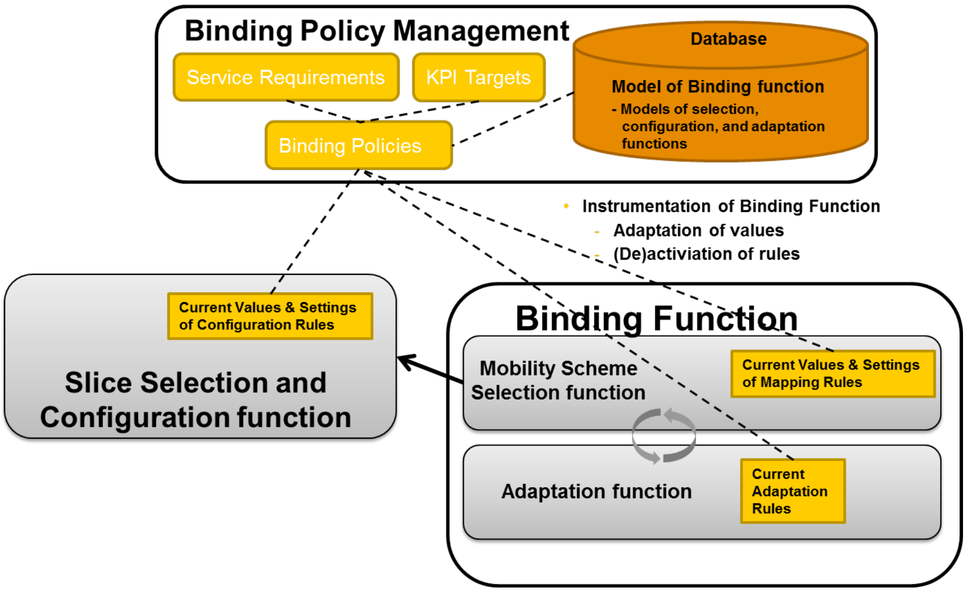

Figure 65: Binding functionality – building blocks

The binding functionality includes three blocks as depicted in Figure 65:

- Binding Policy Management
- Binding Function
- Network Slice Selection and Configuration

The binding between the mobility management scheme and the network slice configuration needs to be done based on predetermined policies which are maintained in the *Binding Policy Management*, see Figure 65. The Binding Policy Management function translates service requirements, operator targets, and KPIs to policies that have to be enforced on the network slice. Based on this, the *Binding Function* executes the actual selection of the mobility management scheme according to the predetermined rules, as well as the adaptation of such selection if needed. The Binding Function includes:

- A Mobility Scheme Selection function that translates mobility requirements to mobility mechanisms/schemes based on policy and mapping rules as provided by the *Binding Policy Management* function as well as context information available from the network.
- An Adaptation function that is applied during the runtime, which verifies the actuality of the mapping between current mobility requirements of a slice and currently deployed mobility management scheme and performs according modifications, i.e. re-mapping between mobility requirements and mobility management schemes.

Finally, a *Slice Selection and Configuration function* is responsible for selection of the right templates for slice instantiation (e.g. with right VNFs type selection and right composition and configuration of different VNFs).

Such a binding functionality in envisioned to be integrated with Management and Orchestration Layer of 5G NORMA, see Figure 66. For a given service requirements and network context the binding functionality gives two important outputs: the fitting template for slice instantiation/configuration and suitable mobility management mechanism/scheme. The resulting slice template will be used to instantiate and configure the network slice. Based on the slice template the new MM App will be instantiated on top of the SDM-C executing the MM scheme which resulted as the most suitable one. Alternatively, the suitable mobility management scheme can be updated/reconfigured on the existing MM App on top of the SDM-C.

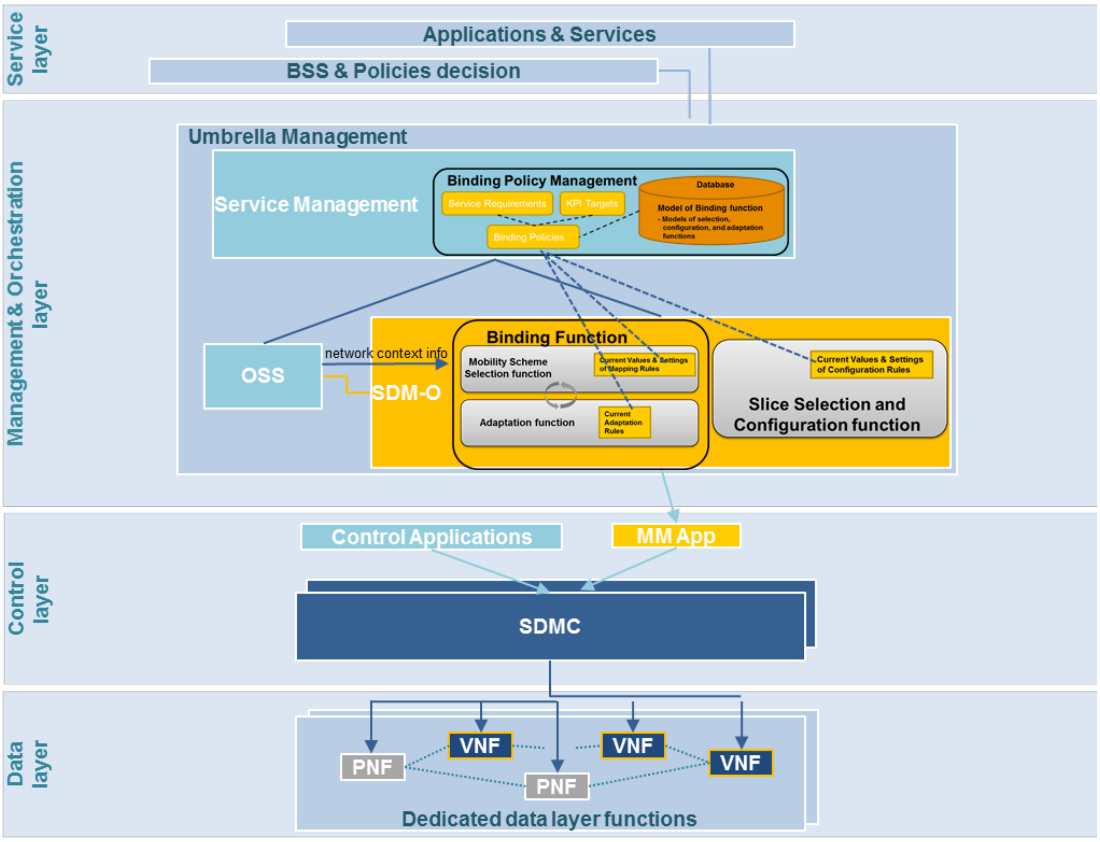

Figure 66: Mapping the Binding functionality into 5G NORMA architecture

7.2.2 Common vs. dedicated Mobility Management

Given the variety of possible slicing scenarios and existence of multiple slices at the same time, a mobile user can simultaneously connect to more than one network slice. We can envision that in such cases the slices can either have dedicated Core Network (CN) instances or have different level of CN sharing i.e. only some parts of the CN can be shared or entire CN can be shared among slices. In such scenarios, the exact implementation of mobility management especially in terms of designing it as dedicated (per slice) Mobility Management (MM) or common MM across multiple slices is impacted by the design and the level of sharing between CN elements. Hereby we can identify three options for mobility management implementation based on level of CN sharing among network slices to which an UE is simultaneously connected:

- Dedicated mobility management in a dedicated CN for each network slice handling the UE - UE obtains services from different network slices running different CN instances. This allows clear isolation between the CN instances of slices.
- Common mobility management in CN which is partially shared among networks slices. E.g., MM and identity/subscription management is shared between the network slices. In this case, other CN functions, such as, session management, are implemented in separate CN instances of network slices.
- Common mobility manager in completely shared control plane of the CN.

The dedicated MM approach in a dedicated CN although enabling the clean separation of network slices might come with the potential drawback of adding signalling in the network and over the air. On the other hand, designing the MM as a common entity adds implementation complexity and lowers the level of isolation between network slices.

Dedicated mobility management can be implemented in 5G NORMA architecture as an application on top of SDM-C, whereas common mobility management can be implemented as an application on top of SDM-X. In our current work (see Section 7.2.1) we considered the dedicated MM approach.

7.3 Mobility management scheme design

Research challenges addressed in this section is to define a framework for MM protocols, which in the context of 5G NORMA architecture is a SDM-C Applicatoin, in order to control user/service/device mobility per network slice and potentially in between slices (intra-/inter-slice mobility).

7.3.1 Mobility design in terms of MM functions granularity description

A highly granular service-aware mobility design shall be abstracted for both HetRAT (radio access agnostic) and multi-service environment to support a broad range of use cases. As far as possible the complexity to handle major use cases shall be reduced, at the same time allowing for adaptability to future new ones (not yet known).

Potential MM scheme implemented in a MM-App from a more formal point of view are whether and how they should include:

- Cross-Layer support (L2/3/4 and above) – i.e. either inherit from lower layer additional information in an abstracted way to improve the specific parameters (e.g. frequency of sending requests or updating timers) or rely on higher layer mechanisms to ensure that the service-specific session performance which was agreed on can actually be provided (since it is done anyway – such as packet re-ordering etc.)..).
- Cross slice/Domain/provider operation – dealing with the open questions whether a single MM functionality is responsible for multiple slices (like the SDM-X), how many different administrative domains of access networks can be combined by same (master) MM function, or whether several providers share a common (central) MM function (in analogy to roaming scenarios in traditional 3GPP architecture) .
- Required Granularity – in terms of session endpoint movement speed (e.g. per 10 km/h steps) or session continuity demands (per 10 s-session duration) or handover loss robustness (in amount of lost packets).).

- Distinction between local and global range – i.e. the question whether overall MM is composed of different Hierarchical MM functions to be applied, e.g. at access domain level, at core level, at inter-slice level etc. – and how the different mechanisms interwork with each other.
- Degree of Technology abstraction – being related to HetRAT specificity and also the cross-layer question.
- Multiple connectivity support – i.e. to which extent has the MM scheme consider multi-path and multi-link characteristics in a future multi-technology (hybrid) scenario on both access, backhaul transport and core level.
- Flexibility within an ongoing session – denoting the question whether during an ongoing session the mobility-related parameters may change (e.g. active radio interfaces) and how the affected service can be kept uninterrupted.

To be as generic as possible for each of the foreseen differentiation criteria a new entry in terms of e.g. the IPv6 protocol header may be specified. This could be done e.g. in terms of a more general connectivity option — perhaps even as option in the Hop-by-Hop Options header so that each node must process it — but in case of nodes not supporting the feature a silent discarding of the information should be possible. In this option flags for either choosing default values allowing for minimum overhead in case of the "no mobility" case for fixed session endpoints – or additional information on the different mobility processing capabilities might be provided. Potential Option Data could consist of flags within an 8-bit word e.g. as 'LDGHTMFR', denoting the above criteria each to be detailed in terms of an additional extension header only present in case the flag value is not 0. The eight flags are represented as following:

L: Layer sensitive information processing

D: cross Domain operation

G: Granularity of mobility support is further specified

H: Hierarchical mobility treatment in terms of e.g. local/global differentiation

T: Technology of access to be considered

M: Multiple physical links to build up a flow (or packet fragments)

F: Flexibility in change of session parameters

R: Reserved – for future use or inclusion of another extension covering more criteria

7.3.2 Decision on MM criteria

This discussion is ongoing (e.g. degree of UE mobility/session continuity level - see discussion at 3GPP SA2).

For aspect G: Granularity seems to be one of the extreme multi-faceted and diverse features as it may range from session endpoint speed via various session parameters to the required session or service performance to be supported. Accordingly, sub-features to be further specified may be defined here in terms of

- Movement granularity
- Session continuity
- HO performance
- Etc.

In case of an 8-bit word Mobility Extension > 0 for each of the flags set to 1 an additional sub-option information shall provide details on the criterion if possible and required – or the information provided allows to locate where the required information can be retrieved from, e.g. a Customer Data Base (CDB) or the EPS-entity HSS (Home Subscriber Server).

An exemplary default MM construction without any of the features above may apply for use case SNM (Sensor Networks Monitoring and event driven alarms) as the sensors are fixed and the performance is assumed to be less than best effort (here). This would mean:

- no layer sensitive information processing (only IP level context available)
- Single-domain MM operation
- No mobility support i.e. portability (session re-build after connectivity loss)
- One (global) mobility area only
- Single-technology (e.g. LTE-only)
- Single-connectivity (one active or available radio interface only)
- Fixed mobility session parameters (here: none)
- No further aspects to be considered

7.3.3 MM processes to detail signaling and interaction between (logical) entities (MSC)

In this section an exemplary MM process shall be analysed in terms of impact of the design criteria above. Choosing the Paging process as being potentially required for different types of mobility (e.g. portability as well as high speed moving terminals) the proposed message sequence chart is shown in Figure 67. This MSC is simplified here insofar as the exceptional handling of session requests due to sleep mode for UE and potential reasons for wake-up (ending this mode) are not shown. In case of discontinuous sessions a UE periodically enters an idle state to save resources. The access node (here: eNB) exchanges with an SDN-C App for MM (MM-App) information on UE status (e.g. connected at radio level) and currently active sessions (together with their mobility and support demands). The detail of these context data depends on the chosen granularity in terms of the above criteria as agreed on e.g. within the underlying policies, and/or determined by UE capabilities and session demands. This context information is centrally stored (here: at CDB/HSS) to be made available to the GW-App representing the interface to external networks and servers (e.g. where sessions are initiated or terminated). In case of such an external request for session continuation the required information as MDD (multi-dimensional descriptor containing e.g. slice instance and service type data) helps the MM-App to decide on the required level of granularity in MM design. E.g. the amount of associated domains or available technologies to be used for UE attachment may restrict the location areas and the effort to physically page the terminal. On the other hand in case of multi-hierarchical MM and outdated localisation information a paging process on global level may be initiated directly before spending too much resources on localised searches.

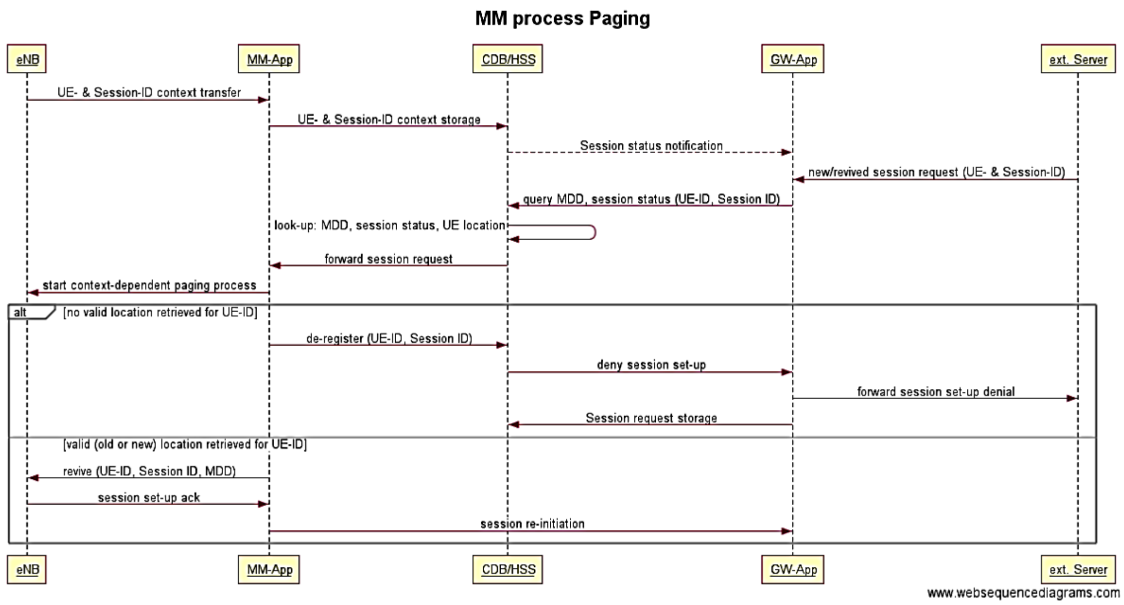

Figure 67: General message sequence chart for exemplary MM process Paging

7.3.4 Mapping of potential MM design approaches to use cases

As shown in Table 11 for the selected use cases of 5G NORMA (see [24]), a first try for identification of required MM features per use case is attempted. Here the column input 'x' denotes that the corresponding feature is further specified, i.e. with a flag set to '1' further specification of MM has to be provided (elsewhere). In case all flags are '0' default MM design (i.e., no mobility) is assumed for this use case (as detailed above) – e.g. for SNM use case.

Table 11 Mapping of selected MM feature impact on typical 5G NORMA use cases [D2.1]

Use case	details	Mobility demand	Comments	L	D	G	H	T	M	F	R.
eMBB	High DR	high	Mult. Serv.	x			x	x	x	x	
V2X	Var. DR	high	Safety/ctx	x	x						
911	Min. DR	variable	EE/prio/		x	x					
Jam	Var. QoS	low	High dens.				x	x	x		
RT RC	MEC	variable	ULL	x		x					
QaC	Var. QoS	variable	ctx	x		x		x		x	
Bl.Sp.	Multi link	low			x				x		
OA F	Var. QoS	low	High dens.				x	x		x	
Ind.c.	ULL/UHR	Low/no							x		
SNM	V Low DR	Low/no	EE/HR								
mMTC		variable				x					
FMC	Var. DR	variable	ctx			x					
Other	t.b.d.										

