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5G Mobile Network Architecture

for diverse services, use cases, and applications in 5G and beyond

Deliverable D2.2

Initial overall architecture and concepts for enabling innovations

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Abstract: This deliverable refines the baseline architecture of 5G-MoNArch (from D2.1) towards the "Initial Overall Architecture". It further captures the project's "enabling innovations" and elaborates on the concepts for architectural extensibility and customisation for the testbeds.

Taking into consideration the requirements, KPIs, and the evaluation criteria from WP6 and the 5G system gap analysis from D2.1, this document refines the baseline architecture model based on three design fundamentals: (i) split of control and user plane, (ii) service-based architecture within the core network (in line with recent industry and standard consensus), and (iii) fully flexible support of E2E slicing via per-domain and cross-domain optimisation, capitalising on a telco-cloud-enabled protocol stack while devising inter-slice control & management functions and refining the operational models via experiment-driven optimisation.

The initial overall architecture model facilitates the commissioning of slices with specific functionalities, such as network resilience and security functions (by WP3) and network elasticity (by WP4). The results form the basis for further adjusting the algorithms (in WPs 2-4), implementing them in the respective testbeds (in WP5) and evaluating and validating their performance (in WP6).

Keywords: 5G Network Architecture, Initial Architecture, E2E Network Slicing, Enabling Innovations, Architectural Extensibility

Executive Summary

This deliverable presents the intermediate results of the architecture design in 5G-MoNArch after completion of the first project year. It refines the baseline architecture of 5G-MoNArch from deliverable D2.1 [5GM-D2.1] towards the “Initial Overall Architecture”. Moreover, it captures the project’s “enabling innovations” and elaborates on the concepts for architectural extensibility and customisation for the 5G-MoNArch testbeds. 5G-MoNArch innovations rely on so-called innovation elements, where each innovation element is composed of one or more enablers. By applying a functional decomposition to the 5G-MoNArch enablers, the required modifications on the overall architecture are analysed, which include functional extensions and interface design implications with respect to the baseline architecture.

The “5G-MoNArch Initial Overall Architecture” reference model employs a fundamental structuring into four layers: (i) Service layer, (ii) Management & Orchestration (M&O) layer, (iii) Controller layer, and (iv) Network layer. The Service layer comprises Business Support Systems (BSS), business-level Policy and Decision functions, and further applications and services operated by a tenant or other entities on the customer-facing service side. The M&O layer hosts functions for end-to-end (E2E) service and network management and orchestration as well as domain-specific M&O operations (including network, technology, and administration domains). The Controller layer consists of intra-slice and cross-slice controllers and according controller applications to allow re-programmability and functional re-configuration of decomposed radio access network (RAN) functions, thereby extending software-defined networking (SDN) principles to mobile networks. The Network layer contains the control and user plane functions of various domains, particularly from RAN and core network (CN).

To realise the individual 5G-MoNArch enabling innovations, a respective set of novel network functions (NFs) and their concrete interworking procedures with the functions of the baseline architecture have been developed. Subsequently, the deliverable shows where the novel NFs have been placed within the architectural reference model. Depending on the innovation element, these network functions can span across multiple layers of the architecture. The enabling innovations developed in 5G-MoNArch consist of *telco-cloud-enabled protocol stack*, *inter-slice control and management*, and *experiment-driven optimisation*. Each of the three innovations is backed by a set of innovation elements and enablers, among them telco-cloud-aware protocol design for the radio access, inter-slice (radio) resource management (RM), or machine-learning-based resource optimisation for virtualised radio functions. The resulting novel functions are elaborated in detail and first evaluation analyses are provided.

Finally, the deliverable describes the framework for architectural extensibility and customisation, targeting use case-specific network slice instances (NSIs). On a more generalised level, the universal means for such service-specific design and operation of network slices is depicted by introducing the comprehensive 5G-MoNArch Network Slice Blueprint concept. Further, enhanced possibilities for extending network infrastructure utilisation are presented by introducing the concepts and algorithms for 5G-MoNArch Network Slice Allocation and Network Slice Congestion Control. On a more practical level, the deliverable elaborates on how these general concepts are used to create and commission use case-specific network slices in the two 5G-MoNArch testbeds, namely the Hamburg Smart Sea Port and the Turin Touristic City.

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List of Acronyms and Abbreviations

2G	2nd Generation mobile wireless communication system (GSM, GPRS, EDGE)
3G	3rd Generation mobile wireless communication system (UMTS, HSPA)
3GPP	3rd Generation Partnership Project
4G	4th Generation mobile wireless communication system (LTE, LTE-A)
5G	5th Generation mobile wireless communication system
5GS	5G System
5G-PPP	5G infrastructure Public Private Partnership
AAA	Authentication, Authorisation and Accounting
AaSE	AIV agnostic Slice Enabler
AIV	Air Interface Variant
AMF	Access and Mobility management Function
AN	Access Network
AR	Augmented Reality
ARP	Allocation and Retention Priority
B2B	Business-to-Business
B2C	Business-to-Consumer
BBU	Base Band Unit
CAPEX	CAPital EXpenditure
CCNF	Common Control Network Functions
CN	Core Network
CP	Control Plane
CSC	Communication Service Customer
CSI	Channel State Information
CSMF	Communication Service Management Function
CSP	Communication Service Provider
CU	Central Unit
DC	Data Centre
DCSP	Data Centre Service Provider
DRB	Data Radio Bearer
DSC	Dynamic Small Cell
DU	Distributed Unit
E2E	End-to-End
eICIC	enhanced Inter-cell Interference Coordination
eMBB	enhanced Mobile Broadband
feD2D	further enhanced D2D
GHO	Group Handover
gNB	NR access node with user plane and control plane
HARQ	Hybrid Automatic Repeat Request
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
ISRB	Inter-Slice Resource Broker
IM	Interference Management
ITS	Intelligent Transport System
KPI	Key Performance Indicator
LTE	Long Term Evolution
MAC	Medium Access Control
M&O	Management and Orchestration layer
MANO	ETSI MANagement and Orchestration
MBB	Mobile BroadBand

MCS	Modulation and Coding Scheme
MME	Mobility Management Entity
mMTC	Massive Machine Type Communication
MOCN	Multi-Operator Core Network
MORAN	Mobile Operator Radio Access Network
NAS	Non-Access Stratum
NBI	NorthBound Interface
NE	Network Element
NEP	Network Equipment Provider
NF	Network Function
NFV	Network Function Virtualisation
NFVO	Network Function Virtualisation Orchestrator
NGMN	Next Generation Mobile Networks
NOP	Network OPerator
NRM	Network Resource Model
NS	Network Service
NSI	Network Slice Instance
NSMF	Network Slice Management Function
NSSAI	Network Slice Selection Assistance Information
NSSF	Network Slice Selection Function
NSSI	Network Slice Subnet Instance
NSSMF	Network Slice Subnet Management Function
NST	Network Slice Template
NWDA	Network Data Analytics
OPEX	OPerational EXpenditure
PAN	Personal Area Network
PDCP	Packet Data Convergence Protocol
PDU	Protocol Data Unit
PGW	Packet Data network Gateway
PHY	Physical Layer
PLMN	Public Land Mobile Network
PNF	Physical Network Function
QoE	Quality of Experience
QoS	Quality of Service
RA	Registration Area
RACH	Random Access CHannel
RAN	Radio Access Network
RAT	Radio Access Technology
RL	Reinforcement Learning
RLC	Radio Link Control
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio Resource Management
RTT	Round Trip Time
SBA	Service-Based Architecture
SDAP	Service Data Adaptation Protocol
SDM-O	Software Defined Mobile network Orchestrator
SDO	Standards Developing Organisation
SDSF	Structured Data Storage network Function
SFC	Service Function Chain
SGW	Serving GateWay