The justification and some more details on the use cases are given below:

Enhanced Mobile broadband (eMBB): Users ubiquitously connect to mobile network which provides extremely high data rates (DR): Users use multiple services and the network (service-aware) adapts accordingly. – Major functional requirements include multi-layer and multi-RAT connectivity and separation/prioritization of common resources.

Vehicle communications (V2X): Vehicles connect using 5G communications: Network provides multiple services to improve traffic safety, to assist drivers with real-time information about road and traffic conditions, etc. – Functional requirements cover massive scalability of protocol NW functions and especially to to keep track of devices' precise location.

Emergency communications (911): Network can be destroyed due to natural disasters: Network is able to adapt to emergency service requirements, prioritizing emergency services, minimizing energy consumption, etc. – Specific functional requirements are to support devices as relays and security.

Traffic Jam (Jam): a non-predictable high concentration of people using different services: Network reconfigures and adapts on a per-service basis to deliver appropriate quality to each end-user. – Functional requirements as sudden significant increase/decrease in access and signaling demand have to be fulfilled.

Real-time Remote Computing (RT RC): Remote execution of tasks allows relief of processing load at UE, rising battery lifetime and service speed: Specific service requirements have to be taken into consideration, adapting and allocating the computing load accordingly. – Functional requirements apply here as support of mobility scenarios (handover) (in terms of performance: at very high speed up to high speed train).

Quality-aware Communications (QaC): To offer an optimal service quality, network must be aware of specific requirements of each service type: Contextual information enables optimal network re-configuration for service quality delivery to end-users. – Performance requirements are important as fast/efficient handling of changing conditions (mobility, etc.)

Blind Spots (Bl.Sp.): Areas lacking resources and/or coverage due to scarce network performance (e.g. as to traffic demands and UE battery life): To effectively cope with this, service-awareness allows optimizing service delivery in this areas. – Functional requirements mainly as ask for multi-connectivity and reaction to transport capabilities.

Open Air Festival (OAF): Similar to traffic jam use case, high concentration of users accessing the network: Network needs to adapt and configure accordingly on a service basis to deliver a proper quality. – Functional requirements as the ability to separate and prioritize non-exclusive resources play an important role.

The following use cases have been characterised in [24] as having only medium or low relation to multi-service scenario:

Industry control (Ind.C.): no mobility, very low latency, high availability, high reliability and uplink data rate in a dense environment, self-organized dynamic networking for local multi-hop network – with functional requirements as fast failover and integration of heterogeneous radio technologies

Sensor Networks Monitoring and event driven alarms (SNM): support of service activation from RAN, of connection-less access, for high small and sporadic UL traffic (small packets) and high reliability of transmitted data in uplink – Functional requirements include no mobility signalling because of no "connected" state

Massive nomadic/mobile machine-type communications (mMTC): Support of dedicated slice(s) for massive machine type communication, of local as well as wide range device connectivity, and of on-demand mobility (e.g. no mobility required for stationary/nomadic sensors) - Functional requirements apply as direct device-to-device/gateway/cluster head/radio node connectivity.

Fixed-Mobile Convergence (FMC): changing mobility level, high heterogeneity in terms of environment, access and devices, converged network functions for both fixed and mobile networks result in simplified network operation (e.g. for AAA, ID management, billing). – Performance requirements as fast and seamless handover between (access) technologies and (fixed/mobile) domains must be considered.

Based on the analysis of use cases vs. design criteria in Table 11 a preliminary decision on Prioritization of MM design criteria is made:

Most prominent out of ten use case was Granularity (5 use cases) and a cross Layer/Technology operation (4 Use cases), respectively.

Use case with all three of these or at least two of the criteria present are: QaC (L, G, T, …) / eMBB (L, T, …) / RT RC (L, G, …). Planned for this document is to describe concept details for major MM model parameters selected (until M15, e.o. Sept. 16) which could be done in terms of process description for selected UCs (e.g. how to achieve mobility characterised by HHO / VHO / SHO / …BBM/MBB) – where the MM-App has to be adapted on all chosen slices flexibly but also efficiently.

7.3.5 Cross-Layer design of MM approach

Cross Layer information utilization could be to derive from signal strength and SNR or SINR criteria for promising connection quality to decide on HO from or to a new AP/AN.

Whereas in single technology (e.g. 3GPP LTE) for handover inter-layer information is used by nature already – at least from lower layers whereas information from higher layers (e.g. requirements and states at application level) not yet plays an important role at the moment.

A L3-based MM solution (i.e. on the first converged Layer in a heterogeneous access environment) requires for inclusion of multiple different Technologies when re-using lower Layer information to abstract this information from technology specifics. This can be achieved by usage of Media Independent Handover (MIH) framework developed by IEEE802.21 [76] proposed within many approaches as e.g. reviewed in in [77]. MIH shall provide capabilities to detect and initiate handoff from one network technology to another by defining mechanisms to easily exchange network information. The standard has designed a function to control access to the lower layers (layer1 and layer2) via Service Access Points (SAPs) and allows for information to be queried by the upper layers (layer3 and above). Media Independent Handover Function (MIHF) can be seen as layer 2.5 in the mobility control plane located between MAC and PHY layers, and the upper layers, namely IP and above. MIHF facilitates cross layer and cross-entity interactions as MIH Information exchange via MIH Command Services like Event Information Service (e.g. Media Independent Event Services as Link up / Link down). MIHF can be used to perform Network- initiated handoff and support the MTs handoff process.

MIH is also referred to in [78] which propose a mechanism via integrating a higher layer Multiple InterFaces Application Program Interface (MIF API) and IEEE 802.21 to support application service better. The two mechanisms, MIF API and MIHF, are working in different layers, defined by different organizations, but require compatibility e.g. in terms of some MIF API functions to be supported by a connection manager (i.e. the MIHF), and vice versa.

[79] describes a Mobility Services Framework Design (MSFD) for the IEEE 802.21 Media Independent Handover (MIH) protocol addressing identified issues associated with the transport of MIH messages. Mechanisms for Mobility Services (MoS) discovery and transport-layer mechanisms for the reliable delivery of MIH messages are described while for securing the communication between a mobile node (MN) and the Mobility Server either lower- layer (e.g., link-layer) security mechanisms or overall system-specific proprietary security solutions usage is assumed. Also higher layer information can be used in addition to support MM.

Context-Aware Mobility Management System (CAMMS) is introduced in [77] as cross-layer, context-aware, and interactive approach to seamless handover of users and services which defines components at both core/access network and user equipment node and takes into account factors such as QoS and cost. Several new architectures and techniques proposed until 2012 for dealing with such scenarios have been reviewed in [77]. The approaches are partly providing protocols for the application layer, the transport layer, or the network layer only. A number of mobility management systems have also been designed to support specific applications (such as IP Multimedia Subsystem and Ambient Networks).

The survey [77] presents a comprehensive review of literature on multiple mobility management architectures for seamless handover of mobile users in heterogeneous networks adopting a cross-layer approach such that gathering an assortment of information from several sources turned out to be a common technique.

Considering that the process of authentication (or re-authentication in the case of inter-domain handover) can lead to unacceptable delays, especially for streaming and interactive applications such as video conferencing and VoIP techniques and protocols to deal with handover keying can be part of the authentication component of such a MM architecture.

A cross-layer information system provided with context awareness at all layers of the protocol stack. The paper [77] focuses on mobility notifications and describes how application-mobility could be simplified in a network-layer mobility environment. An IPv6 solution is described that further enhances existing mobility management solutions. Discussed is the issue of how cross-layer communication could enhance detection of a mobility event. By sharing information between layers; mobility impact could be managed better (e.g. indicating link-layer parameters). This solution would also enable mobility adoption of multimedia traffic [80] .

In [81] the benefit of cross-layer information is evaluated from a Cognitive Radio application point of view which also can support mobility decisions e.g. in terms of information exchanged between the link layer and layers above it. Network coding which spans across the physical, link, and network layers; also gains from information sharing between layers for correct operation.

Awareness of the traffic demands of other users is important to allow addressing the trade-off between fulfilling the user demand and achieving increased radio resource utilization. Transport layer throughput can be maximized by employing cross-layer schemes e.g. for TCP to consider link layer frame size.

[82] states that most of existent solutions for seamless handover attempt to solve the problem at L2 (access and switching) and L3 (IP) with particular consideration given to L4 (transport). The fact that they are generally not yet working properly, may result in service disruptions. Because of this, it is important to develop cross-layer architectural solutions where cooperation is established between L2 and L3 to assist the IP handover process and to improve the performance. Even better would be to develop architectural solutions where IP has control over specific L2 handover-related actions.

Important limitations are the lack of cross-layer awareness and cooperation. For instance, the congestion control mechanism of TCP is not able to distinguish packet losses due to link properties from those due to handover. Because of this, TCP does not perform well for seamless roaming. In a similar way, the lack of L2/L3 cross-layer interaction further deteriorates the performance. Another fundamental limitation of transport protocols is because they cannot deal with mobility on their own.

[82] propose an application layer mobility system (based on SIP [83]) together with IEEE 802.21 and Media-independent Pre-Authentication (MPA).

[84] proposes a cross-layer mobility handover scheme for IPv6-based vehicular networks. The scheme is based on a proposed architecture for vehicular networks made up of three hierarchies. A vehicular network is made up of multiple road domains, a road domain consists of multiple road segments, and a road segment includes multiple clusters. A vehicle can either be cluster head (CH) with routing and forwarding function, cluster member (CM) without routing or forwarding function, or an isolated vehicle (IV). A CH communicates directly with a base station, and a CM achieves the communication with the Internet through its CH. An IV is a node which does not join a cluster. The corresponding cluster generation algorithm is based on the link duration time. The cross-layer mobility handover algorithm launches the handover in the network layer (L3) before the one in the link layer (L2). Through the L3 handover process the information on the L2 handover can be acquired in order to achieve the fast L2 handover. Moreover, during the L3 handover process, a vehicle does not need to be configured with a

care-of address (CoA), so the L3 handover delay and packet loss are reduced. Evaluations comparing this approach with standard MIPv6 and ePFMIPv6 (enhanced Fast Handover for PMIPv6 for Vehicular Networks) [85] show that as a function of speed both loss rate and delay will considerably benefit, though less at higher velocity. Numerical results reported in [85] underline e.g. loss rate decrease to about a tenth and delay reduction by at least a quarter, respectively (i.e., loss rate decreases from 6-8% to less than 1% at 100 km/h and 3% to 0.3% at 70 km/h and delay is reduced by 15-9% at 100 km/h and 24-17% at 70 km/h, 77-82 ms to 70ms at 100 km/h and 64-69 ms to 53 ms at 70 km/h).

[86] gives an overview on major architectures supporting management of handover in mobile wireless communications. Examination of about hundred schemes highlights that a solution to provide optimum handover management is not yet available. Disadvantage of widespread approach based on MIPv6 is the unmanageable deployment in current IPv4 networks and the existence of symmetric firewalls and NATs preventing an end-to end communication. This fact together with popular applications and protocols violating protocol stack stratification by using cross-layer information leads the authors to the conclusion that exploiting two proxies on top of the transport layer (locally and externally) is more workable than some network-layer solutions.

The handover support of MIPv6 solutions without cross-layer interoperation is restricted to single-network interface usage at the MN due to expected poor performance in terms of introduced latencies and connection continuity intervals in case of multi-homing.

For short- or medium- term the re-use of application and related protocols-based use of external proxies (e.g. VoIP-, SIP-, and partially HTTP-based ones) to cater for mobility issues as has already been proposed earlier by same authors in [87] and [88].

Cloud computing environments are seen as usable infrastructure providing dynamically set up (and release) of the proxies on the server-side, allowing for an on-demand resource utilization and cost model.

Parameters available at the physical and datalink layers which could be used for differentiation in cross-layer design and as metric to decide on a handover are mentioned throughout literature. At PHY level they comprise the Received Signal Strength Indicator (RSSI) (as measurement of power level received at the NIC to decide on best AP), In-phase Quadrature (IQ) sampling information, Channel state information (CSI), Propagation information, External interference as e.g. Interference Signal Code Power (ISCP) and SINR patterns [81]. At L2 the number of frame retransmissions (needed at the Data-Link layers for delivery between MN and AP), MIH primitives offered at the operating system level (as described in [76]), or at L4 the Transmission Error Detector (TED) (as software tool providing the MN with information about success rate of datagram reception at the AP) [87] can be delivered to higher (i.e. application) layers of the protocol stack to trigger a handover decision respectively. In this way, it is possible to devise cross-layer strategies for managing NICs and performing vertical handovers.

Outcome of the review above is a collection of parameters measured or parameter changes detected, and provided by different layers to support MM decisions. Depending on the technologies used at various layers and also the applications or environments in mind this may comprise:

- L1 (PHY): RSSI, IQ sampling information, CSI, Propagation information, ISCP and SINR
- L2 (Link): Retransmissions, Frame size
- L2.5/L3: MIH primitives, MIHF, Event Information Service
- L3 (Network): IP Routing information
- L4 (Transport): TED
- Above L4 (e.g. Application): MIF API, VoIP/SIP/HTTP Proxy

7.3.6 Cross-Technology MM schemes

As the diversity of available networks increases, it is important that mobility technologies become agnostic to link layer technologies, and can operate in an optimized and secure fashion without incurring unreasonable delay and complexity [89]. Supporting handovers across heterogeneous access networks, such as IEEE 802-basedWi-Fi or WiMax and global mobile cellular communications – and in the view of FMC also fixed line connections - is a challenge, also due to different characteristics in terms of QoS, security, access control, and bandwidth. Similarly, movement between different administrative domains poses a challenge since MNs need to perform access authentication and authorization in the new domain. Thus, it is desirable to devise a mobility protocol enhancement or even a protocol-independent optimization technique that can reduce these hurdles and subsequent delays as e.g. described in [90]. As the technology characteristics differ generally on lower layers similar issues as in cross layer information issues apply: In MIH, the handover procedures can use the information gathered from both the mobile terminals and the network infrastructure. At the same time, several factors (some of which are slice- or service-specific) may determine the handover decision, e.g., service continuity, application class and QoS, negotiation of QoS, security, power management, handover policy etc. IEEE 802.21 facilitates, speeds, and thereby increases the success rate of inter-technology handover decision making and other pre-execution processes.

Similar as above also for a cross-technology handover a context aware decision making should be supported. The underlying context management shall be standardized across the technologies and must be fast enough to provide the fresh context for decision making procedure, while the overhead of gathering the context should be tolerable. A unified framework managing network context information is helpful to integrating heterogeneous networks. [91] has identified the gap that currently there is not any standard method for context management in context-aware handovers. Vertical Handover Decision (VHD) Criteria cover Received Signal Strength (RSS), Network connection time, Available bandwidth, Power consumption, Monetary cost, Security, and User preferences.

A detailed analysis of VHD algorithms resolves that a multi-criteria solution is needed. The criteria for comparison of 12 algorithms referred to in [91] are Delay, Number of handovers, Handover failure probability, and Throughput – and a grouping into four categories, i.e. RSS based, Bandwidth based, Cost function based, and Combination algorithms has first been provided by [92].

A Handoff Protocol for Integrated Networks (HPIN) proposed in [93] implements access router and network discovery based on message exchanged between the IDE (Interworking Decision Engine) and mobility agents, minimizing the usage of limited wireless resources and providing fast mobility and secure transfer. The Resource Management Module (RmM) enables QoS mapping and re-negotiation between participating access technologies. A Handover Decision Module (HdM) shall enforce handover policies, i.e. which technologies to be considered.

Summary on VHO/cross technology and heterogeneous mobility is the need for a flexibility to consider multiple types of context information which has to be available in an abstracted and thus comparable manner. Based on the criteria (differing per service and slice) to trigger a handover initiation the decision algorithm has to compare different technology performance parameters. Based on lower Layer information a priority mapping containing each of the available technologies has to be provided to the MM decision algorithm.

7.3.7 Granularity consideration in MM protocols

Granularity of a MM protocol is understood as flexibility to serve different types of users and usage scenarios with respect to e.g. the coverage offered in combination with a service. This may be reflected in required cell size according to speed of the terminal. According to [94] a classification can be applied as given in the following definitions:

- Mega-mobility is the mobility between the networks of different providers or technologies, e.g. satellite to UMTS to WLAN to Bluetooth, etc.
- Macro-mobility is the mobility between different “visited domains” but still within one network.
- Micro-mobility is the mobility between different “location areas” but still within one visited domain.
- Mini-mobility is the mobility between different “access point regions” but still within one location area.
- Pico-mobility is the mobility between different “access points” but still within one access point region.
- Nano-mobility is the mobility within the zone covered by one access point, where the cell zone can vary from mega-cell down to nano-cell (of personal area with 1m-10m cell size). One access point may employ several logical channels.

Mobility of various granularities can be discussed in terms of typical operations of mobility management as location and handoff processes Usually MNs can be operated in different states – e.g. active and idle state during which the location has to be known (and be tracked) with different precision. In the simplest case an MN in active state has to be tracked at the finest granularity such as its current base station whereas an MN in idle state needs to be tracked at a much coarser granularity (paging area). The MN updates the network less frequently in idle mode (every paging area change) than in active state (every base station). The cost of paging, however, is the complexity of the algorithms and the protocols required to implement the procedures, and the delay incurred for locating an MN. In addition to these two states more granularity would be provided by introducing states in between (as e.g. semi-active or semi-idle allowing for more delay between successive data transmissions, e.g. for web browsing or non-real time file transfer compared to streaming).

A different understanding of granularity is followed by [86]: Their classification relates to the granularity of the service, i.e. to the target (node, channel, packet, etc.) to be assigned to a selected NIC. When triggered, per-node solutions migrate every active flow by adopting a coarse-grained approach and exploiting one NIC only, according to the requirements of the whole node. The MM feature is how fine granular the protocol can support an independent per packet/flow/session handover or between multiple channel (in case of aggregation or bundling) or multiple access nodes and technologies (assuming that the MN has activated the corresponding NICs).

Criteria for granularity identified so far are network and service specific features such as cell size and MT speed, MT type (e.g. handhelds, vehicles, MTC devices – see results mentioned above in section 7.3.5 and [85]), MT activity, session continuity requirements, QoS degrees to be supported. A tight correlation with amount and type of available access technologies has to be considered.

7.4 Edge Mobility

Mobile edge clouds are a new approach for reducing the load on the core network, since moving applications and services to the edge allows for lower operational costs, network overhead and latency. Users will be served by different edge clouds as they move around the world. They will also expect service continuity. This means that applications, services and VNFs will have to be somehow migrate across the network as users change their covering edge cloud. Migration will entail different transmission costs, and potentially lead to brief service outages. On the other hand, continue to serve a user now located in distant edge cloud will increase latency and potentially degrade QoE. Assuming a user moves from one cloud to another, the challenge then is to decide if/when to make this migration.

The 5G NORMA architecture allows for dynamic allocation/instantiation of VNFs, placing them either in the edge cloud or in the central cloud. User mobility influences service performance, especially for edge clouds, so the architecture must have a placement decision method for those functions. This method should use different criteria and provide the optimal position for the function to be at any given time.

It is important here to emphasize that migration could mean either live migration or duplication and reconfiguration. Live migration means the instantiation of the same VNF, followed by the live transfer of memory, storage and network connectivity from the original VNF to the new VNF. This type of migration is suitable for a function like Content Caching. Duplication and reconfiguration means a new instance of the VNF in another location, followed by redirecting all users to using the new instance. There is no transfer of memory or storage. This type is best suitable for stateless functions.

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.

The goal is seamless service connectivity. The decision method for VNF migration should minimize service outages, while at the same time prevent QoE from degrading when users move between edge clouds. Any proposed solution should be a trade-off between these two requirements. It could be assumed that the VNF should always follow the user to maximize QoE, but that would lead to the VNF hopping between edge clouds as the user moves around. Therefore, the migration should only take place when the impact of remaining in the original cloud is large enough to warrant "paying" the migration costs.

Any placement decision method must model the following issues:

- The user mobility
- The migration and communication costs

For the user mobility, the model is a uniform 2-D random walk model, where the user moves within a hexagon cell structure. At each time step, the user has the probability $\boldsymbol{m}$ of moving to any of its neighbour cells, while the probability of staying in the same cell is $\mathbf{1 - 6}\boldsymbol{m}$. The migration cost model will be based on distance between the cell of the mobile edge cloud and the current position of the user. The central cloud is considered equidistant between both original and serving edge clouds. In figure 54, 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.

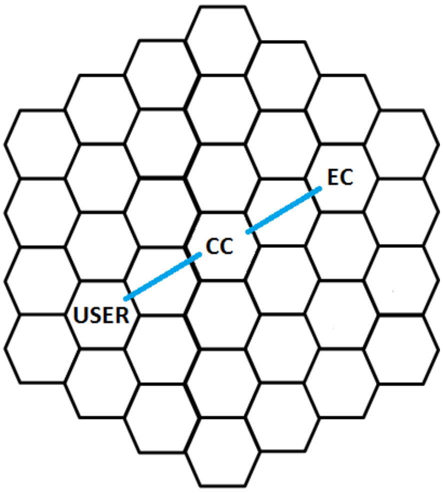

Figure 68: User Mobility Model

Next, the migration and communication costs must be modelled. The migration costs represents the "price" to pay for migrating, and the communication cost represents the price of continuing to use the VNF hosted in the original cloud, transmitting the data to the serving cloud. Ideally, we would like to have a way to model the migration and communications costs as functions only of the distance between hosting and serving cloud in our mobility model. Many factors influence migration and communication costs, but we are interested in comparing them head-to-head in our decision method.

A function called constant-plus-exponential can be used.

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

Variable $\boldsymbol{d}$ here represents the length of the shortest path between two cloud hosting cells. Parameter $\boldsymbol{\theta}$ can be manipulated to create any arbitrary cost function that best fits the migration and communication costs for a certain network function. If the user is in the same cell as the hosting cloud, then the cost is zero. Using this cost function, it is possible to quickly calculate the migration and transmission costs of all cells in the considered grid at a certain time.

Our placement decision method will use Markov Decision Processes (MDPs). The main decision here is if at any given time the network function should be moved. User movement is random and the migration and communication costs are not constant. This type of scenario (outcomes are partially random and partially under control) is ideal for MDPs.

Let us define the MDP:

- The set of state **S** will consist of all position in the hexagon structure where the user can be
- The action set **A** has three possible actions : no migration $\boldsymbol{a_{nm}}$, migrate to central cloud $\boldsymbol{a_{mcc}}$ and migrate to serving cloud $\boldsymbol{a_{msc}}$
- The state transition probabilities are given by the mobility model: the user has the probability $\boldsymbol{m}$ of moving to any of its neighbour cells, while the probability of staying in the same cell is $1 - 6\boldsymbol{m}$ This holds regardless of which action is taken
- The reward function is the communication cost $\boldsymbol{cc}$ minus the migration cost $\boldsymbol{cm}$**.** As mentioned before, the costs function are based on the distance between two cells. The distance used varies depending on the action:
    - For $\boldsymbol{a_{nm}}$ and $\boldsymbol{a_{msc}}$,use the distance between the hosting cloud and cloud the user will be, to calculate both the communication and migration costs

- For a_{mcc} , use the distance between the hosting cloud and the central cloud to calculate the migration cost, and the distance between the central cloud and the cloud the user will be, to calculate the communication cost
- The discount factor γ can be set through fine-tuning

Modified policy iteration can be used to solve this MDP. Every time the user changes cell, this solution will be run again. If migration occur, the same procedure can be executed, only with changed hosting cloud, central cloud and serving cloud positions.

While there is some work on the area of service migration in mobile edge clouds, the solution described expands this by considering the division of edge and central cloud. The existence of the central cloud makes the current solutions not sufficient, since they assume services can only reside on a mobile edge cloud.

We plan to have simulations in other to compare our placement decision model to other approaches:

- never migrate (functions will never move, and user requests are routed to the edge cloud running the functions)
- always migrate (functions follow the user closely)
- always migrate first to the central cloud

The SDM-O will have a module for determining the placement of a network functions or service. As output, the module will provide a placement decision. The SDM-O will then organize the migration using the VNFMs and VIMs.

7.5 SDM-C based mobility

The current distributed architecture for RAN and EPC is based on different interfaces that interconnect several eNBs to the elements that take care of control and data planes. With *network programmability* and *network virtualization*, this difference is much more blurred.

These are two key features of the SDM-C approach. However, to increase the flexibility of the controller, heterogeneous Southbound interfaces and Applications may be designed.

Namely, with the involvement of the RANaaS concept, the higher layers of the RAN stack can be decoupled from the lower ones and possibly integrated into the functionalities that are commonly carried out by EPC. According to the chosen RANaaS split, different optimizations are possible. They are detailed throughout the rest of the section.

7.5.1 RRC-PDCP

The first possible split below the full eNB configuration (a use case already considered by the current ONF architecture) is the RRC-PDCP split. The proposed architecture is depicted in Figure 69.

This split is a pure c-/u-plane split. The RRC layer does not handle any data- path functionalities, so the architecture is identical to the one already proposed by the ONF. S1-U tunnels are directly managed by the PDCP layer, so the tunnel creation requests are handled as the usual way.

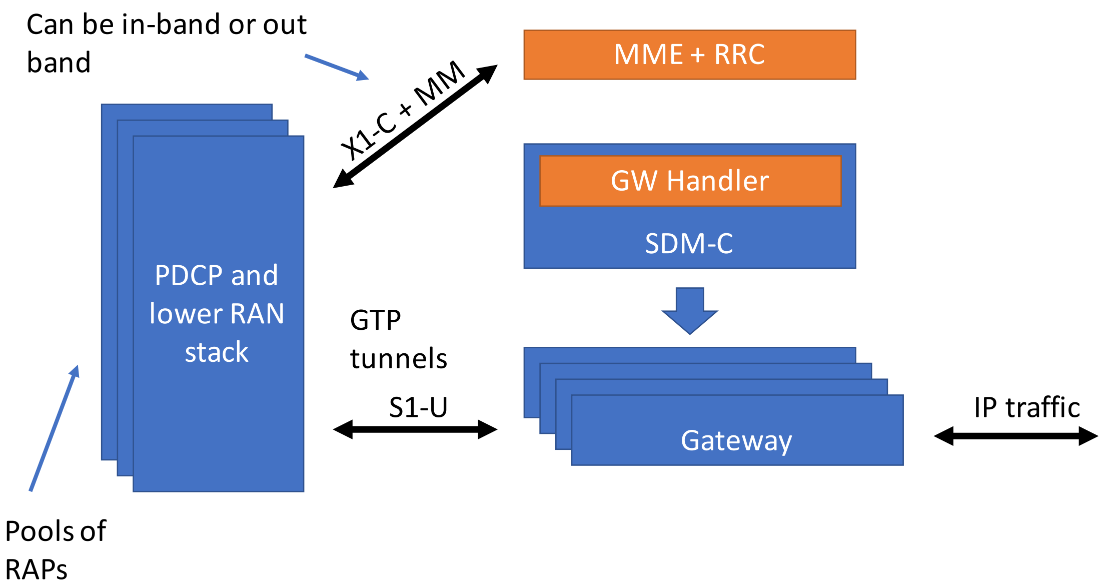

Figure 69: RRC-PDCP split

Although not directly related with the ONF architecture, possible improvements are possible within the MME entity, that can be enriched, leveraging the information coming from the RRC. Ideally, having a unified RRC layer allows to take joint handover decision, removing part of the message exchange for handover requests, allowing thus a more optimized handover procedure.

In this case the mobility management algorithms are not affected by the split itself, but rather by the availability of centralized handover decisions. This will help the handover decisions and it will be the first step towards the joint optimization of RAN and Core functions.

Modules

The SDM-C application that optimizes the handover decisions takes into account the several base stations it manages, and assign user flows (GTP tunnels through the S1-U interface to the best path). The information about the available eNB comes from the already considered, but not yet standardized X1-C interface. This communication can be in band or out of band.

Interfaces

For this split, two interfaces need to be defined. The one marked as A in Figure 69 that controls the switch configuration. This interface has to configure GTP tunnels from the eNBs (up to the PDCP) and the SDN enabled switches that act as S- and P-GW. Similar extensions are currently being standardized by ONF, in which tunnels IDs are directly used to setup Openflow rules.

Additionally, two control interfaces are needed to abstract the RRC and Mobility Management/ NAS messages. RRC information can be delivered through an X1-C interface, while the interface to the Mobility Management functions has to be abstract from the Low level mobility messages (i.e., UE attach, Handovers, Paging…).

As reference we include in Figure 70 the MSC for a generic handover process and how the MM Application (and the GW-application controlling the gateways) performs an handover between eNBs.

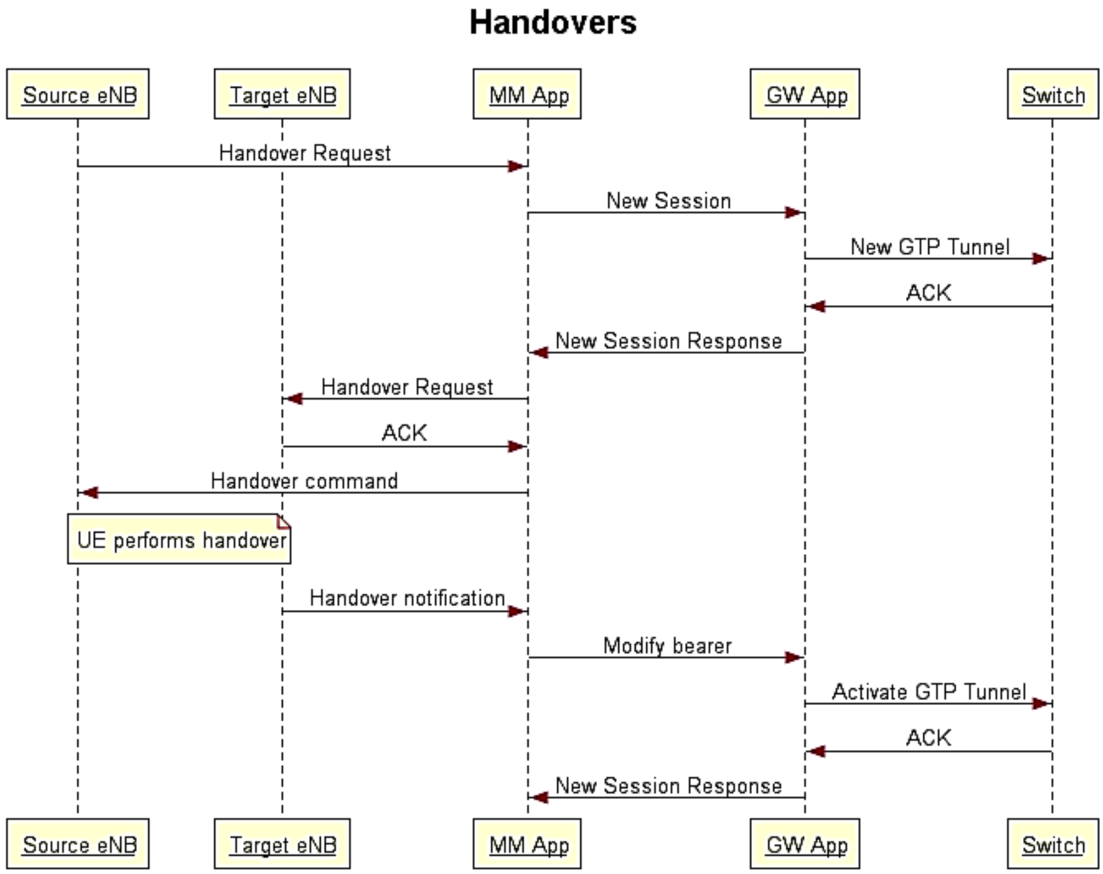

Figure 70: MSC for the Handover procedure using the SDM-C Mobility Management

The granularity required by the Mobility Management interface include messages currently exchanged between the UE and the NAS.

7.5.2 PDCP-RLC

This deeper splits involves more complex procedure compared to the RRC-PDCP split detailed above. As the functional split is performed through two u-plane functions, different primitives have to be defined in order to deliver user flows (radio bearers in this case) between the machines running the RLC and PDCP entities.

More in details, two specific problems have to be tackled:

- Define a message format for delivering data from RLC to PDCP. 3GPP is currently standardizing the Xn interface, which may be used as starting point for this split.
- In order to apply the SDM-C concept to this function, some of the PDCP functionalities may be treated with a Logic – Agent approach as defined by SDM-C.

The RLC layer expose logical channels to the PDCP layer:

- Transparent Mode, TM (BCCH, PCCH, CCCH): Packets are send through these channels without any modifications. It is used for Broadcast, Paging and RRC Control Messages.
- Unacknowledged Mode, UM (DTCH): Packets sent through this channel are segmented and reassembled but unacknowledged. Therefore, they need re-ordering and decapsulation (performed at PDCP layer)
- Acknowledged Mode, AM (DTCH): Packets sent through this channel are segmented, reassembled and acknowledged. Re-ordering and decapsulation are also needed.

These three channel types are clearly envisioned for providing different kind of services:

- Transparent Mode: PDCP layer is completely bypassed here. RRC control messages are sent using this mode. No concatenation, segmentation or guaranteed delivery.
- Unacknowledged Mode: Used for delay-sensitive and error-tolerant traffic. RLC performs re-ordering, re-assembly using a RLC header.
- Acknowledged Mode: Used for error-sensitive and delay-tolerant traffic (TCP traffic). RLC performs re-ordering, re- assembly and retransmissions using a RLC header.