SMF	Session Management Function
SMm	Security Monitoring Manager
STZm	Security Trust Zone Manager
TAU	Tracking Area Update
TN	Transport Network
UDSF	Unstructured Data Storage network Function
UE	User Equipment
UP	User Plane
UPF	User Plane Function
VIM	Virtual Infrastructure Manager
VISP	Virtual Infrastructure Service Provider
VNF	Virtual Network Function
VNFM	Virtual Network Function Manager
VR	Virtual Reality
V2X	Vehicle to Anything
WG	Working Group
WP	Work Package

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1 Introduction

This deliverable refines the baseline architecture of 5G-MoNArch (from Deliverable D2.1 [5GM-D2.1]) towards the "Initial Overall Architecture" as presented in Chapter 3. D2.2 further captures the project's "enabling innovations" and elaborates on the concepts for architectural extensibility and customisation for the 5G-MoNArch testbeds. 5G-MoNArch has applied a structured approach in building the overall architecture as illustrated in Figure 1-1. This approach includes the design of the fundamental elements called enablers. Simply put, 5G-MoNArch innovations are constructed by innovation elements, where each innovation element is composed of one or more enablers. By applying a functional decomposition to the 5G-MoNArch enablers, the modifications on the overall architecture are analysed, which includes functional extensions and interface implications on the baseline architecture.

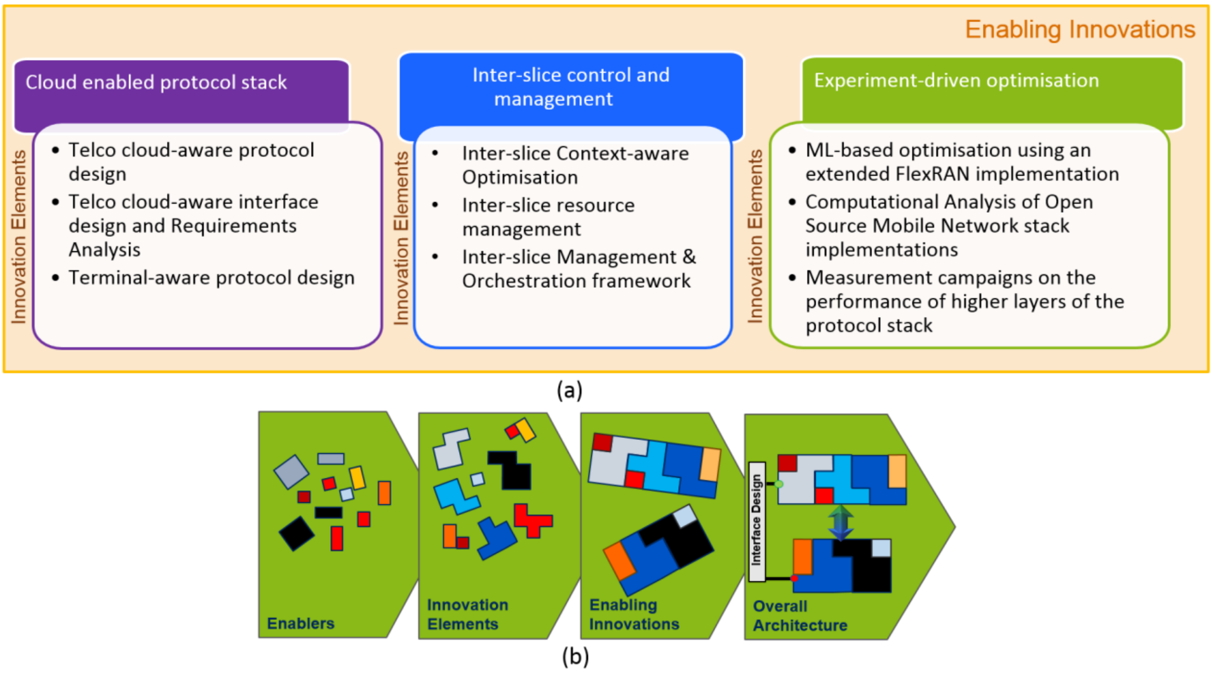

Enabling Innovations
Cloud enabled protocol stack
Innovation Elements
• Telco cloud-aware protocol design
• Telco cloud-aware interface design and Requirements Analysis
• Terminal-aware protocol design
Inter-slice control and management
Innovation Elements
• Inter-slice Context-aware Optimisation
• Inter-slice resource management
• Inter-slice Management & Orchestration framework
Experiment-driven optimisation
Innovation Elements
• ML-based optimisation using an extended FlexRAN implementation
• Computational Analysis of Open Source Mobile Network stack implementations
• Measurement campaigns on the performance of higher layers of the protocol stack
(a)
Enablers
Innovation Elements
Enabling Innovations
Interface Design
Overall Architecture
(b)

Figure 1-1: (a) High-level 5G-MoNArch enabling innovations; (b) the approach of 5G-MoNArch in building the overall architecture based on these innovations

The document is structured as follows. Chapter 2 sets the overall context for the architecture design: use cases are briefly re-visited, associated requirements are summarised, and the 5G ecosystem and its stakeholders are presented. Finally, these technical considerations are complemented by the economic benefits of the 5G ecosystem evolution.

Chapter 3 provides the details on the "5G-MoNArch Initial Overall Architecture" reference model with the envisioned four layers: (i) **Service layer**, (ii) **Management & Orchestration (M&O) layer**, (iii) **Controller layer**, and (iv) **Network layer**. The main concepts behind each layer are as follows.

(1) The **Service layer** comprises Business Support Systems (BSS), business-level Policy and Decision functions, and further applications and services operated by a tenant or other entities external to the mobile network operator (MNO) or mobile service provider (MSP).

(2) At the **M&O layer**, the Communication Service Management Function (CSMF) transforms consumer-facing service descriptions from service layer into resource-facing service descriptions, and therefore works as an intermediary function between the Service layer and the Network Slice Management Function (NSMF) within the M&O layer. The NSMF splits service requirements as received from CSMF and coordinates with multiple management domains for end-to-end (E2E) network slice deployment and operation.