Therefore, RLC offers three SAPs to the upper layers: TM-SAP, UM-SAP and AM- SAP that should be used by a "centralized" implementation of the PDCP layer using extensions of the OpenFlow protocol. The functionalities carried out at the PDCP layer are essentially three: i) header compression, ii) security and iii) re-transmission and re-ordering during an handover.

The architecture of PDCP is depicted in Figure 71 Control Bearer and Data Bearer are mapped to different PDCP entities and then to different RLC Channels (AM for control, AM or UM for data). Note that sRB-0 is sent over transparent mode (no ciphering) and bypasses the PDCP.

For this purposes three kind of PDUs are defined: CP Data PDU, UP Data PDU and PDCP Control PDU. They are used by the Control Plane and User Plane packet management as depicted in Figure 72 and Figure 73.

Splitting between RLC and PDCP means to handle the concept of radio bearer, as it is not transparently handled by the sub-RRC anymore. Different radio bearers (SRB-1,2 and all the U-RBs) have to be explicitly handled by the PDCP OpenFlow extensions, carrying out some atomic functions that are currently fulfilled there: Sequence Numbering, Integrity and ciphering, Header Compression and Header Management.

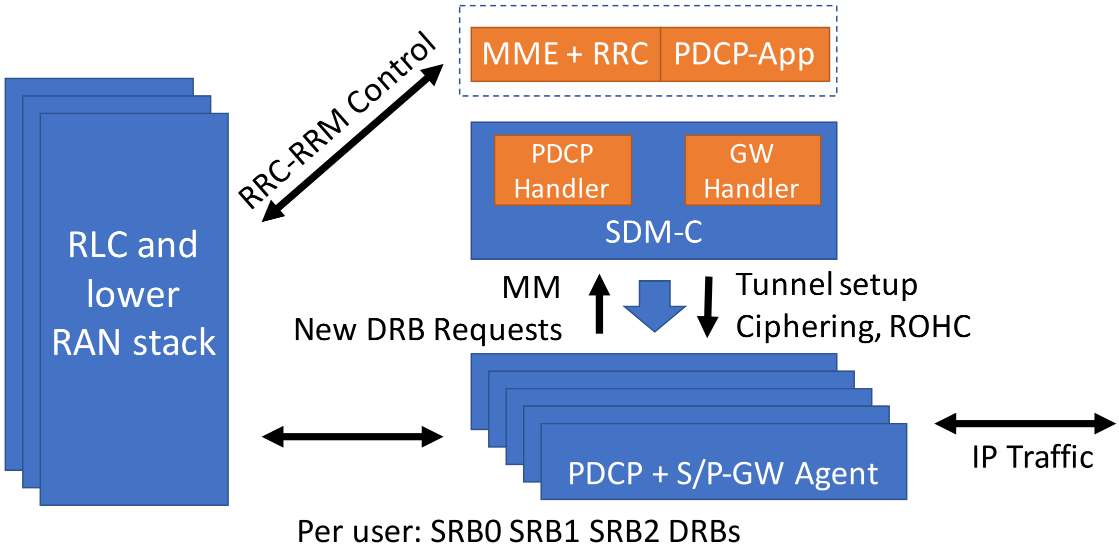

Figure 71: PDCP - RLC split

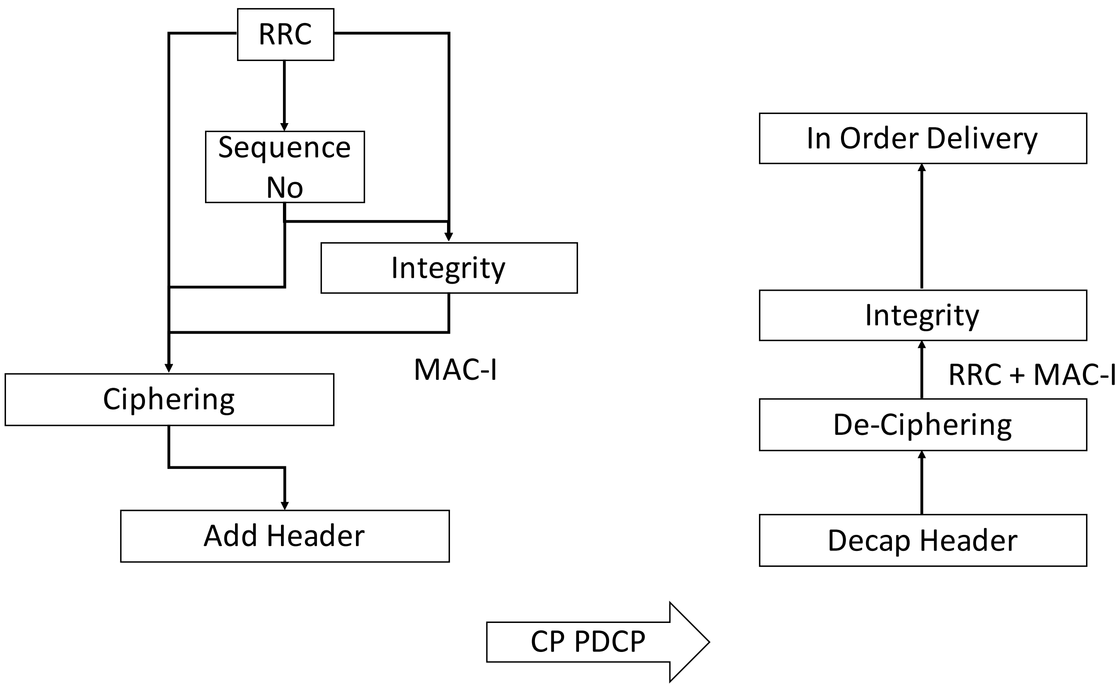

Figure 72: PDCP functionality (Control)

Sequence numbering: For each UE, there are at least 2 Service Radio Bearer to be managed and many User Radio Bearer. According to the type (Service or User), the Sequence Number has a different length (5 bits for Service, 7 or 12 bits). Therefore, this functionality can be split into his control plane (UE ID, Bearer ID, initial sequence number) and the actual incremental sequence number generator. This functionality can be useful for sequence number continuity even if the UE traffic is managed by different switches.

Integrity - Ciphering: the output of this procedure (used just by Control Plane traffic) is the MAC-I value. It is calculated using the sequence number of the packet, the bearer ID and the session keys. Those can hence be supplied from the handler application on a per-UE basis. The same applies for ciphering, that takes the same subset of parameters (plus the MAC-I for control packets). Therefore, an Integrity-Ciphering handler may use OpenFlow extension to set up rules such as the security keys for each service or data bearer. As for the sequence number generation, the advantage of this approach is to have a centralized management for the security part that may be useful for enhanced mobility management solutions.

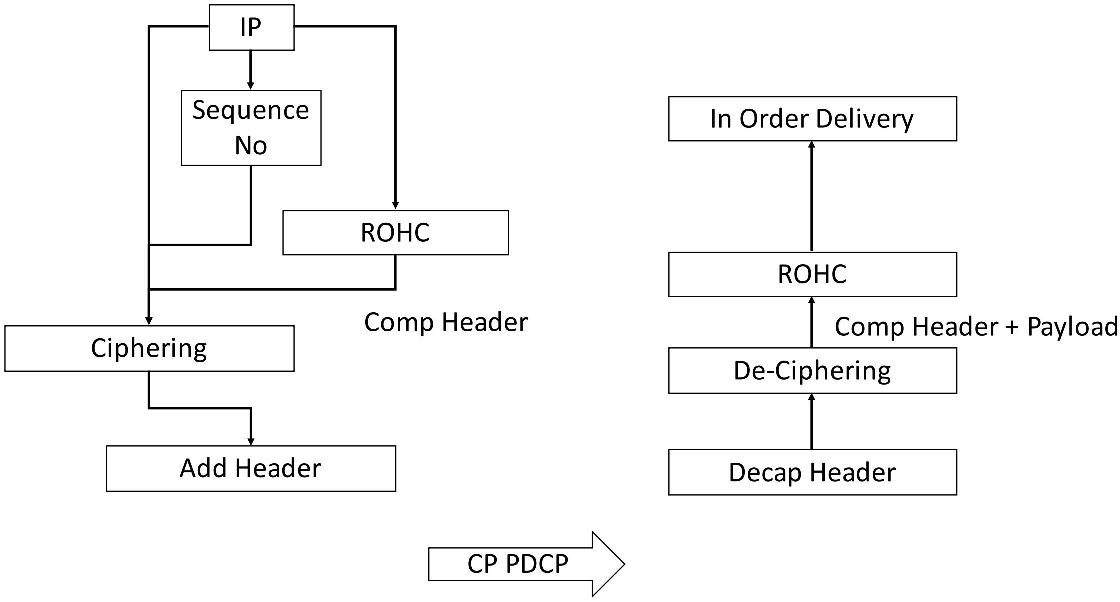

Figure 73: PDCP functionality (User)

Header compression. PDLP implements ROHC a technique that improves the channel utilization by compressing the header of packets. For this purpose, headers fields are classified into 5 categories (i.e., inferred, static, static-def, static-known and changing) according to their level of “predictability”. It is typically used for VoIP traffic.

According to the kind of traffic, different profiles are defined (see Table 12).

Table 12 ROHC configurations

Profile	**Usage**	**Ref**
0x0000	No compression	RFC 4995
0x0001	RTP/UDP/IP	RFC 3095, RFC 4815
0x0002	UDP/IP	RFC 3095, RFC 4815
0x0003	ESP/IP	RFC 3095, RFC 4815
0x0004	IP	RFC 3843
0x0006	TCP/IP	RFC 4996
0x0101	RTP/UDP/IP	RFC 5225
0x0102	UDP/IP	RFC 5225
0x0103	ESP/IP	RFC 5225

0x0104	IP	RFC 5225

Also, three operation modes are defined: Unidirectional, Bidirectional Optimistic, and Bidirectional Reliable mode. According to the chosen mode, each Radio Bearer needs to be assigned to one or more channels (i.e., SAPs) at RLC level. New features may be added to extended to support this case as in Figure 74.

Upon new flow creations, the MME+RRC application decides (according to overall QoS parameters of the network) what is the best operation mode and profile to be associated to each flow. A ROHC engine at the switch performs the protocol operation and decapsulates datagrams that are then sent over a GTP-tunnel. The advantages of this approach are, besides the multiplexing gain of centralizing the computation, the possibility of an overall dynamic decision on the ROHC parameters to be used by each flow.

In-order delivery. Especially during handovers, RLC packets may arrive out of sequence. One of the tasks of PDCP is to re-order them and encapsulates them into GTP-U tunnels (for user traffic) or to the RRC (for control traffic). This functionality cannot be really controlled by a handler with OpenFlow extension, but it must be implemented in the OpenFlow enabled switch.

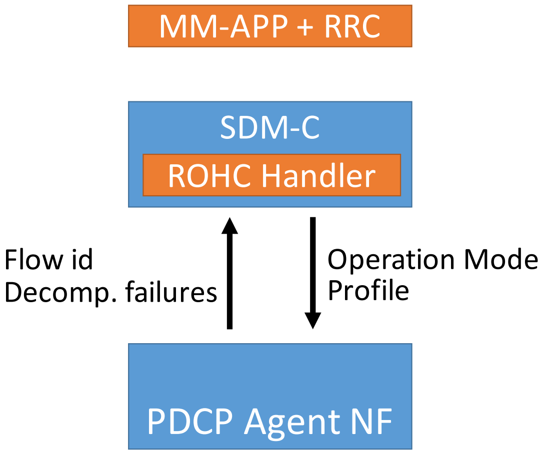

Figure 74: SDM-C ROHC Application

7.5.3 Other Splits

The RANaaS concept envisions further functional splits (e.g., RLC-MAC, Upper/Lower MAC, MAC-PHY). However, they highly fall outside the Mobility Management realm. Still, the advantages introduced by the programmability features of SDM-C can be introduced in these cases and will be further investigated.

7.6 Multipath

Multipath TCP (MPTCP)-alike techniques are not the only way of introducing multipath capabilities in 5G NORMA. Exploiting multiple paths is possible at both radio access technology (RAT) level and in the edge cloud. Using a SDN approach, different virtual Network Function appliances may be connected by using multiple paths, increasing reliability and performances. Moreover, multiple paths may be exploited to opportunistically anticipate mobile terminal movements to fulfil its QoE/QoS constraints by providing replicas of the virtualized Network Function in the correct edge cloud.

This is a networking related issue that has a strong relation with VM migration and re-location schemes. It can be seen as one of the operation that has to be available on the SDM-C SBI when triggering the movement request: SDM-O is in charge of relocating/instantiating the virtual machine, while the SDM-C builds multipath connectivity among edge clouds.

The advantages given by this kind of approach are especially useful for mobility purposes, but also other application may exploit them as well. The first application is hence the make-before-break technique: the data plane may be bifurcated before the actual change of point of attachment in order to minimize the possible disruptions at the UE. Another possible target scenario is the one depicted in Figure 75. The resiliency provided by multipath solution such as MPTCP may be employed to enhance the reliability between a pair VNFs belonging to the same service chain. Multipath transport solution may react to the possible outages in the transport network, increasing therefore the overall reliability of the system: one of the envisioned goals of 5G Mobile Networks.

Exploiting multiple paths improves the resiliency of the system. However, several challenges should be tackled to introduce this family of solutions in the 5G NORMA architecture.

- A thorough evaluation of how many paths (or flows) should be used according to the network conditions (i.e., required KPIs, status of the links) is necessary in order to provide the optimal operation of the network.
- The set of primitives that must be used by the SDM-C SBI has to be defined. Also, multipath capabilities should be offered to SDM-C applications on the northbound interface.
- An assessment of the SDM-C implementation of multipath routing strategies should be provided.

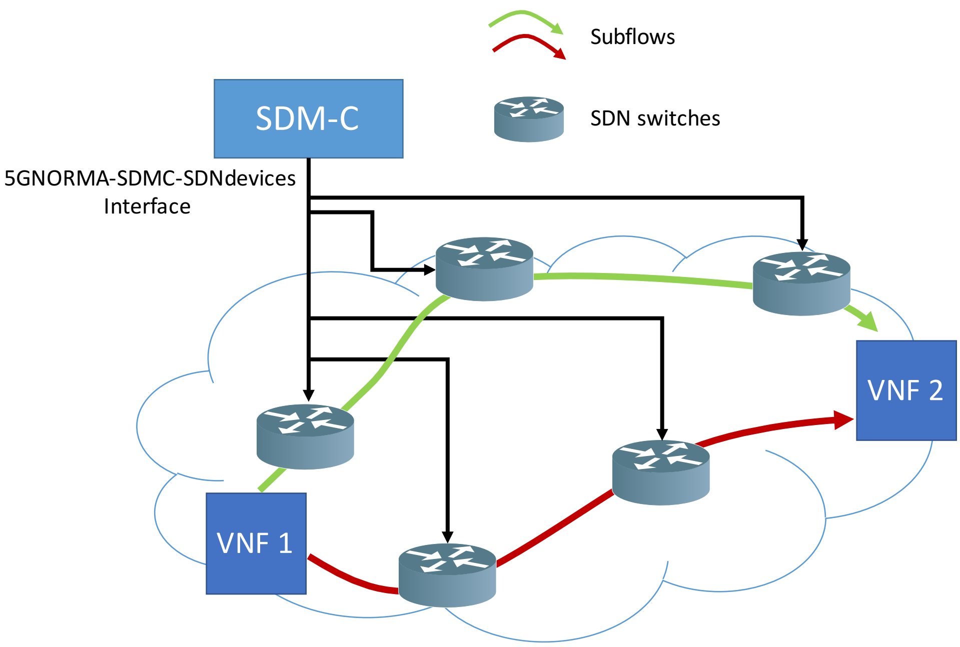

Figure 75: Multipath between VNFs

7.6.1 Problem statement

As stated above, MPTCP is one of the most promising solutions for introducing heterogeneity in the path selection, especially in the access network. However, the enhanced reliability and efficiency provided by multipath solution may also be beneficial for core Network Functions. Currently multi-path solutions may be based on complex and heavy path monitoring. On the contrary, MPTCP (see Section 9.1 for more details on the state of the art) may naturally benefit by its path selection algorithm to automatically select the least congested ones. Therefore, if VNFs in a service function chain transparently use MPTCP, they can instantaneously benefit from the availability of multiple paths between network functions, created using, for example VXLAN. Not all the VNFs in a service chain may use this approach, but Network Functions like TCP Optimizers and P-GWs may include MPTPC-Proxys that automatically translate single-path TCP to MPTCP.

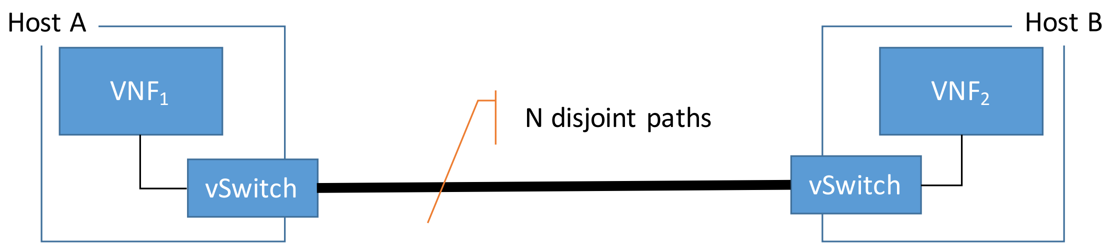

Figure 76: The multipath scenario

Therefore, we focus on the scenario depicted in Figure 76, in which a Multipath capable Network Function has to send multipath flows to the next VNF in the service function chain.