(3) The **Controller layer** is an optional architectural layer of 5G-MoNArch consisting of intra-slice and cross-slice controllers, bringing **re-programmability** and **functional re-configuration** of decomposed RAN functions to efficiently share and optimise radio

resources. Investigated is the applicability of such solutions in the framework of the RAN architecture

(4) At the **Network layer**, 5G-MoNArch's innovative intra-slice and cross-slice functions (so-called innovation elements) are placed in order to meet E2E network slice requirements and operation, involving the operation of the core network (CN) or (Radio) Access Network ((R)AN) network functions (NFs). These innovation elements include: (i) **slice-aware Radio Resource Management (RRM)** with **both intra- and inter RAN configuration modes**, (ii) utilisation of **network and User Equipment (UE) data analytics** in **slice selection / radio resource optimisation,** (iii) **slice-aware functional operation / admission control,** and (iv) **extensions to 3rd Generation Partnership Project's (3GPP's) network slice data analytics function (NWDAF)** and **service-based architecture (SBA)** design. Furthermore, interaction between intra-slice and cross-slice control functions and different implementation options for control functions' realisation at RAN-level are discussed. The functions for elastic resource management (Work Package 4, WP4) and reliability control and management (WP3) are integrated into the Network layer architecture.

Chapter 4 further details the so-called 5G-MoNArch enabling innovations and the associated network functions (NFs) to address the specific requirements of the 5G-MoNArch communication services. The three enabling innovations are described under five sections:

- **Cloud-enabled protocol stack**, comprising (i) telco-cloud-aware protocol design, (ii) cloud-enabled RAN protocol stack, and (iii) terminal-aware protocol design,
- Inter-slice control and management built by
    - **Inter-slice context-aware optimisation**, comprising (i) inter-slice context sharing and optimisation, (ii) inter-slice coordination, and (iii) terminal analytics driven slice selection and control,
    - **Inter-slice Resource Management** (RM), comprising (i) inter-slice RRM for dynamic Time Division Duplex (TDD) scenarios, (ii) context-aware relaying mode selection, (iii) slice-aware Radio Access Technology (RAT) selection, (iv) inter-slice RRM using the Software Defined Networking (SDN) framework, and (v) big data analytics for RM,
    - **Inter-slice management & orchestration**, comprising (i) framework for slice admission control, (ii) the framework for cross-slice congestion control, and (iii) slice admission control using genetic optimisers,
- **Experiment-driven optimisation**, comprising (i) machine-learning-based optimisation using an extended FlexRAN implementation, (ii) computational analysis of open source mobile network stack implementations, and (iii) measurement campaigns on the performance of higher layers of the protocol stack.

Chapter 5 reports on the project's concept of **architectural extensibility and customisation**. The 5G-MoNArch **Network Slice Blueprint** concept provides the major means for service-specific customisation of a network slice's functional architecture. Network slice lifecycle management mechanisms, particularly **slice allocation** and **slice congestion control**, have been developed to efficiently deploy multiple logical network slice instances on a shared infrastructure, i.e., to realise multi-slice networks. Furthermore, the 5G-MoNArch major use cases (**Smart Sea Port** and **Touristic City**) are used to illustrate how the abovementioned extensibility concepts are applied to **integrate use-case specific functionalities from WP3 and WP4** with the general WP2 architecture and to **concurrently deploy multiple network slice instances (NSIs)**.

Chapter 6 concludes the deliverable by summarising the most important results and achievements. Moreover, it provides an outlook towards the next interim report (IR2.2) of WP2 and the final deliverable (D2.3).

The **key novelties** of the architecture and approaches proposed in this deliverable include the following:

- The design of the 5G-MoNArch architecture has revisited network management and orchestration functions of both the 3GPP and the European Telecommunications Standards Institute (ETSI) Network Function Virtualisation (NFV). The initial overall architecture proposed here extends the reference architectures of the 3GPP 5G System and ETSI NFV

MANO by building on these architectures while addressing several gaps identified within the corresponding baseline models.

- Within the proposed architecture, there are various novel NFs that are not specified elsewhere and need to be designed. In this document, the design guidelines of some of the key modules within the architecture are presented, corresponding to innovation elements and enablers.
- One of the key results is the unique assembly and interworking of novel technologies within the architecture (SDN, NFV, enhanced network management and orchestration procedures, multi-service capable RAN, etc.) to facilitate network slicing. Applying these technologies in a harmonised and automated manner requires new NFs that are instantiated with the use case-specific network slice orchestrated by the M&O layer functions, satisfying the specific requirements of the use cases. This is addressed here by leveraging the results of WP3 and WP4.

2 Architecture Design – Objectives and Principles

This chapter provides a brief overview of the overall context for the 5G-MoNArch architecture design. On the one hand, it gives a summary of the underlying use cases and the associated requirements, as already defined in an earlier phase of the project [5GM-D2.1]. On the other hand, it elaborates the assumptions regarding the stakeholders in the 5G ecosystem, their expected roles and how they influence the architecture design. On the non-technical angle, the chapter summarises the expected economic benefits of a 5G system design that incorporates the technical enablers to support a multitude of novel business models in the mobile network industry. While the chapter includes a few forward references to concepts described in subsequent chapters, the level of abstraction should easily allow the reader to extract the major takeaways of the architecture design principles and objectives. Moreover, Deliverable D2.1 [5GM-D2.1] has provided a gap analysis with respect to ongoing 5G system architecture design efforts in the industry and academia, cf. Table 2-1. The objectives and principles of the architecture design shall address these gaps. A detailed description of the gaps is also provided in Appendix A.

Table 2-1: List of gaps as observed by 5G-MoNArch [5GM-D2.1]

Gap	Description
GAP #1	Inter-dependencies between Network Functions co-located in the same node
GAP #2	Orchestration-driven elasticity not supported
GAP #3	Fixed functional operation of small cells
GAP #4	Need for support for computational offloading
GAP #5	Need for support for telco grade performance (e.g. low latency, high performance, scalability)
GAP #6	E2E cross-slice optimisation not fully supported
GAP #7	Lack of experiment-based E2E resource management for VNFs
GAP #8	Lack of a refined 5G security architecture design
GAP #9	Lack of a self-adaptive and slice-aware model for security
GAP #10	Need for enhanced and inherent support for RAN reliability
GAP #11	Indirect and rudimentary support of telco cloud resilience mainly through management and control mechanisms
GAP #12	Need for (radio) resource sharing strategy for network slices

2.1 *Summary of 5G-MoNArch use cases*

As the first step in designing the architecture, 5G-MoNarch considers three use-cases, base on which the innovations and algorithms are going to be evaluated. These three use cases are (i) Resilient network slices for industrial applications, (ii) Elastic network slices enabling local peak performance, (iii) Integration of resilient and elastic slices into smart city environments. These use cases are associated with the two testbeds, i.e., Smart Sea Port and Touristic City.