MPTCP may work using two operational modes: *mesh* and *ndiffports*. The first one is the most used and works as follows: each host opens a different subflow among each *srcIP* – *dstIP* combination. If both the hosts are single-homed, then the connection rollbacks to a single path TCP. This is likely to be the case of core VNFs however, MPTCP may be used with the *ndiffports* operational mode. In this case the sender hosts generate k different subflows using the same *srcIP* – *dstIP* changing the source port value. This can be easily accommodated to a typical virtual machine setup in a datacenter with a L2 overlay topology.

In this scenario there are two sub problems that have to be tackled

- Given that the number of disjoint paths towards the destination is unknown, what is the optimal number of sub-flows that have to be generated
- The best forwarding strategy to be applied ad the edge switches. Sub-flows may be forwarded through different paths according to several policies: this task should optimize the overall utilization of the available links.

The answer to both sub problems should be provided in a joint fashion, maximizing both the achieved throughput and the reliability obtained by the solution.

7.6.2 Forwarding strategies

As stated above, as the number of available paths n to the destination is an unknown parameter, defining the number of subflows k that have to be generated impacts on the overall performance. If $k < n$ then not all the available paths are exploited. On the other hand, if $k > n$ there may be penalties in terms of flow oversubscription.

Path assignment is a topic that has been widely studied in the literature, since the introduction of ECMP (Equal cost multipath routing). However, in this case the problem is fundamentally different, as we are not considering path assignment of single path flows, but rather path assignment of subflows belonging to same parent multipath flow.

MPTCP, in fact, is composed by two main elements: i) a scheduler, managing the k generated subflows, and ii) a decoupled congestion control algorithm that decides the size of the windows to be transmitted.

In order to tackle the problem mentioned above we followed an empirical methodology, measuring the achieved throughput using different configuration of number of VNFs hosted by the container, number of available paths and generated sub-flows. The goal is to assess the behaviour of the protocol according to different configurations.

We compared two different forwarding strategies:

- **Hash Forwarding**: the selected output path is computed using a hash function that takes into account the 4-tuple (*srcIP – dstIP – srcPort –dstPort*): $F \rightarrow [0 \ldots n\text{-}1]$. Therefore, as for each end to end connection the only changing parameter is the *srcPort*, the selected path has a pseudo-random behaviour. This solution is completely stateless and guarantees the path symmetry.
- **Round Robin**: This forwarding strategy is stateful as it has to maintain state for each flow. That is, the port selection happens in an incremental manner. When the first subflow of a 3-tuple (*srcIP – dstIP–dstPort*) arrives, a Random path q is selected. Then, when the following subflows arrive the path $q+1$, $q+2$, … are selected. The space is circular, so when $q = n$, next q is 0. The resulting path selection is even, but it comes at a price of maintain state for each flow. As a central controller is needed in this case, we assume that the number of available paths is known.

7.6.3 Preliminary results

We selected the achieved throughput as the final evaluation metric: we tested the two forwarding strategies in a controlled, virtualized, environment. We emulated the VNFs hosted in a physical container using Dockers[9] connected through a pair of OpenvSwitch[10]. As mentioned above, we initially performed a sweep varying different parameters such as the number of VNFs hosted by each physical machine, the number of generated subflows or the capacity of each path. We have two link configuration defining the capacity of the links. Namely, Link configuration #1 is 10Mbps/path and Link configuration #2 is 20 Mbps/path We included the results of single path TCP as reference. The MPTCP congestion control is OLIA. Results, depicting the normalized throughput (the achieved throughput across all the flows divided by the available capacity) are shown in Figure 77 and Figure 78.

Results clearly show the efficiency of a multipath solution; single path techniques cannot exploit the full available path heterogeneity. However, we wanted to evaluate also the behaviour of the different forwarding strategies. We can appreciate how the evenly spread number of flows can achieve always the best results.

Hash forwarding has a different behaviour when compared to Round Robin. It can achieve suboptimal results for either a non-spread path selection (left-hand side of Figure 78) or oversubscription of subflows to path (right-hand side of Figure 78).

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[9] https://www.docker.com/

[10] http://www.openvswitch.org/

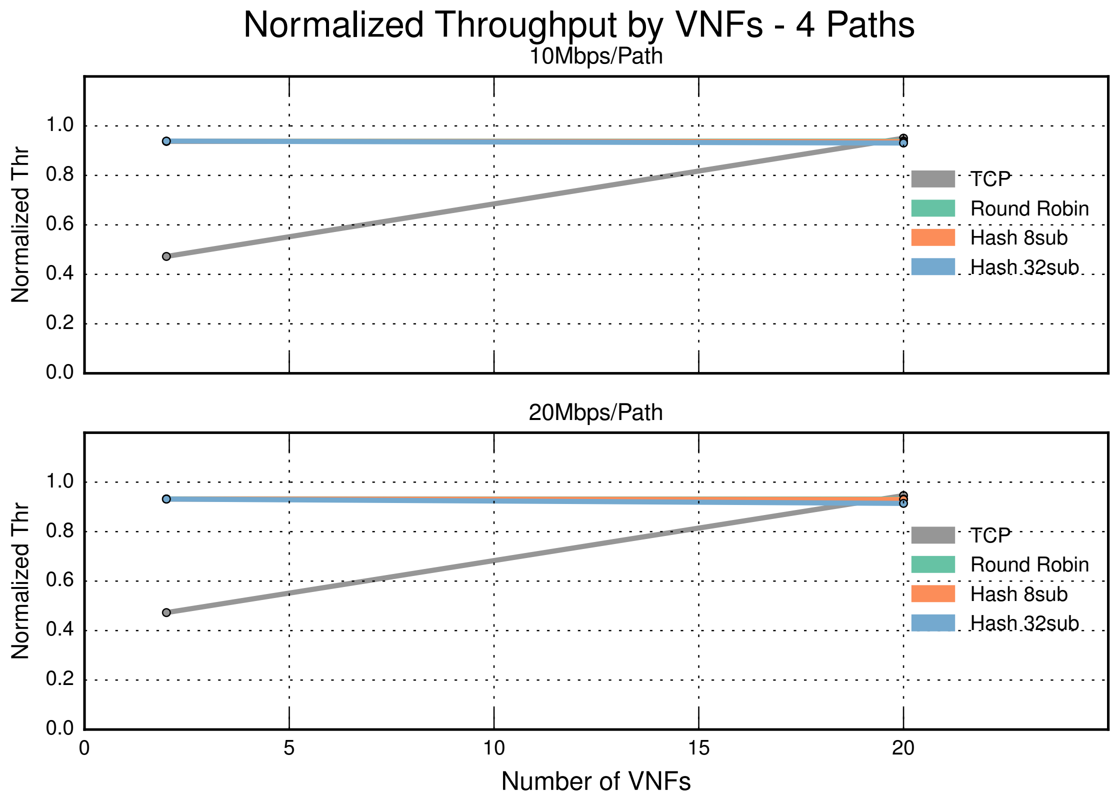

Figure 77: Throughput: 4 paths scenario

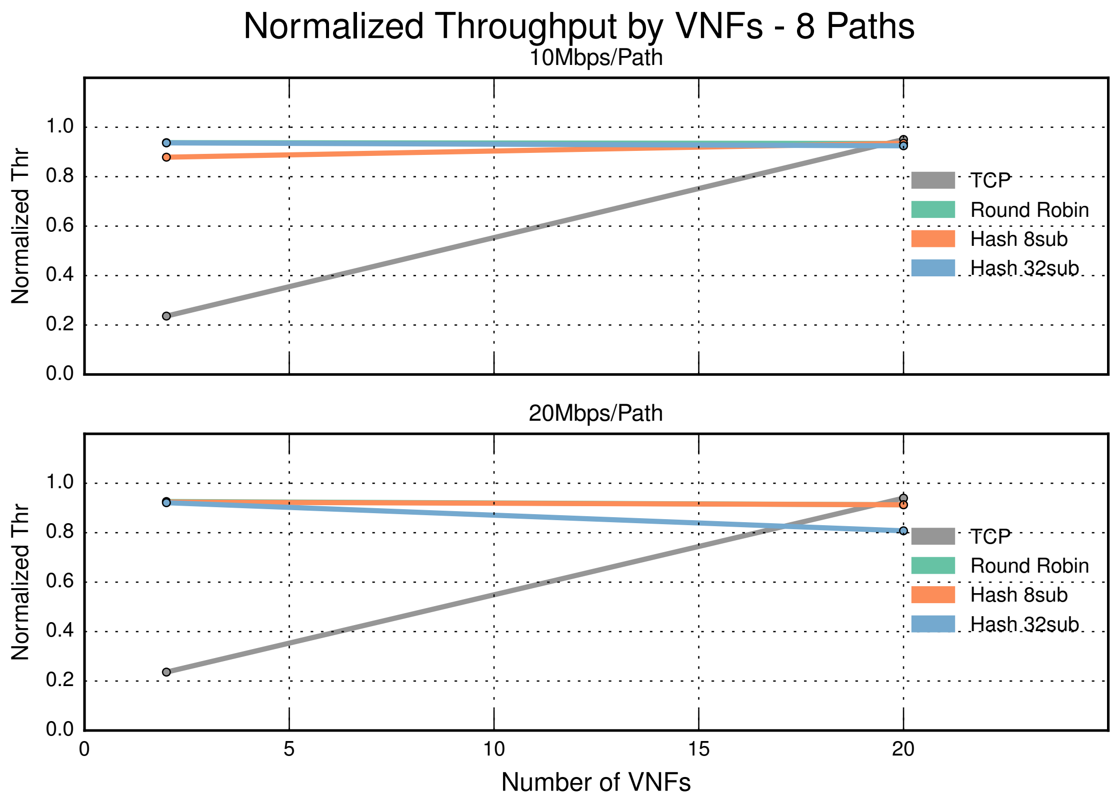

Figure 78: Throughput: 8 paths scenario

7.6.4 Next steps

Our next goal is to understand the pro and cons of applying the aforementioned forwarding strategies for multipath traffic. We will evaluate the scalability and the performance of each solution under different perspectives (improvement to the Hash Forwarding strategies, lightweight Round Robin forwarding solution). In addition, more concrete results concerning the non-MPTCP solution will be provided.

8 Conclusions

This document has reported on the current progress of WP5 in the 5G NORMA project. A substantial part of the effort in the WP so far has been focused on the design of a consistent architecture that integrates all the functions of the WP5 architecture. To this aim, the WP has identified three main building blocks (Mobility management, inter-slice management and intra-slice management) that implement the key concepts of the WP (Software-Defined Mobile Network Control, Network Orchestration and Network Slicing). The project has defined a high-level architecture that specifies the interaction between each building block and has broken down the design for each one into a number of sub-modules with the corresponding interfaces. This contribution is contained in Part I of the document.

Besides the architectural design, the other main contribution of this document is the initial design of the novel algorithms and protocols required for each of the modules defined. This is contained in Part II of the document. For each module, we have justified the need for new solutions required in the context of the proposed architecture, and we have designed the necessary protocols and algorithms to implement the required functionality. In many cases, the novelty of these algorithms comes from the fact that, when designing a fundamentally new architecture as the one based on the proposed concepts, new problems arise that require new algorithms, applications and protocols, such as the ones shown by the following examples:

- A good example of a new algorithm is the optimization algorithm for network orchestration, which solves a problem that we do not have in traditional networks.
- An example of a new application is the design of SDM-C Apps that run on top of the controller – again such applications were not part of the design of traditional networks
- Finally, examples of new protocol are the south and northbound interfaces of SDM-C and the associated protocols, which again were not needed in traditional networks.

It is important to highlight that the innovative aspects of the WP comprise the novel conceptual ideas behind the WP architecture, such as SDM-C and network slicing, as well as the design of new algorithms and protocols. The novelty of these ideas is confirmed by the publications resulting from these ideas, and the potential for exploitation is supported by the standardization proposals that have been prepared.

As a summary, the following main achievements can be highlighted because of the work conducted by WP5 so far:

- 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**, and have validated the overall design via processes. The architecture proposed is very detailed, specifying the modules and interfaces required, and has further been validated by means of processes that assure the that the various functional requirements are satisfied.

- We have provided the design of more than **15 different algorithms/protocols** required for or enabled by this novel architecture. All these proposals contain novel ideas and most of them have been patented, standardised or presented in major scientific venues.

As for the next steps that will be conducted in WP5 and reported in future deliverables, we can highlight the following:

- *Finalize last details of architecture specifications*. While the architecture definition presented here is fairly detailed, as a result of the validation process currently in place we may detect some open issues that need to be fixed in the next iteration of the architecture definition. In any case, we consider that only minor refinements will be needed.
- *Continue the design of individual modules* (algorithms and protocols). While the design of the protocols and algorithms is fairly complete in some cases, in other cases it is still ongoing, and some open issues remain in many cases. Therefore, one of the important pending tasks is to finalize and/or refine the design of the various algorithms and protocols.
- *Performance evaluation* of the modules design and (partially) their interaction. While some performance evaluation results have been presented in this document, most of the work on evaluating the performance of the various algorithms and protocols still remains. Thus, one of the major pending tasks is to complete the evaluation of the various proposals, including the evaluation of individual algorithms as well as their interaction.

9 Annex: State of the art

In this section, we are describing the state of art of a set of challenges addressed in the following document.

9.1 Multipath:

TCP/IP communication is currently restricted to a single path per connection, yet multiple paths often exist between peers. The simultaneous use of these multiple paths for a TCP/IP session would improve resource usage within the network and, thus, improve user experience through higher throughput and improved resilience to network failure. Multipath is described in RFC [95].

The opportunity of using multiple flows on different interfaces (and different IP addresses) has been extended to support seamless mobility across different point of attachment to the networks. Therefore, opportunistic mobility using MPTCP has been proposed by many works [96] [97], proving its feasibility and showing promising performances.

The main drawback of using MPTCP for mobility management approach is its need to be configured end-to-end. Both the mobile user terminal and the application server have to be MPTCP-capable, otherwise the communication falls back to a single-path communication.

To overcome this limitation, proxy-based solutions have been proposed [98] [99], and increasing interest in this class of solutions has fostered the creation of several Draft RFCs in the MPTCP working group at IETF.

In addition to MP-TCP also other protocol schemes for hybrid bandwidth aggregation have been proposed. These include among others a GRE Tunnel Bonding solution with per-packet switching and recombination on the remote end [100] and a LISP based solution [101], which enables load balancing between routers within the mobile node and the network including a reorder and feedback function. Protocol "Flow Binding for Mobile IPv4" [102] specifies header extensions to the Mobile IP protocol [103] which allow a mobile node with multiple interfaces to simultaneously establish multiple IP tunnels with a router (home agent) by registering a care-of address for each of its network interfaces and enabling policy negotiation. A corresponding solution for end hosts using Mobile IPv6 and for mobile routers enabled based on flow binding as defined in [104] and the extensions for Proxy Mobile IPv6 (PMIPv6) are currently under final evaluation [27].

Furthermore a "Solution to augment bandwidth for a Mobile Router in a vehicle" was proposed in [105] and implemented which is based on existing RFCs [106] and [107]. More details are given in a living document maintained by IETF Mailing List (ML) BANANA (BANdwidth AggregatioN Activity) [108].

9.2 Mobility Management:

Mobility management schemes standardized by IETF for IPv6 networks are extensions to or modifications of the well-known Mobile IPv6 protocol (MIPv6) [109], and can be classified into two main families: client-based mobility protocols, and network-based mobility protocols.

Client based mobility solutions, such as MIPv6, enable global reachability and session continuity by introducing the Home Agent (HA), an entity located at the home network of the Mobile Node (MN) which anchors the permanent IP address used by the MN, called the Home Address (HoA). The HA is in charge of defending the MN's HoA when the MN is not at home, and redirecting received traffic to the MN's current location. When away from its home network, the MN acquires a temporal IP address from the visited network – called Care-of Address (CoA) – and informs the HA about its current location. An IP bi-directional tunnel between the MN and the HA is then used to redirect traffic to and from the MN.

With network-based mobility management protocols, such as Proxy Mobile IPv6 (PMIPv6) [110], MNs are provided with mobility support without their involvement in mobility management and IP signalling, as the required functionality is relocated from the MN to the network. In particular, movement detection and signalling operations are performed by a new functional entity called the Mobile Access Gateway (MAG), which usually resides on the Access Router (AR) for the MN.

The IP prefixes (home network prefixes) used by MNs within an Local Mobility Domain (LMD) are anchored at an entity called the Local Mobility Anchor (LMA), which plays the role of local home agent of the LMD. Bi-directional tunnels between the LMA and the MAGs are set up, so the MN is enabled to keep the originally assigned IP address despite its location changes within the localized mobility domain.

Whatever flavour of IP mobility a modern day MNO chooses to deploy, a constant feature of the operator's architecture will be the presence of a central entity (HA/LMA/PGW/GGSN) which anchors the IP address used by the mobile node.

While this centralized way of addressing mobility management has been fully developed by the Mobile IP protocol family and its many extensions, it brings several limitations that have been identified in: sub-optimal routing, scalability and reliability problems.

To address these issues, a new architectural paradigm, the so-called DMM, is being explored by both research and standards communities. DMM[11] introduces the concept of a flatter system architecture, in which mobility anchors are placed closer to the user, distributing the control and data infrastructures among the entities located at the edge of the access network.

The conceptual aspects of DMM have been addressed both in terms of the mentioned functional split into AF, FM, and LM [111], and in terms of protocol implementation scenarios for NFV-based CP/DP function deployment as e.g. described in [112] for existing Evolved Packet Core (EPC).). A detailed analysis of the breakdown of DMM functionalities to a framework of functional entities in DP and UP has been provided in [113] both for a condensed deployment as a mobility protocol centric solution and for a cooperative deployment in form of a distributed architecture. Several underlying protocols to be used in DMM approach have been specified and numerous draft extension proposals exist describing both tunnel based (e.g. PMIP [110] or AERO [114]) and also standard routing protocols (e.g. BGP or OSPF). Since naming and addressing is an important aspect especially in the heterogeneous 5G environment also approaches to separate endpoint location from the identifier/name of the customer or device (e.g. based on IETF Locator/Identifier Separation Protocol, LISP [115], or IRTF proposed Information Centric Networking, ICN) shall be taken into consideration here since although new functional entities for mapping and a change in infrastructure is required for scenarios considering global/inter-domain operation within separated domains a considerable efficiency improvement is expected.

In the Evolved Packet Core architecture, many of the DMM functionalities may be implemented in the Mobility Management Entity (MME) that is in charge, for example, of the selection of the gateway: Serving Gateway (SGW) or the centralized Packet Gateway (PGW). Hence, the strategy adopted by the MME heavily affects the overall performance of the network. As PGW in current deployments usually cover very large portions of the operator network (usually there

[11] https://datatracker.ietf.org/wg/dmm/

are few of them in each one) and IP mobility is not supported for PGW – PGW handovers, the straightforward solution of having a PGW covering a much smaller portion of the network cannot be easily implemented with standard techniques.

In 3GPP Release 10 - 12, a Local GW (LGW) has been introduced (LIPA, SIPTO), [116] [117]. It has been also discussed to use a local mobility anchor but finally in Rel.12 LIMONET work item the requirement for mobility was removed. One approach to provide local break out and mobility on demand is DMM as specified in IETF [118] [119]. Further, within IETF WG DMM (Distributed Mobility Management) solutions for application aware on-demand mobility (such as permanent reachability, transient session continuity, short-term connectivity without mobility) are under development currently focusing on granular and resource/time efficient choice/assignment of fixed, sustained, or nomadic IP addresses. [120] describes a solution for an application on a mobile terminal to indicate the required type of mobility in terms of IP session continuity or IP address reachability by different IP addresses, whereas [121] defines a new option as extension to DHCPv6 protocol [122] to specify the type of mobility services associated with an IPv6 address.

9.3 Network Sharing:

9.3.1 RAN Sharing

(RAN sharing emerged as a rather static sharing concept for 2G and 3G networks, e.g., for sharing base stations among multiple (up to 6) tenants/operators. It was expected to be particularly beneficial for rural areas with reduced overall traffic volume so that not each mobile network operator would have to deploy network equipment. The concept has been supported by radio network equipment from different vendors with different degrees of sharing. Three typical examples as depicted in Figure 79.

- Passive RAN sharing (with or without transmission sharing) – Sharing is limited to antennas.
- Active RAN sharing – Sharing includes base stations and radio network controller (BSC, respectively).).
- Roaming-based sharing – Sharing is further extended (beyond RAN) to include selected functions of the mobile core network.

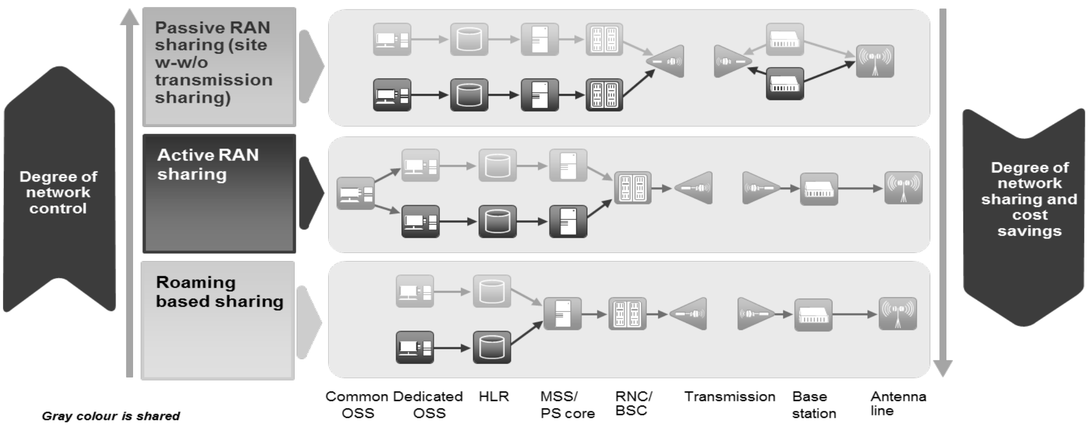

Figure 79: Network sharing methodologies

9.3.2 MORAN / MOCN

Multi-Operator RAN (MORAN) and Multi-Operator Core Network (MOCN) exploit the concept of network sharing. For example, a MORAN-enabled LTE network access network could use the following basic configuration:

- LTE six cell configuration 2+2+2, where each operator has one cell per sector.
- Enhanced Node B (eNB) is configured so that each cells broadcasts the Primary Public Land Mobile Network (PLMN) plus the dedicated PLMN for that cell.
- S1 flex needs to be enabled.
- Each operator sharing the RAN has its own core network, i.e. the core does not need to support (be aware of) MORAN.
- Two separate LTE carriers are supported by one RF Module or RRH within one 3GPP RF band.
- One RF Module or RRH supports two LTE cells at one RF band simultaneously per RF sector (TX/RX and RX pipe).).

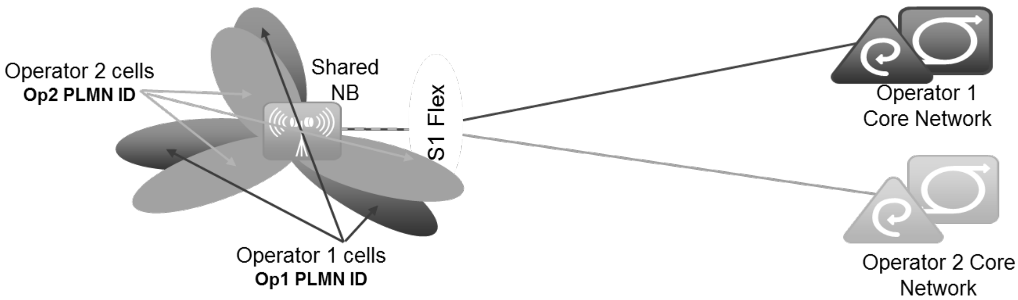

Figure 80: MORAN- Basic features

In the depicted example (see Figure 80), shared resources include:

- Transport interface (resource splitting).).
- eNB hardware.
- baseband capacity.
- Feeder cables and antennas (combiner if needed).).
- Racks, power supply and batteries at a NB level.

The following resources are dedicated:

- Cell level parameter settings (a dedicated PLMN is broadcasted).).
- Licensed frequencies.
- S1 interfaces.
- EPC and services.

Further MORAN / MOCN variants with varying levels of sharing exist.

9.3.3 Dedicated Core Networks

3GPP TSG SA2 currently works on a work item description targeting dedicated core networks [123]. It targets architecture enhancements for dedicated core networks. This work is motivated by the assumption that devices and customers with very different characteristics, such as machine type devices, MVNO, data usage, etc., need to be supported in the future. These classes of devices and customers may have different requirements from the core network in terms of optional feature support, traffic characteristic support, availability, congestion management, ratio of signalling to user plane traffic, etc. One mechanism for operators to support these different classes of devices and customers is to create separate dedicated core networks consisting of specialized core network elements that are designed and deployed to meet the requirements of these different devices and customers.

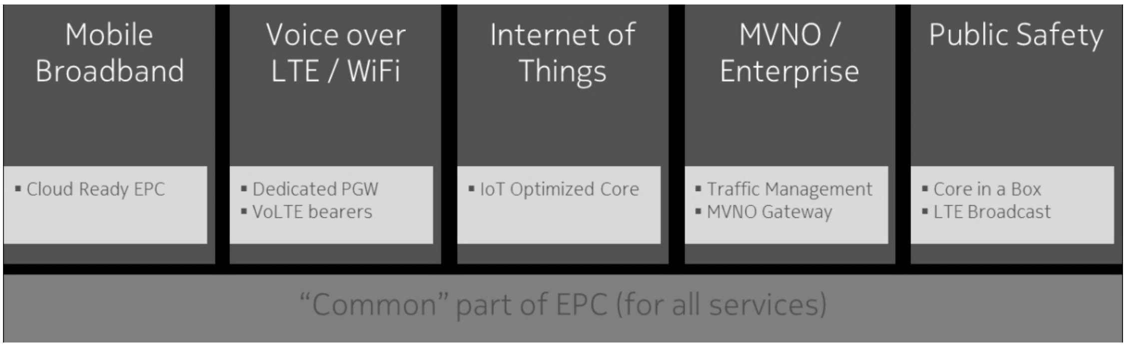

Figure 81: Dedicated core networks for exemplary service categories, use cases, or customers

As shown in Figure 81, dedicated core network consists of a set of MMEs, SGWs and PGWs. The objective of the WID includes studying and creating solutions for the following:

- Defining the subscription information and configuration used to determine the selection of the specific dedicated core network that shall serve the UE.
- Enable the initial allocation of serving MMEs or SGSNs from the dedicated network selected for the UE and maintaining the UE's association with the selected dedicated network during MME/SGSN change.
- Enable the allocation/reallocation of serving SGW and PGW from the dedicated network selected for serving the UE.
- Whether other network elements, e.g. Policy and Charging Rules Function (PCRF), also need to be included as part of the dedicated network and if additional functionality is needed for selection of such network elements.
- Whether dedicated core network may also consist of Gn/Gp SGSNs and GGSNs is to be determined during the study.
- Handling of possible relocation of UEs from one dedicated network to another. Handling of dedicated core networks in roaming scenarios and GWCN/MOCN shared networks.

9.4 Multi-Domain Interfaces:

In this section, we present a brief review of the interfaces supported between different domains. For the IETF model of Abstraction and Control of Traffic Engineering (TE) networks (ACTN) as referred to above the interface specification work has been started and is described in [124]. The coordinator function defined as MDSC (Multi Domain Service Coordinator) is a multi-functional building block which implements beside multi domain coordination (both towards customer and physical network domains) also capabilities for virtualization/abstraction, customer mapping, and virtual service coordination. Service (or slice) specific tasks include requests for creation of network resources, topology or services for corresponding applications, but also report of potential network topology availability if queried for current capability from the Customer Network Controller – representing here a tenant or slice owner.

The ACTN model foresees different interfaces towards different network controller per coordinator communicating creation requests, if required, of new connectivity of bandwidth changes.

Examples for potential internal system architectures and corresponding building blocks of the MDSC can be found in the Application Based Network Operations (ABNO) architecture [125] and in ONF defined SDN architecture [26].

[125] specifies the element of an Application Service Coordinator where an application may be a sophisticated control system that is responsible for arranging the provision of a more complex network service such as a virtual private network and in general in some way is responsible for coordinating the activity of the network to provide services for use by applications. In practice, this coordinator function may be distributed across multiple applications or servers and communicates with the ABNO Controller to request operations on the network. The ABNO controller is seen as main gateway to the network for NMS, OSS, and Application Service Coordinator for provisioning advanced network coordination and functions. The ABNO Controller governs the behaviour of the network in response to changing network conditions and in accordance with application network requirements and policies. It is the point of attachment, and it invokes the right components in the right order.

[26] on the other hand specifies SDN architecture at a high level in terms of reference points and open interfaces to enable the development of corresponding control software. This software can control network connectivity provided by a set of physical and/or virtual network resources and the flow of network traffic utilizing these resources. Control may include inspection and modification of traffic in the network. Virtualization permits abstract views of network resources. These resources can be tailored to a particular client or application, and can be interrogated and manipulated by those clients or applications. An SDN application interfaces the SDN controller via the A-CPI (application-controller plane interface). Both application and controller also contain coordinator functionality. Various architectural topics detailed in [26] include delegation of control, control hierarchies, virtualization, an information model, interworking with non-SDN environments, deployment considerations, as well as aspects of management and security.

9.5 QoE video optimization delivery:

One of the remaining challenges is the provisioning of enhanced and fair Quality of Experience (QoE) to multiple multimedia users in mobile network. In fact, besides a higher probability of traffic congestion in the wireless networks, mobile users will still experience different channel conditions with limited link capability and large throughput fluctuations due to the time-varying nature of the wireless interface.

HTTP Adaptive Streaming (HAS) [126] has emerged as the prominent technology. In addition to the commercial implementations, i.e., Microsoft smooth streaming (MSS) [127], Apple HTTP live streaming [128] and Adobe HTTP dynamic streaming [129], HAS has been recently standardized by 3GPP [130], and denoted as Dynamic Adaptive Streaming over HTTP (DASH) [131].

In HAS based technologies, the video content is encoded at multiple bit-rates, also called profiles, which may consist of different temporal, spatial and quality resolutions. For each profile, the video is diced in several chunks, whose durations generally range between 2 and 10 seconds. At the end of profiles encoding, or periodically during encoding, the server generates a manifest file, which contains synthetic information describing the available profiles of each chunk. The client, after receiving a chunk, requests the subsequent chunk by selecting one of its available profiles according to the playout buffer status and current downloading rate, thus enabling adaptive streaming.

So far, HAS principle has targeted an end-to-end optimization between the client and the server in an OTT view which prevent the implementation of many optimization through specific network capabilities inside the network and break the OTT behavior of the video delivery. In addition, in multiuser cellular systems the achievable data-rate depends on the UEs channel conditions, which may be widely heterogeneous. Hence, QoS/QoE-aware channel-dependent optimization is the primary key-tool to improve the fairness among HAS UEs.

However, if the optimization is performed only in term of QoS, e.g., by trying to provide the same data-rate to the UEs [132], the QoE may become significantly unfair. In fact, the UEs requesting low-motion videos, e.g., interviews or news, require less data-rate to achieve an excellent QoE compared to UEs streaming high-motion videos, e.g., sport or music events. We should keep in mind that video quality does not depend on the encoding rate only, but it also depends on the complexity of the video scenes [133] [134]. Moreover, the QoE can be significantly degraded if stalling occurs during the video playout due to a re-buffering event. In particular, the probability of stalling may increase for the user equipments (UEs) coming up into the network when the cell load is high, since they may have less possibility to build an adequate play-out buffer with respect to the already present UEs.

Early researches on HAS have focused on the optimization of a single server-client link, by improving the Rate Decision Algorithm (RDA) of state-of-the-art commercial clients according to the trade-off among number of re-buffering events, video quality, quality oscillations and video play-out deadline [135] [136]. However, a user-driven approach is generally suboptimal in a system where multiple HAS clients compete for the same radio Massive Broadband (MBB) slice resources. In fact, the Authors in [137] have shown that, in a constant bandwidth multi-user scenario, three major issues, i.e., efficiency, stability and bandwidth estimation accuracy, have to be tackled. The Authors in [138] analyzed the main causes of these problems and proposed a novel fair, efficient, and stable adaptive RDA. It combines an optimized bandwidth estimator based on the harmonic mean of the past measured throughput samples, an improved profile selector that allows the RDA to converge to a stable profile, and a randomized chunk scheduler, which increases the accuracy in the estimation of the bandwidth. Nevertheless, the large window used to estimate the throughput, which improves the stability of the quality levels selection, could not cope with uneven large throughput drops typical of wireless channel with mobility. To improve the stability-responsiveness trade-off, the Authors in [139] proposed PANDA, a probe and adapt client RDA, which results in better bandwidth utilization. The work in [140] extended the PANDA approach to also consider the content of the video by showing that content-aware adaptation schemes achieve better QoE when compared to conventional PANDA scheme.

9.6 QoS in LTE:

In 4G network, QoS is handled by the use of QCI [141] defined in the core network. In the Policy and Charging Enforcement Function (PCEF) it is possible to handle QoS control on a service data flow level. In fact, the PCRF/PCEF policy infrastructure was primarily designed to describe and enforce individual limitations and subscription boundaries (closely integrated with the charging system) to enable the implementation and enforcement of various subscription plans.