Resilience network slices for industrial application is going to be considered in the sea-port scenario (based on the testbed in Hamburg). The Smart Sea Port is a typical large environment operated by a vertical industry player for different end customer groups, e.g., shipping companies (both passenger and cargo), logistic companies, railway companies, retailers. Sea ports manage the traffic and trade of goods, aiming at maximising its throughput. The innovations involved in this use-case can be summarised as resilience, security, network slicing, and inter-slice control. The selected applications for this use-case are traffic light control (URLLC), video surveillance (eMBB), and sensor measurements (mMTC). While there are many technical and economical Key Performance Indicators (KPIs) to be considered in this use-case, the most important KPIs are: coverage area probability, E2E reliability, incremental cost (i.e., the extra cost to offer higher level of reliability and resilience) per GB, and incremental revenue per GB.

Elastic network slicing enabling local peak performance: is going to executed in the Touristic City (Turin) testbed related verification scenario. The Touristic City (located in Turin) testbed represnets a typical case of futre advanced multimeda service deliveray in a Touristic City. The main innovations involved in this use-case are computaitonally-elastic network functions, cloud-enabled protocol stack, and slice-aware elasticity. In addtion to torutistic city senarios, a combined smart city (for simplicity restricted to eMBB) and sea-port related scenario in Hamburg with focus on cost efficiency gains by elastic network slices fulfilling the smart city as well as demand hot spot service definitions. Since elestice management of network resources is the main goal in this use-case, the main KPIs among all the KPIs to focus on are: cost efficiency gain, incremental cost per GB, and incremental revenue per GB.

Integration of resilient and elastic slices into smart city environments is executed in the Hamburg verification scenario considering a wider range of tenants than was the case in the first use-case. These tenants now include those for smart city services as well as for the Smart Sea Port services (investigated in evaluation case 1) to understand how the benefits of the 5G-MoNArch enablers change for scenarios of different scales and scope of services. In addition, the localised temporary hotspots of demand from evaluation case 2 are combined in this scenario to understand how accommodating these might be impacted by trying to utilise network elasticity on a multi-service network. In this case all performance profiles of the former cases are applied in order to investigate benefits of and flexibility introduced due to 5G-MoNArch enablers in a combined scenario. The integration of resilient and elastic network slices into future smart city environments will allow for verification and demonstration of the full potential of 5G-MoNArch enablers within fully fledged future 5G network architectures. The important KPIs for this use-case are coverage area probability, E2E reliability, and cost efficiency gain.

2.2 *Summary of 5G-MoNArch requirements*

One important step in defining the 5G-MoNArch architecture has been to list and detail all the necessary requirements. In this section, an overview of the requirements defined so far in the project is given. The reader can find more details in deliverable D6.1 [5GM-D6.1]. The requirements are grouped in four categories: general, resilience and security, resource elasticity, and techno-economic requirements.

- The **general requirements** group is a consolidated version of general requirements taken from the 5GPPP Phase 1 projects, industry forums and SDOs. These requirements can be in turn further classified into generic, network slicing, RAN-related, capacity exposure, and security.
- The second set of requirements relates to **resilience and security**. More specific to the 5G-MoNArch project, they are further classified into protection, detection, and reaction.
    - Protection refers to how efficient is the network when protecting itself from encountering malfunctions; radio link outage probability should be minimal in order to achieve the required high network reliability and availability.
    - The Detection group deals with exposing network faults and malfunctions as well as security threads critical to 5G systems.
    - Proper Reaction should occur to malfunctions or security attacks to ensure the performance of the 5G systems.
- The third set of requirements is related to **resource elasticity**. The list of requirements is:
    - Elastic VNFs should adapt to variations in resource availability, avoiding abrupt degradation in the performance.
    - An elastic network slice should match available resources to instantaneous demand by gracefully adapting itself.
    - At the infrastructure level, the number of network slices and the resources reserve to them should be flexible to allow for more network slices on the same infrastructure
- Finally, the last set of requirements refers to the **techno-economic evaluation**. They are related to the commercial benefit of the 5G-MoNArch architecture. They consist of four requirements:
    - Improve user experience on existing services to improve willingness to pay and drive up revenues from consumers.

- Enable service providers to provide a greater variety of services, to access higher value business-to-business (B2B) rather than purely business-to-consumer (B2C) revenues for their wireless services
- Support a layered multi-tenant ecosystem to allow service providers to maximise value from their services and minimise costs.
- Improve network utilisation in order to provide a larger number of wireless services.

Assuming all the above requirements are achieved, they will show the long term commercial viability of mobile networks implementing the 5G-MoNArch architecture.

2.3 *5G-MoNArch ecosystem*

The 5G-MoNArch architecture will represent a change in the current mobile network stakeholder ecosystem. Mobile network operators (MNOs) will change from a vertically integrated model, where they own the spectrum, antenna and core network sites and equipment, to a layered model where each layer might be managed or implemented by a different stakeholder. This new situation arises from the 5G virtualised network capability as proposed by 5G-MoNArch. Besides that, the seamless integration of new verticals into the mobile ecosystem, opportunities for new revenues streams for mobile service providers, and enable realisation of benefits to society more generally would also ideally take place. One example of this layered stakeholder model enabled by a flexible 5G network is shown in Figure 2-1 [5GM-D6.1].

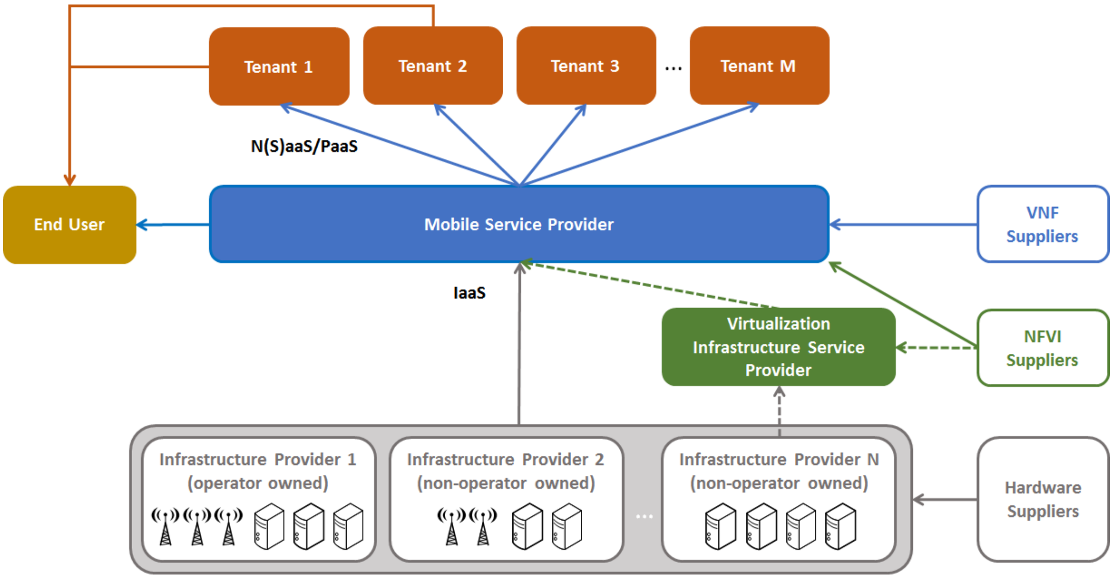

Tenant 1
Tenant 2
Tenant 3
...
Tenant M
N(S)aaS/PaaS
End User
Mobile Service Provider
VNF Suppliers
IaaS
Virtualization Infrastructure Service Provider
NFVI Suppliers
Infrastructure Provider 1 (operator owned)
Infrastructure Provider 2 (non-operator owned)
...
Infrastructure Provider N (non-operator owned)
Hardware Suppliers