The QoS concept in LTE is based on EPS bearer as illustrated in Figure 82. An EPS bearer/E-RAB is the level of granularity for QoS control in the EPC/E-UTRAN. That is, service data flows (SDFs) mapped to the same EPS bearer receive the same bearer level packet forwarding treatment (e.g. scheduling policy, queue management policy, rate shaping policy, RLC configuration, etc.).

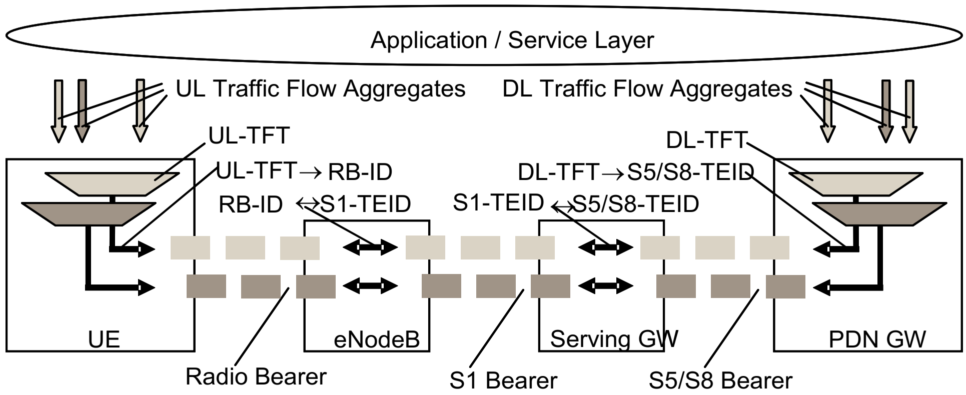

Figure 82: LTE EPS bearer concept

One EPS bearer/E-RAB is established when the UE connects to a Packet Data Network (PDN),), and that remains established throughout the lifetime of the PDN connection to provide the UE with always-on IP connectivity to that PDN. That bearer is referred to as the default bearer. Any additional EPS bearer/E-RAB that is established to the same PDN is referred to as a dedicated bearer. Each dedicated bearer is associated with a Traffic Flow Template (TFT) that defines a set of packet filters (typically a 5-tuple).

The initial bearer level QoS parameter values of the default bearer are assigned by the network, based on subscription data. The decision to establish or modify a dedicated bearer can only be taken by the EPC, and the bearer level QoS parameter values are always assigned by the EPC. Setup of default and dedicated bearer requires end to end signalling between UE and MME on NAS (Non-Access-Stratum) level and between UE and eNB on AS (Access-Stratum) level.

The LTE bearer centric QoS architecture is not able to differentiate traffic flows that are served by same EPS bearer unless dedicated EPS bearers are used for different traffic flows. However, different traffic flows of the same service that needs to be treated in the network in different way for better QoE/QoS support may not differ in 5-tuple. Or 5-tuple needs to change very dynamically in order to differentiate the traffic flows via different EPS bearer, which may introduce significant overhead to the network to update UE and GW for traffic flow mapping.

9.7 QoE-based Routing:

In recent years, Quality of Experience is becoming more prominent for mobile networks. The emphasis has switched from guaranteeing Quality of Service, to ensuring the end-user has the best experience. Software Defined Networking, by decoupling control and data plane, gives the network the flexibility to improve QoE. The routing can be dynamically changed based on the feedback from the users.

Reinforcement learning (Q-learning) is a promising approach for QoE-based routing. It is used in many scenarios, such as wireless mesh networks, optimizing QoS routing [142] and mobile networks [143].

The system in [143] uses reinforcement learning to provide QoE in mobile networks. A data provider sends a data packet to the end-user, and each routing node selects the next node using a Q-value table. When the packet reaches the end-user, he sends a QoE feedback that travels back in the routing path. Each node then updates its Q-value table using that feedback. This process of selection, evaluation and learning creates an adaptive, dynamic and evolving routing system that can guarantee end-to-end QoE.

A recent proposal for QoE-based routing in multiservice wireless mesh networks applies double reinforcement learning, using the QoE knowledge acquired in each node to adjust dynamically their routing schemes. Double reinforcement learning means that each node in a flow sends its predecessor the expected path quality, and sends the estimated path quality towards the user to its successor. Alternative paths are explored with some probability, in order to find better routes.

An alternative to the use of reinforcement learning is fuzzy logic. A fuzzy routing protocol for wireless mesh networks is introduced in [144], which determines the best route for video streaming and multimedia based on the user experience. It also tries to optimize the usage of network resources by minimizing the number of transmissions and the link delay. Subjective and objective QoE metrics are used to assess the quality of multimedia applications. However, this proposal is not a dynamic adaptive mechanism.

9.8 Vehicular mobility pattern:

Vehicular movement patterns are a well-studied topic: the study of the interactions among vehicles at both microscopic and macroscopic levels has been targeted for years, but just recently the topic acquired significance in the field of wireless networking due to the rise of V2V communications.

The studies proposed in [145] [146] analyse the vehicular mobility pattern under a vehicular networking perspective for highway environments. Analogously, in [147] the vehicular mobility patterns are studied for the case of a large city.

Wireless connectivity in VANETs is mainly provided by two radio access technologies: the cellular and the short range one. While those technologies have different, intrinsic, characteristics, they share the fact of having a fixed deployment. Both Road Side Units (RSU) for the case of Dedicated Short Range Communications (DSRC) and Remote Radio Headers (RHH) have a stable, known, position, thus can be used as proxy for the User Equipment (UE) position.

Two metrics are especially relevant to studies on the impact of user mobility on cellular network: i) cell-inter-arrival, i.e., the time elapsed between two subsequent arrival of users at a given cell, and ii) the cell residence time (also called sojourn time), i.e., the time spent by users within a cell.

By merging the analysis on cell inter-arrival time (a paramount metric for evaluating the handover frequency) and the cell residence time it can be possible to map certain flows to the vehicular category.

9.9 Monitoring:

Monitoring mechanisms that minimize the signalling overhead are currently an open research topic that most likely will experience a push due to the rise of SDN.

Existing mechanisms are for example OpenTM [148], a traffic matrix estimation system for OpenFlow networks that uses built-in features provided in OpenFlow switches to directly and accurately measure the traffic matrix with a low overhead; and A-GAP [149], a protocol for continuous monitoring of network state variables that aims at achieving a given monitoring accuracy with minimal overhead.

There is a large body of research and projects focusing on various aspects of Monitoring and Measurement Systems (MMS). Nagios [150] and Ganglia [151] are traditional tools for IT infrastructure monitoring. They are mature and stable. However, these tools only provide basic statistics of monitoring data and cannot satisfy the complex processing requirement today. The MISURE system [152] is an application-level cloud monitoring system that uses stream processing. It proposed a scalable and fault tolerant framework for monitoring applications running in a cloud environment; however, MISURE is mainly for application monitoring and therefore is not suitable for infrastructure monitoring.

Ceilometer is a telemetry component of OpenStack, an open source cloud platform. It provides mechanisms for monitoring virtual compute, network, and storage resources. Ceilometer provides very limited analytics capability for monitoring data (only average, sum, max, and min). CloudView [153] and MONaaS [154] are other systems that integrate with Open- Stack, but they have the same limitation as Ceilometer. The authors in [155] and [156] present solutions for cross layer monitoring. In [156], we use Ceilometer and assume that application layer data are available using a monitoring as service model, which raised the question of how to provide application layer monitoring data as a service. This question is addressed in this paper.

For SDN, FlowSense [157] is a push-based SDN monitoring system for network utilization. It provides basic OpenFlow network monitoring. PayLess [158] proposed a network monitoring framework for monitoring OpenFlow networks. It uses a variable frequency flow-statistics collection algorithm to improve the monitoring overhead. OpenNetMon [159] provides per-flow metrics monitoring in an OpenFlow network: bandwidth, delay and packet loss. The SDN monitoring research work are area specific and cannot be used as a general monitoring system in a cloud environment, but it can provide network monitoring data for the MonArch system.

On the monitoring analytics side, Monalytics [160] presents a hierarchical monitoring and analytics system. It proposes integration of monitoring and online analytics, and suggests that analytic tasks should be executed locally at the monitoring data acquisition point. This analytics model suffers from lack of global view and fault tolerance.

9.10 QoE Management:

QoE management is currently a wide-open evolving research topic, in which research can go in many directions. Even the definition of the term QoE is still not very well defined [161] and different QoE measurement scales are being considered [162]. However, QoE research has seen important advances mainly in the field of multimedia applications [163], but it needs to evolve towards other applications and scenarios such as mobile networks and services.

One aspect addressed in literature is for example that the overall user's QoE rate can be derived as a functional combination of the different QoE metrics. To address this, a useful concept is to consider a QoE space, being the orthogonal dimensions the different QoE metrics. Methods to derive the QoE rate from the QoE space is for example the "ideal quality vector" and the "ideal point" method [164]. Topics like this are to be explored and advanced focusing on 5G networks.

The subjective QoE is correlated with the objective QoS parameters presented by the communication and network conditions at that moment. An approximation of this correlation is depicted in the following Figure 83 [164], where the horizontal axis represents the QoS disturbance (deviation from the optimal).

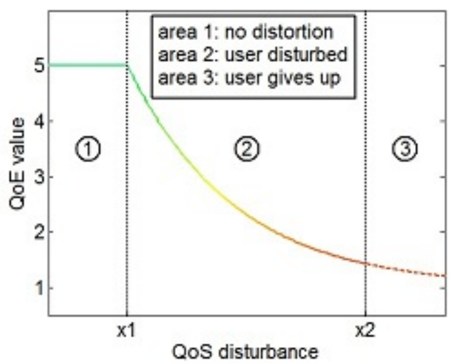

Figure 83: Correlation between QoE and QoS.

In turn, QoS can be divided in Network QoS (NQoS) which is the one provoked by the network-related aspects (e.g. delay, jitter, etc.) and Application QoS (AQoS) which is due to application-related aspects (e.g. transmission rate, frame rate, etc.).

9.11 Edge Function Mobility

5G NORMA allows for network function to be dynamically allocated either at the edge cloud, or at the network cloud. When a user leaves the area of an edge cloud, three options present themselves: the network function could continue running in the same cloud, move to the network cloud, or be reallocated to the new cloud serving the user. This decision should take into account parameters like delay requirements, communication overhead, reallocation costs and user QoE. The goal is to provide seamless service continuity. However, a tradeoff between guaranteeing QoE and reducing cost exists. Usually, keeping the network function closer to the user would be ideal, but that can incur high costs.

Research in the area of dynamic automated placement of network functions is quite new. Some relevant works in the area will be listed and detailed here.

The work in [165] proposes architecture based on an orchestrator that performs the automatic placement of virtual nodes and the allocation of network services on them. As an example of network function, the authors choose a virtual router. Their placement algorithm for network functions is based on host status. It can focus on keeping load balance (least used host strategy), saving energy (N at a time in a Host), and balancing network traffic (least busy host).

In the area of service migration in mobile edge clouds, the works in [166] use Markov decision processes (MDPs) and dynamic programming [167] to minimize the total migration and transmission cost. The approach in [166] considers 2-D mobility, with the state space of the MDP approximated by the distance between user and service location. User mobility is assumed to follow a Markov chain, and the transition probabilities are known. In [167], the solution given makes decisions using a look-ahead window. Placement decisions are made using dynamic programming based on the predicted costs within that window.

Markov decision processes also show up in [168], related to the Follow Me Cloud (FMC). The idea behind FMC is a framework that provides smooth service migration for federated clouds and mobile networks. Multiple federated data centers connect with EPC gateways serving certain geographical areas. Using a MDP, a decision policy for service migration was created. It is triggered when an UE is at a certain distance from the source data center providing the service. A one-dimensional mobility model with a specific cost function for one user is considered. Value and policy iteration are used to solve the MDP. These methods can be quite time-consuming when the MDP is large.

9.12 Service Function Chain:

Common way of deploying the Service Function Chain (SFC) is by connecting the VMs running the individual virtual service functions. The resulting composition of VMs builds the SFC graph. However, such solution experiences a latency issue due to the communication between VMs. There are numerous approaches on how to mitigate such delay. One of the options is utilizing the DirectPath I/O [169] acceleration technique. DirectPath I/O is a technology that enables the direct access from the VM to the physical device, i.e. without the intervention of the hypervisor in every I/O. Since the VM can access the physical device directly, latency is much lower in this mode. Pass-through and SR-IOV [170] is another approach for acceleration of VM to VM communication where a host's PCI network device is directly assigned to a guest. In this way it is possible to bypass the hypervisor and other switching processing done inside the host and thus improve the networking performance of the guest. Some recent works [171] have analysed the benefits of using the Data Plane

Development Kits (DPDKs) for running VNFs. The results show very good i.e. near-native performance in the cases of small and large packet processing. In addition, Field-Programmable Gate Arrays (FPGAs) can be seen as another approach for enhancing the performance of VNFs [172] and [173]. However, as mentioned above, although by such acceleration means the networking performance between virtual machines that host the service functions can be accelerated still their benefits are subject to availability and might not be sufficient to overcome the latency introduced by the classical SFC deployment.

9.13 Virtual Network Function Orchestration

Over the last few years the area of NVF has gained a significant research attention from both industry and academia. A general framework on NFV management and orchestration is detailed within ETSI[12]. One of the earliest related research works in the area is [30] which was an initial effort to provide a systematic unification model of middle-boxes which can be considered as nodes that can host VNFs. The aim was to provide a model where different middle-boxes could be orchestrated without considering optimization models and/or efficient algorithms for orchestration. The work in [31] proposes the so-called Stratos[13] framework, which can be considered as a network orchestration layer built on top of a Floodlight controller. The role of Stratos orchestrator is estimate where to place various network functions in the network, to inform a VM manager about this decision, and finally to instructs an OpenFlow[14] controller to distribute flows to the corresponding switches. Another effort on the control/orchestration is the OpenNF framework [32] that provides a design of the APIs to provide a joint control between network forwarding state and internal VNF state. The work in [33] can be deemed as another effort to provide orchestration between virtualized NFs especially focusing on issues such as VM migration and split/merging flows. The work in [34] provides an optimization problem for placing the chained VNFs in a network taking into account as constraints various requirements of the tenants and the operator – but routing between and location of VNFs is not explicitly taken into account. An overview of the challenges, which emerge in virtual network function scheduling is presented in [174]. The authors explain the application of SDN and NFV technologies focusing in optical networks. The VNF problem is viewed analogous to the classical Job-Shop problem. For this reason, the authors use a mixed integer mathematical program outline to frame the scheduling problem. Within this framework, results of the problem yields optimal results for small topologies. The authors in [36] address inefficiencies in resource and energy consumption in online virtual network embedding scenarios. The Energy Aware-Virtual Network Embedding-Node-Link Formulation (EA-VNE-NLF) is proposed to addresses these inefficiencies by considering two objective functions; the first to address resource usage and the second for energy consumption. The performance of the ILP formulation is compared to results obtained using a shortest distance path heuristic. The simulation results show gains in favour of the proposed minimization formulation compared to those of the heuristic. In [37] the authors provide a holistic treatment of VNF opportunities, emerging new architectures, and discussion for successful deployments. In [38] four different greedy heuristic algorithms are detailed for the problem of VNF chaining and a wide set of numerical investigations are presented providing an insight on the performance of the different heuristic algorithms. The work in [39] focus on delay requirements for VNF placement with application in 5G networks; An optimization problem is formulating resembling the resource constrained shortest path

[12] Network Functions Virtualisation (NFV); Management and Orchestration, ETSI GS NFV-MAN 1 V1.1.1, 2014

[13] http://www.projectfloodlight.org/floodlight/

[14] https://www.opennetworking.org/sdn-resources/openflow

problem with the aims to minimize routing latency for flows requiring variable number of VNFs.

9.14 QoS/QoE Mapping – State of the art

QoS/QoE mapping is currently a vibrant area of research. A number of researchers are currently using different methods considering different media type (e.g. video, voice and image), and for each media, different measurement methods requiring different computational resources. In addition, different mapping models are under consideration.

Generally speaking, the goal here is to get a QoE value (or a QoE vector composed by different QoE components) from a set of measurable input parameters. This can be seen as the general problem of modelling a mapping function ***f*** to assign QoE values from a set of measurable parameters $P_1, P_2, \ldots ,P_n$ as represented in Figure 84.

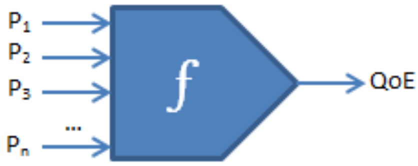

Figure 84: The QoS/QoE Mapping General Problem

In the following sections we will summarize the QoS/QoE Mapping state of the art considering the three main components involved in the problem: the input parameters, the mapping function itself and the QoE output.

9.14.1 Mapping Function Input Parameters

Before talking about QoE itself, a key point is to clarify what input parameters are normally under consideration. Following two different types of input parameters can be considered:

- QoS Objective Parameters
- Other QoE Influence Factors

The QoS objective parameters are the physical and objective network and application parameters (jitter, delay, etc.); these are the parameters conventionally used in legacy and 4G mobile networks, where QoE is derived from these metrics through a QoS/QoE mapping process using the appropriate mathematical functions. In this case, the general approach is to use parameters in the OSI network and application layers (i.e., layers 3 and 7) [175]. The Application Layer includes services, which are provided by the application in order to achieve the required QoS. For example, if we consider a video streaming application, parameters such resolution, frame rate, color or the video codec type are considered. However, usage of the application layer sometimes could require using DPI in order to access the desired parameters. On the other hand, the Network Layer services (provided by devices such routers and switches) consider parameters line jitter, delay, packet loss, etc.