Figure 2-1: A layered stakeholder model (from [5GM-D6.1])

A **Stakeholder** is an individual, entity or organisation that affects how the 5G-MoNArch system operates. The stakeholder roles defined for 5G-MoNArch are:

- A **Mobile Service Provider (MSP)** provides mobile internet connectivity and telecommunication services to end users. The network resources are offered as network slices realising the associated service function chains, e.g., eMBB or mMTC. An MSP designs, builds and operates its service offerings.
- A **tenant** purchases and utilises a 5G-MoNArch network slice and services provided by a MSP. Examples of a tenant are today's MVNO, enterprises or any organisation that requires telecommunications services for their business operations.
- An **Infrastructure Provider (InP)** owns and manages the network infrastructure (antenna sites, base stations, remote radio heads, data centres, among others), and offers it to the MSP, i.e., Infrastructure-As-A-Service (IaaS).

- A **Mobile Network Operator (MNO)** operates and owns the mobile network, combining the roles of MSP and InP.
- A **Virtualisation Infrastructure Service Provider (VISP)** may exist, responsible for designing, building and operating a virtualisation infrastructure on top of the InP services, and offering its infrastructure service to the MSP.
- A **hardware (HW) supplier** offers hardware to the InPs (server, antenna, cable …)
- A **NFV Infrastructure (NFVI) supplier** provides the corresponding NFV infrastructure to its customers, i.e. to the VISP and/or directly to the MSP
- A **VNF supplier** offers virtualised software (SW) components to the MSP.

It is possible to use these stakeholder roles to provide high-level mappings to the two testbeds scenarios and the three evaluation cases of 5G-MoNArch [5GM-D6.2], as depicted in Table 2-2 through Table 2-6[1].

Table 2-2: Stakeholder roles in resilient network slices for industrial applications evaluation case

Stakeholder Role	Fulfilled by
InP	Existing MNOs
MSP	Existing MNOs
Consumer	Tourists, pedestrians and passengers in vehicles using consumer handheld devices, drivers (assisted driver services), logistics companies, drivers (assisted driver services)
Tenant	Port Authority (here, Hamburg Port Authority - HPA)

Table 2-3: Stakeholder roles in elastic network slices enabling local peak performance evaluation case

Stakeholder Role	Fulfilled by
InP	Existing MNOs
MSP	Existing MNOs
Consumer	Cruise ship passengers using consumer handheld devices
Tenant	eMBB consumers

Table 2-4: Stakeholder roles enabling future smart city evaluation case

Stakeholder Role	Fulfilled by
InP	Existing MNOs
MSP	Existing MNOs
Consumer	Pedestrians and passengers in vehicles using consumer handheld devices, drivers (assisted driver services), logistics companies, city councils (smart city applications), energy companies (smart metering and smart grids)
Tenant	Port authority (here HPA), eMBB consumers, city councils

Table 2-5: Stakeholder roles in the Smart Sea Port testbed scenario

Stakeholder Role	Fulfilled by
InP	MNOs (e.g., Deutsche Telekom/DT (also w.r.t. fixed network), with Nokia as possible HW supplier), Hamburg Port Authority/HPA (own network infrastructure), venue owner, city council
MSP	DT, HPA
Consumer	HPA, logistics management company, train operator
Tenant	Port authority (here HPA)

[1] The listed mappings are subject to further changes as the project progresses.

Table 2-6: Stakeholder roles in the enhanced Touristic City experience testbed scenario

Stakeholder Role	Fulfilled by
InP	MNOs (e.g., Telecom Italia/TIM (also w.r.t. fixed network), with Huawei as possible HW supplier)
MSP	TIM
Consumer	Tourist
Tenant	Venue owner, city council

2.4 *Economic benefits of the 5Gs ecosystem evolution*

As was highlighted in the socio-economic assessment already carried out in the EU 5GPPP Phase 1 project 5G NORMA [5GN-D2.3], today's mobile industry faces significant commercial challenges. This is due to:

- Revenues for MBB services in Western European countries remaining flat or even reducing due to subscriber penetration levels already being close to saturation and mobile subscription charges already being close to the limits of willingness to pay from consumers.
- Costs for MBB services growing due to increasing user expectations and traffic generated on networks.

Combining the above two effects means that the margin between the revenue per GB and cost per GB is rapidly reducing with there being significant risk to the business case for mobile networks even in dense city areas over the next ten years unless operators take action to limit mobile data growth trends. However, limiting mobile data growth stands to stifle innovation in mobile services and applications with associated social and commercial benefits from these being lost.

Network slicing in 5G networks promises to help to de-risk this situation in two ways:

- Increasing revenues by introducing new mobile services. These new mobile services do not only increase revenue by introducing new subscribers. As many of these new services can be tailored to the individual requirements of customers they are also more likely to be higher value (in terms of revenue per GB) business to business (B2B) services for verticals.
- Reducing the cost per GB compared with MBB and eMBB only networks by providing a wide range of services from a single multi-service network. This means that network providers can not only extend the benefits from economies of scale already seen by delivering higher volumes of traffic (as already seen for MBB) but can also benefit from economies of scope delivered by multi-service platforms.

The economic benefits of multi-service networks have already been examined in [5GN-D2.3] from the perspective of additional revenue generation and economies of scope on costs in a smart city environment. 5G-MoNArch further develops these themes by:

- Supporting highly tailored secure, resilient and reliable industrial services to verticals.
- Supporting a highly flexible network architecture that can be dynamically deployed and deliver further cost savings via network elasticity.

As mentioned earlier, in 5G-MoNArch, WP6 examines verification and validation and has developed a number of evaluation cases for assessing the 5G-MoNArch architecture and enablers. Verification of these evaluation cases will be performed via technical and economic simulation models being developed in WP6 with measurements from the testbeds supporting these where practical. The first of these evaluation cases will examine the potential to deliver new higher value services. This is being examined in the setting of Hamburg Smart Sea Port with the use of network slicing to deliver industrial services such as environmental sensor networks, traffic light control systems and mobile Augmented Reality (AR) to support port maintenance. However, 5G-MoNArch goes beyond network slicing as presented in 5G NORMA by providing additional tailoring to network slices and notably the ability to ensure security, resilience and reliability. These will be crucial for the industrial services delivered to the port authority and will greatly impact the value that can be derived from these services. This presents a requirement in the architecture to consider security, resilience and reliability requirements of services and to be able to flexibly instantiate network slices that include the appropriate network functions and infrastructure mapping to deliver against these requirements.

5G-MoNArch also promises to provide further cost benefits by providing not only a virtualised network with a separation between hardware and software elements but also to be able to make the most of this separation by dynamically instantiating and deploying network elements as demand on the network dictates. This is particularly applicable for ensuring that networks are not over dimensioned to deal with temporary demand hotspots. The network elasticity features of 5G-MoNArch will be assessed in the second evaluation case in the context of large cruise ships with up to 4,000 passengers arriving in Hamburg port and generating a demand hotspot. To enable these cost efficiencies from network elasticity the 5G-MoNArch architecture and protocol stack must support highly dynamic slice instantiation and re-configuration of network slices. This flexibility requirement extends beyond the baseband processing elements of the network to antenna sites and radio resource usage also as this is where the bulk of network costs are currently incurred.

Economies of scale and scope benefits will be revisited in 5G-MoNArch under the third evaluation case where the scenario of serving an industrial tenant in the form of Hamburg Port Authority is combined with also delivering smart city services to other tenants such as a city council from the start point of an existing eMBB network. This combined scenario will also include the demand hotspots from evaluation case 2 and investigate the cost savings of network elasticity in this wider scenario with a greater range and diversity of services.

A final requirement from the economic perspective for the 5G-MoNArch architecture is ecosystem related. De-coupling of the network service from the infrastructure in virtualised networks not only promises improved cost efficiencies via flexibility and elasticity, as indicated above, but also presents opportunities for new players in the ecosystem as per the tiered stakeholder model introduced in 5G NORMA and re-emphasised in 5G-MoNArch Deliverable D6.1 [5GM-D6.1]. However, to enable this new stakeholder model open interfaces and harmonised network function specifications are needed. Feedback from existing MNOs considering the transition to virtualised networks indicates that they remain sceptical that VNFs, orchestrators etc. will truly be plug and play across a range of infrastructure providers. There is therefore a challenge for 5G-MoNArch to address this concern.

3 5G-MoNArch Initial Overall Architecture

This chapter details the 5G-MoNArch initial[2] architecture reference model and describes the fundamental design aspects: (i) E2E slicing support across different technological, network, and administrative domains, (ii) the envisioned service-based architecture (SBA), and (iii) split of control plane and user plane (CP/UP) and the resulting impact on CN and (R)AN network functions. Starting with the overall architecture design which elaborates on the fundamental structuring into network layers and domains, the chapter further depicts where the architecture relies on already existing architecture components, e.g., from 3GPP or ETSI NFV. Further, novel network functions for core and radio access network as well as innovative management and orchestration functions introduced by 5G-MoNArch are mapped into the architecture, thus completing the overall picture of the 5G-MoNArch architecture. The detailed role of network functions, particularly their mutual interaction to enable the 5G-MoNArch innovations, is then presented in Chapter 4.

3.1 *Overall architecture design – network layers and domains*

The initial design iteration of the 5G-MoNArch overall functional architecture considers the requirements from the project's use cases, results from 5G-PPP Phase 1 projects (including the White Paper of the 5G-PPP Architecture WG (v2) [5GARCH17-WPv2]), as well as the 5G requirements initially defined in [NGMN15]. Figure 3-1 depicts the four fundamental layers of the architecture. For each of these layers, there are a set of architectural elements that deliver the system's functionality, including the key functional elements, their responsibilities, the interfaces exposed, and the interactions between them.

[5GM-D2.1] (Section 2.1.2) motivates the necessity of an E2E view of a network slice to ensure the satisfaction of service requirements from the customers. The performance of an E2E network slice is determined by multiple network domains, including RAN, Transport Network (TN), and CN, as well as by CP/UP network functions in the Network layer and by the M&O layer. Figure 3-1 further shows the Controller layer and the separation into intra-slice and inter-slice functions.

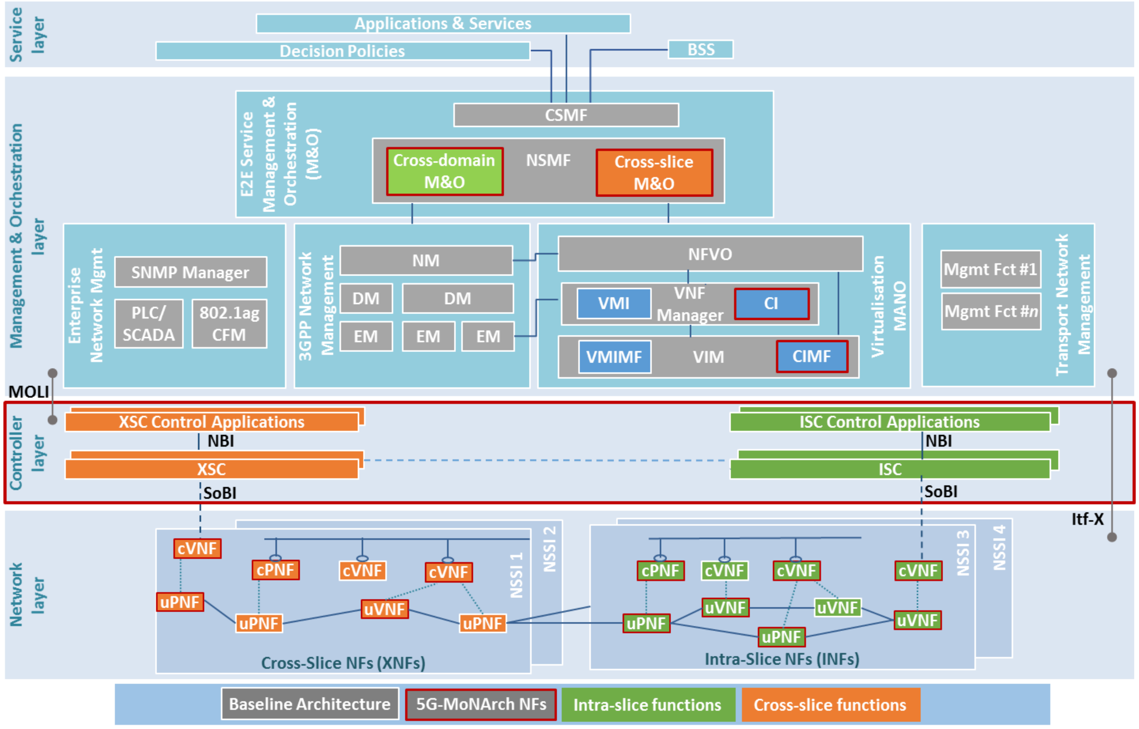


Figure 3-1: Initial 5G-MoNArch overall functional architecture

[2] The architecture presented here is a draft version of 5G-MoNArch architecture which will be refined in subsequent deliverables.

The **Service layer** comprises Business Support Systems (BSS), business-level Policy and Decision functions, and further applications and services operated by a tenant or other external entities. These functions of the Service layer interact with the Management & Orchestration (M&O) layer via the CSMF, see below.