On the other hand, the QoE Influence Factors are the user-centric parameters, that is, those parameters that cannot be measured directly in the network or the application, but can influence the final user experience (i.e., environment, terminal type, user age, business factors, etc.). The consideration of these influence factors is what makes the difference between conventional QoS measurements and the more modern and accurate QoE rating approaches. This of course adds some complexity to the problem; as a sample Table 13 shows a general classification considering different QoS parameters and other QoE influence factors:

Table 13: QoS parameters and other QoE influence factors

Domain	Level		Example Factors
Network	Fixed network-level QoS		Propagation delay, link capacity and error rates.
	Variable network-level QoS		Throughput, link utilization, congestion level, jitter, loss.
Application	Application-level QoS	Fixed	Encoding, resolution, sampling rate, frame rate, loss level of compression and coding.
		Variable	Re-buffering duration and frequency.
	Application type		Multimedia, gaming, augmented/virtual reality.
	Content type		Voice, speech, music, video, 3D movie.
Service	Service-level QoS		Service failure or availability (or non-access), setting-up delay and time.
Terminal	Terminal-level QoS		Display resolution, screen size, screen brightness, blurriness, image scaling procedure, display rendering, screen capability for reproducing motion.
User	Physical	Sensory	Human Visual System (HVS) & Human Auditory System (HAS) models, vision/hearing impairments.
		Corporal	Heartbeat, body temperature, blood pressure.
	Psychological	Capability	Skills, capabilities, expertise.
		State	Mood, concentration, attention, motivation, tendency.
		Cognition	Expectations, personality, needs, goals, beliefs, preferences, tastes, socio-cultural, economic and educational aspects.
	Psychophysical		Minimum noticeable difference of stimuli variation.
Context	Spatial		Functional place (home, work, street, train, plane…), location coordinates, velocity, movement direction.
	Physical		Peacefulness, noisiness, lighting conditions, weather conditions (temperature, humidity…).
	Temporal		Time of day, time of year, season.
	Social		Culture, inter-personal relations during the experience, social networks involved, shared information between users, behaviour and habits of family and friends.
	Task		User activity (working, resting, sitting, standing, walking, jogging…), other tasks carried out during the experience (multi-tasking).
Business			Price, subscription type, brand-related aspects (brand fans, customer-brand attachment…), marketing effectiveness, Customer Relationship Management (customer service, technical support…).

9.14.1.1 Data Integration

One important point regarding input parameters is the input data integration. As we see, input parameters could come from heterogeneous sources, and also on different temporary windows. For example, information about the user's terminal could be a collection of text strings stored in a database, while real-time jitter measurements could be represented as a rational number stream that should be integrated during an interval specified by certain sliding window. The normalization and integration of such a different data is also a challenge that needs to be considered.

For the QoE/QoS control process, Data Integration can be a major issue when the number of input parameters is high and their relationship is not clear. For example, together with real time measurements and static data from databases it would be necessary also to integrate data from user surveys (we will see about this below); this could be done statically or even in real-time.

As a whole, Data Integration as become the focus of extensive theoretical work and numerous open problems remain unsolved. In [176], [177] and [178] you can get an approach to the state of the art regarding this topic.

9.14.2 Mapping Functions Modelling

Of course, the main goal here is to find a good mapping function that best relates the input parameters with the QoE. To get this, two methods commonly used are the so-called “objective” and “subjective” approaches. In the objective approach the QoE is obtained only from physical QoS network measurements (jitter, delay, etc.), while the subjective approach can integrate (also) the users experience and a defined set of QoE influence factors in some way[15].

9.14.2.1 Objective approach

In this case the selection of the input parameters set is just a selection of predefined QoS physical parameters. A mix of network parameters such delay, jitter, packet loss or throughput is used. The selection of the proper set of input parameters is delegated on an experts team. The main advantages of this method came from the automatization: it is low cost, and once the QoE/QoE mapping function is defined, it is possible to get online QoE values in real time.

This approach can be understood as the classical top-down computing approach; i.e., to delegate on an experts team that, based on their experience, could define the mapping function and select the set of service parameters that could have a major influence on the user’s experience (see Figure 85 below). It is assumed that from this set of parameters it should be possible to infer a function that could assign the correct weight to each input parameter in order to get the expected QoE.

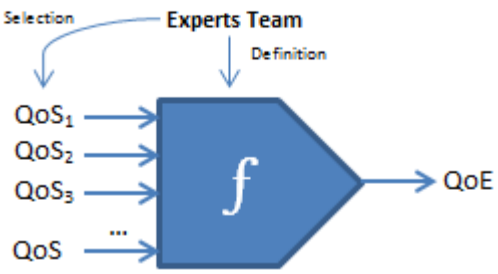

Figure 85: Objective Approach

Besides, within the objective approach, there are two different ways to do things: the objective approach can be also ‘intrusive’ or ‘non-intrusive’. The non-intrusive methods are purely based on monitoring the already available QoS parameters (i.e.: latency, jitter, packet loss…), while intrusive methods are based on installing specific purpose applications to get additional QoS parameters; an example could be to install a specific program in the user’s terminal to compare original and received images in order to detect signal distortions [179] [180]. Other solutions focus on including new network elements (e.g., network probes and analyzers, deep packet inspectors, etc.) which are responsible for capturing the traffic from a certain service and analyzing its performance [181]. Generally speaking, intrusive methods are accurate, but it is not always possible to install or execute special purpose applications to get QoE (or related measurements). Non-intrusive methods are more easy to implement (no specific applications or infrastructure is needed), but not always is easy to map QoE with already available network

[15] Also, a combination of objective and subjective approaches can be performed to overcome limitations of each indivicual technique. A relevant example is the “PSNR-mapped-to-MOP” method has been ratified by the ITU-T J.144 Recommendation [197].

parameters. Anyway, the use of intrusive or non-intrusive methods does not makes any relevant difference in the general approach; the only difference lies in the additional input parameters coming directly from the application installed in the end users terminal.

A well-known example of objective approach is the so-called "IQX hypothesis" which is often used to estimate the QoE in VoIP and web browsing [182]. The IQX hypothesis expresses QoE as an exponential function of the QoS degradation. This is the expression commonly used[16]:

$$QoE = \alpha * exp(-\beta * QoS) + \gamma \tag{1}$$

Here QoS is evaluated through three different criteria: packet loss, jitter and download time. Results are good for the specific field of application, but the main weakness of the model is that it does not consider how the time-varying nature of the internet protocol influences quality as perceived by end users.

No doubt, the objective approach is perfectly valid and efficient in many cases, but: How to be sure that a really good mapping function for general use is obtained? What if the network usage varies and some parameters that were very relevant when the function was defined are no longer so important?[17] How to be sure that selected parameters and the weight assigned to each one really have an effect on QoE perceived by users? The experts team could be too influenced by a purely technical point of view and not by the real users experience, so we can't be totally sure about if the experts team really represent the final users experience; it is true they are experts, but they are not in fact the final user, so we should be wary about this.

The main drawback of the objective approach is that we do not have feedback from the final users, just the assumptions of the experts' team who initially designed the system. The network conditions can change over the time (i.e. we do not send much SMS or MMS right now, but in the past these were very popular services), but these changes could not be easily integrated in the original model. To try to avoid those drawbacks the subjective approach is used.

9.14.2.2 Subjective approach

A good illustrative example of the subjective approach is the well-known MOS method, which has been used for decades in telephony networks to obtain the human user's view of the quality of the network. The MOS method is standardized in the ITU-T recommendation [183]. It is a quantization method that defines a numeric scale from 1 to 5 (i.e. from 'poor' to 'excelent'); users are asked about their subjective experience according that scale, and their responses are used to improve QoE in some way. Besides MOS, other common subjective methods, which also collect data from users, are the TUQ method (Testing User-perceived QoS) and the SSQ method (Surveying Subjective QoE) [184]. The ITU has developed a classification to standardize different objective models based on a focus of each model type [185]. Obviously, the most evident advantage using objective methods is that we really get information directly from the final user. On the other hand, the main drawbacks are high cost, time consuming and that it can be annoying for the user and complex regarding time correlation (i.e.: time when the poll is done vs time when the service is actually used), and of course, users may lie when they are asked (perhaps the last bill was to high). Although the outcome of this type of methods is not perfect, if the poll is well designed and a sufficient population is asked the final result can be accurate enough.

[16] α, β and γ are positive parameters.

[17] Few years ago services like SMS or MMS were intensively used, while today the video streaming services has become very common.

The subjective approach could be seen as a bottom-up computing approach, i.e., the information provided by the users is used to infer the mapping between certain set of objective parameters (jitter, delay, etc.) and QoE. The final users could also influence the input parameters set. This is illustrated in Figure 86.

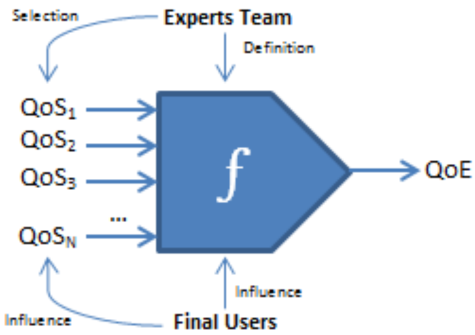

Figure 86: Subjective Approach

That is, the core idea here is to generate models integrating the final users experience in order to determine the influence of a set of objective QoS parameters into the perceived QoE. So, not only experts analysis is used, but also the reported users experience.

9.14.2.3 Getting the Mapping Functions

Of course, obtaining a good mapping function is the core task of the QoS/QoE mapping process. In some cases, when relationship between input parameters and QoE is fairly evident, the direct intuition can be used to develop a good algorithm[18], but normally (when the number of input parameters is high and their relationship is not self-evident) other resources are necessary.

According the literature, a possible approach to get the mapping functions is by using the so-called *Utility Functions*. These functions have been widely used to map one or several QoS metrics to QoE [186] [187]. As a whole, a utility function measures the user's relative preference for different levels of decision metric attribute values[19]. They can be used to map one or several QoS metrics to QoE. Utility functions can be used for both: objective and subjective approaches. For the first case input parameters are just objective QoS measurements, since for the second case, the feedback from the end users should be included in some way. An example of this method can be found in [188].

A different approach to get the mapping functions is the usage of *Statistical Analysis*. This is based on using techniques like the classical statistical regression and other more modern techniques such as Principal Component Analysis (PCA) or Linear Discriminant Analysis (LDA) [189] [190]. Statistical analysis can be used for both: objective and subjective approaches. For the objective approach, it can be used to find the formula relating QoS measurements with QoE. For the subjective approach, it can be used to find and isolate the objective parameters that are affecting the final user experience. In this case, to build the model, a set of final users could be asked about their subjective experience, and once the most relevant parameters are identified, a simple formula can be used to determine QoE in real time by

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[18] For example, for a given type of service (i.e. load a web page) a high delay usually implies a low QoE (or vice versa).

[19] The term *utility* comes from the field of Economics. It is an abstract concept and is derived largely from Von Neumann and Morgenstern [12].

measuring the relevant QoS parameters; i.e: the formula is a model containing information about real users experience.

An example of this method used for evaluating QoE for video streaming can be found in [191]. In this case, viewers were presented with the same video with descending or ascending order of quality. Then viewers marked the point at which the change of quality becomes noticeable. Then, linear discriminant analysis is used to find a linear combination of features in the video streaming that can be used later for QoE rating. The resulting discriminant function formula is a linear function like this:

$$QoE = u_1 * QoS_1 + u_2 * QoS_2 + \ldots + u_p * QoS_p \tag{2}$$

where QoS_1 ... QoS_p are the relevant QoS parameters found thanks to the statistical analysis, while u_1 ... u_p are the corresponding empirically found factors for each one.

Other commonly used approach to find the mapping function is using *Machine Learning* (ML) methods. This approach is mainly suitable for the subjective approach, where the relation between the user's responses and the objective parameters is not evident; anyway, it could be used also for the objective approach when the amount of data to manage is big. Actually, this case is very similar to the previous one (statistical analysis) but, instead of using traditional statistical methods to figure out the relevant input parameters and their relationship, modern machine learning methods are used (Artificial Neural Networks [192], Genetic Algorithms [178], Decision Trees [177] or Support Vector Machines [176] for instance). The whole idea is basically the same, i.e., to collect data from real users about their quality perceptions, and use those data to train the selected machine learning algorithm. Sometimes accuracy obtained with these methods is very high, being above 90% in some cases [193]. Probably this is because the ability to find relevant objective parameters and non-linear relationships among them using these techniques.

9.14.3 The Mapping Function Output

The mapping function output expresses, of course, the sought QoE value; but this value could be encoded in different ways according the application requirements. In practice, it can be a bounded rational number, or a vector with multiple components to express QoE for different features (audio, video, etc.). It can be delivered also as an event (or events set) to notify only when the QoE value reaches certain threshold, or it can be encoded also as a qualified QoE value (QQoE), i.e., a numeric value linked to a certain code to explain the possible QoE lack.

Also, besides the way it is encoded, QoE can be associated to different metrics. For example, it could be necessary to compute the QoE regarding the noisiness/loudness, responsiveness or video distortion. The following Table 14 shows a classification of different QoE metrics.

Table 14: QoE metrics examples and classification

Type	Description	Sub-levels	Example QoE metrics
Direct perception	Created immediately and spontaneously; related to human sensory channels.	Visual	Brightness, contrast, flicker, sharpness, distortion, colour saturation, fragmentation, movement disturbance, blurring, freezing, blocking, stalling.
		Audio	Clarity, intelligibility, noisiness, loudness, continuity, timbre, echo.
		Audio-	Balance, synchronism.

		visual	
Interaction	Perception of human-to-human and human-to-machine actions and reactions		Responsiveness, naturalness of interaction, rapport, communication effectiveness, involvement, social presence/ immersion, user input redundancy.
Service usage	Perception of the service usage situation	Hedonic	Enjoyment, gratification, goal fulfilment, user-friendliness.
		Pragmatic	Learnability, effectiveness, efficiency, accuracy, ease of use.
Service	Perception of the usage of the service beyond a particular instance		Appeal, utility, acceptability, trustworthiness, reliability.

In addition, sometimes very specific encoding functions are used. An example is the usage of the Weber-Fechner law (WFL) of psychophysics [194], which relates the physical stimulus that a person receives with the subjective perceived intensity in a logarithmic manner (see Figure 87). The subjective perception is comprised of discrete noticeable intervals (horizontal dashed lines) within which the user perceives the same subjective intensity. This concept can be seen comparing points A and B in the figure. In the A-B interval, the subjective perception of the user is the same, while the upper part of the interval (point B) involves up to twice as much of resources as the lower part (point A). The conclusion is that to achieve the same user perception, moving away from point A involves a waste of resources.

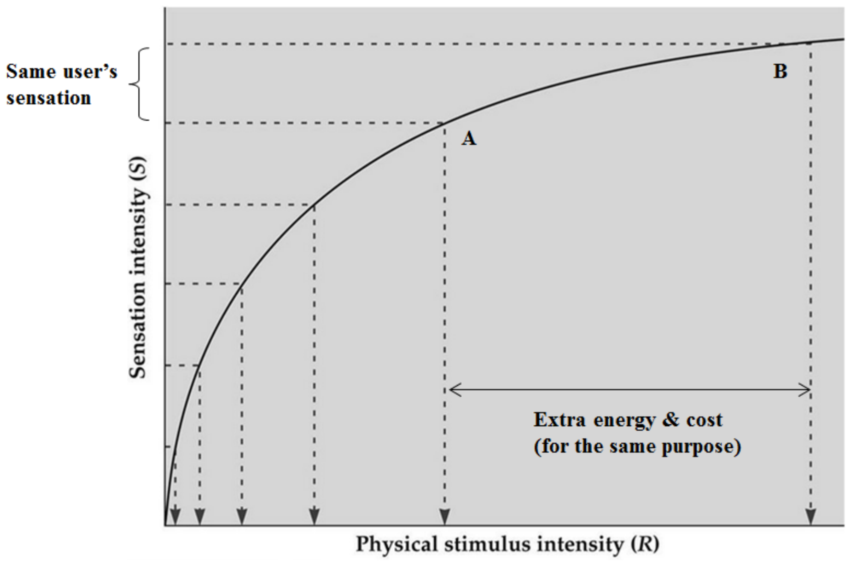

Figure 87: Weber-Fechner law of psychophysics

Of course, this is just an illustrative example of how relevant QoE events could be generated to save resources and energy. Other approaches could be used depending on the specific application and needs.

So, as a general conclusion we can tell that, like with the mapping function itself, if we consider the different encoding schemes and the different QoE metrics, the mapping function output can be expressed in very different ways as well. There is no general consensus on this, being the solution depending very much on each specific application field and requirements.

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