The **Management & Orchestration layer** is composed of the M&O functions from different network, technology, and administration domains (3GPP public mobile network management, ETSI Network Function Virtualisation (NFV) Management and Orchestration (MANO) [ETSI NFV13], ETSI Multi-access Edge Computing functions [ETSI MEC16], management functions of transport networks (TNs) and private enterprise networks). Further, the M&O layer comprises the end-to-end M&O sublayer hosting the Network Slice Management Function (NSMF) and Communication Service Management Function (CSMF) that manage network slices and communications services, respectively, across multiple management and orchestration domains in a seamless manner. In the so-called *Virtualisation MANO* domain, the ETSI NFV MANO architecture for lifecycle management (LCM) of Virtual Machines (VMs) is extended towards LCM of virtualisation containers (e.g., Docker). Therefore, it comprises, besides the ETSI NFV components, corresponding functions for LCM of containers. Therefore, the Virtualised Network Function Manager (VNFM) has according components for virtual machine infrastructure (VMI) and container infrastructure (CI). Similarly, the Virtualised Infrastructure Manager (VIM) contains a VMI Management Function (VMIMF) and a CI Management Function (CIMF). NFV Orchestrator (NFVO) provides the dispatching functionality. Further, the layer accommodates 3GPP network management function, such as, Element and Domain Managers (EM and DM) and Network Management (NM) functions. Such functions would also implement ETSI NFV MANO reference points to the VNFM and the NFVO. The CSMF transforms consumer-facing service descriptions into resource-facing service descriptions (and vice versa) and therefore works as an intermediary function between the Service layer and the NSMF. The NSMF splits service requirements as received from CSMF and coordinates (negotiates) with multiple management domains for E2E network slice deployment and operation. Aa a major 5G-MoNArch novelty, NSMF further incorporates a Cross-slice M&O function for inter-slice management (e.g., common context between different slices/tenants, inter-slice resource brokering for cross-slice resource allocation, particularly in the case of shared NFs, etc.). In contrast, the Cross-domain M&O function works on strictly intra-slice level, but across multiple network and technology domains. The M&O layer performs the management tasks on Network Slice Instances (NSI), which are uniquely identified by an NSI identifier. An NSI may be further associated with one or more Network Slice Subnet Instances (NSSI). The details are further described in Sections 3.3.3 and 5.1.

The **Network layer** comprises the VNFs and physical NFs (PNFs) of both control plane (i.e., cVNF, cPNF) and user plane (i.e., uVNF, uPNF). NFs can include, for example, 3GPP Rel. 15 control plane (CP) functions (AMF, SMF, AUSF, RRC, etc.) and user plane (UP) functions (e.g., UPF, PDCP, etc.) or novel NFs developed in the project, e.g. for resource elasticity, resilience, and security. Generally, the 5G-MoNArch Network layer can comprise different CP/UP architectures, i.e., also a 4G mobile network with EUTRAN and EPC functions could constitute an instance of the Network layer. Interfaces towards the M&O layer are provided via the *Itf-X* reference point. It is an evolution of the 3GPP *Itf-S* interface between Element Manager (EM) and Network Element (NE), e.g., eNB, and facilitates domain-specific fault, configuration, accounting, performance, and security (FCAPS) management as well as domain-agnostic LCM procedures. For associating a UE to the correct NSI, the Network layer uses the Single Network Slice Selection Assistance Information (S-NSSAI), which is provided by the UE. Moreover, the CN part of the CP in the network layer is realised as a service-based architecture (SBA) [3GPP TS 23.501]. Further details of CN functionality, slice identification, and SBA are explained in Sections 3.2.2 and 3.3.2, details on the 5G-MoNArch RAN architecture are shown in Sections 3.2.1 and 3.3.1.

The **Controller layer** realises the software-defined networking concepts [ONF14], extends them to mobile networks, and therefore accommodates two controller types:

(1) the Cross-slice Controller (XSC), e.g., a RAN controller (cf. Section 4.5.1) for the control of Cross-slice Network Functions (XNFs) that are shared by multiple network slices, and

(2) the Intra-slice Controller (ISC), e.g., a CN controller for Intra-slice Network Function (INFs) within a dedicated CN-NSSI.

These controllers expose a northbound interface (NBI) towards control applications and a southbound interface (SoBI) towards VNFs and PNFs in the Network layer. Interfaces towards the M&O layer are provided via the *MOLI* reference point. The Controller layer facilitates the concept of **mobile network programmability.** Generally, software-defined networking (SDN) splits between *logic* and *agent* for any functionality in the network. This means that the NFs are split into the decision logic hosted in a control application and the actual NF in the Network layer (usually a uPNF or uVNF) that executes the decision. In other words, for the given uVNF or uPNF, the according cPNf or cVNF would disappear. The controller resides "between" application and NF and abstract from specific technologies and implementations realised by the NF, thus decoupling the control application from the controlled NF, cf. Figure 3-1. 5G-MoNArch investigates the applicability of this paradigm, focusing on the concepts for elasticity (WP4) and resiliency (WP3). If no such split between control logic and agent is applied, i.e., the cPNFs and cVNFs incorporate both, the Controller layer disappears. In this sense, it is an optional layer of the 5G-MoNArch architecture.

Moreover, it is worth mentioning that the interfaces depicted between the different layers will be further defined within 5G-MoNArch future work. In particular, this comprises the interfaces from M&O layer to Controller layer and Network layer, respectively. Figure 3-1 implicitly illustrates **three fundamental design aspects** that shall be followed in the 5G-MoNArch architecture:

(1) **Support for E2E network slicing:** The architecture allows for combining different options of slicing support across M&O and Network layers for each slice instance. The first supported option includes slice-specific functions, i.e., each slice may incorporate dedicated and possibly customised functions that are not shared with others. The second option includes the possibility to operate functions (or function instances) that are shared by multiple slices and have the capability to address requirements from multiple slices in parallel. Figure 3-1 depicts this split into common or so-called inter-slice functions and dedicated (intra-slice) functions. This split can be maintained in the M&O layer, the Network layer, as well as the optional Controller layer, i.e., dedicated NFs may be controlled and managed by the tenant's own instance of ISC and M&O layer functions. Shared functions are usually operated by the Mobile Network Operator (MNO) or the Mobile Service Provider (MSP) according to the stakeholder model defined in D6.1. The MNO (together with potential third-party infrastructure providers) is also in charge of managing the infrastructure. The policies regarding the utilisation of shared functions, particularly the resource allocation to active slices, are determined by the Cross-slice M&O function, and communicated towards the respective Network layer functions for further enforcement. Finally, the third option is to not only have slice-dedicated NFs but to additionally assign the associated infrastructure hardware resources (HW), including spectrum, exclusively to a single slice. The slice-specific functions and shared functions in one logical slice are bind together by the network slice identifier at the network layer. More details on how the Network layer performs network slice selection is described in Sections 3.2 and 0.

(2) **Service-based architecture (SBA):** The service-based interaction between core network CP NFs provides a set of features and associated advantages. Among others, NFs can be realised in a stateless manner since such state-related data (e.g., session data) are shared via a message bus, sometimes referred to as data bus. SBA facilitates the design of modularised NFs, uniform interaction procedures between NFs (e.g., NFs can offer their functionality as a service to other NFs), unified authentication framework between NFs, and concurrent access to services. Further details on SBA can be found in Section 3.3.2.

(3) **Split of control and user plane:** 5G-MoNArch applies a consistent split of control plane and user plane throughout all network domains, including RAN, CN, and TN. Among others, this allows for hosting associated CP and UP NFs in different locations and also facilitates to aggregate CP and UP NFs differently. The split further allows independent scalability and evolution of NFs.

Moreover, the network architecture needs to support the mapping of resilience, reliability, and security requirements (cf. [5GM-D3.1]) as defined by the MNO or a vertical enterprise to concrete network slice instances and network slice operation procedures. Such functionality is provided by CSMF, which extends existing slice templates with further deployment, management, orchestration, and control instructions for specialised NFs. These NFs may exist within different layers of the architecture. For example, a set of functions for RAN reliability, realising the architectural support for multi-connectivity, are placed in the Network layer and in the Controller layer for increasing the reliability level in the RAN for services such as ultra-reliable and/or ultra-low latency. Further, for distributed and more robust security solutions, distributed/local security functions provide fundamental access control capabilities in a 'standalone' manner, i.e., without permanent connectivity to the central cloud. Further details on how the overall architecture design supports WP3 innovations are depicted in Section 5.3.1.1.

Temporal and spatial traffic fluctuations may require that the network re-allocates available resources as needed. It is referred to this flexibility as *resource elasticity*, which includes the ability of NFs (and network slices as a whole) to scale resources according to the demand and to gracefully downscale the network operation when only insufficient resources are available. This is addressed by WP4 within 5G-MoNArch. Two major challenges comprise the short-timescale RAN functions operate on (when compared to those of cloud LCM solutions) and the limited availability of cloud resources at the edge, preventing a major exploitation of multiplexing gains. Therefore, the first challenge is tackled by a cloud-enabled (RAN) protocol stack that eliminates cross-layer dependencies as much as possible. For the second challenge, resource orchestration and LCM functions in the 5G-MoNArch architecture must support computational elasticity, such as relocating VNFs between different edge clouds and potentially between different network domains, also taking into account transport network capacity, particularly between edge cloud and antenna sites. Such "orchestration-driven elasticity" is facilitated, among others, by the cross-domain M&O function. Moreover, "slice-aware elasticity" is realised by cross-slice M&O functions in order to dynamically share computational and communications resources across slices, within the constraints of the slice requirements. Further details on novel elasticity mechanisms and their impact on the overall architecture design can be found in Section 5.3.2.1.

3.2 *Relationship with standards and standardisation roadmap*

3.2.1 Radio access network

A baseline architecture including the RAN protocol stack and the essential functional elements has been provided in D2.1 [5GM-D2.1]. Therein, it is shown that a fundamental support for network slicing is provided in the RAN. From the specification perspective, 3GPP Release 15 for next generation-RAN (NG-RAN) is to be frozen by the time of the publication of this deliverable [3GPP-RP180554][3]. This specification comprises slicing awareness in RAN via NSSAI including one or more S-NSSAIs, which allow to uniquely identify a network slice [3GPP TS 38.300]. While the fundamental slicing support is achieved by Release 15, e.g., granularity of slice awareness and network slice selection, various enhancements and optimisation can be considered for future releases. Such enhancements may imply, for example, specification-relevant signalling changes and implementation-dependent algorithms, e.g., related to RM between slices. The 5G-MoNArch approach aims at both types of enhancements, where novel RAN components and interfaces are highlighted in Section 3.3.1.

In principle, network slicing offers additional degree of flexibility, where NFs can be tailored according to the requirements of slice tenants. To this end, it can be expected that different tenants can have vastly changing needs which can be categorised under three levels, as illustrated in Figure 3-2 [GSA WP17]. On one end, some of the slice tenants may only require a performance differentiation, e.g., in terms of Quality of Service (QoS) requirements, such as latency and data rate, which can be extended by further Service Level Agreement (SLA) requirements, such as number of connections for a given time and location. On the other end, slice tenants can require different management functionality, e.g., a self-operation of the network services (NSs), such as VNF deployment, monitoring, and fault management

[3] A so-called late drop of Release 15, which includes further architecture options, is planned to be frozen by the end of 2018.

with dedicated network deployment. In addition, differentiation can be partially on a functional level, where customised NFs can be introduced by the slice tenants, such as customised security and isolation.

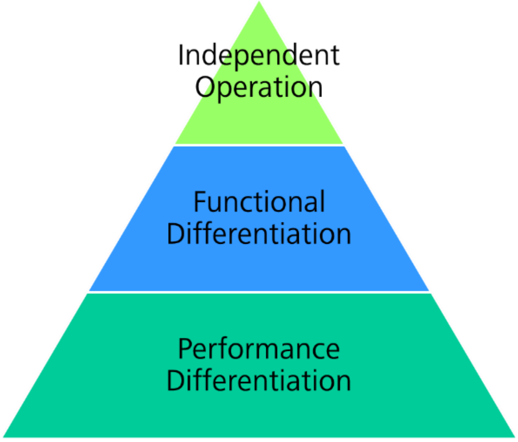


Figure 3-2: High-level classification of the slice tenant requirements [GSA WP17]

Accordingly, slice tenant requirements can be supported by different network slicing realisation variants as depicted in Figure 3-3 [5GM-D2.1]:

- In the first realisation variant (L0), an independent operation can be realised by a dedicated network, e.g., in case of public safety or railway communications.
- In the second realisation variant (L1), the slices may be allocated with dedicated spectrum, where multiple slices can share the baseband processing and antennas.
- A third possible realisation variant (L2) can be to share spectrum dynamically among different network slices, making the spectrum allocation on a time slot basis or on a semi-persistent way.
- A fourth realisation variant (L3) is to share the whole RAN protocol stack by slices where SLA differentiation can be performed with QoS enforcement. In particular, in line with the latest 5G specification, for an NSI one or more Protocol Data Unit (PDU) sessions can be established, where a PDU session belongs to one and only one specific NSI [3GPP TS 23.501]. Further, RAN maps packets belonging to different PDU sessions to different data radio bearers (DRBs), where within a PDU session there can be one or more QoS flows [3GPP TS 38.300]. On this basis, the RAN treatment of different network slices can be in terms of radio resource management (RRM) schemes performed based on the QoS profiles of QoS flows mapped onto the respective DRBs, where QoS profiles can include performance characteristics, e.g., packet delay budget and packet error rate, and allocation and retention priority (ARP).
- The last two variants do not only share the RAN among the various slices but also the TN in L4 and both the TN and CN in L5.

The choice toward the slicing realisation variants described above (involving the design of the slice-tailored NFs at different levels) depends on the needs of the slice tenants and how these needs can be realised on the RAN side. Thus, it is expected that different realisation variants or combinations thereof (e.g., partly shared core NFs and partly slice-specific core NFs) can co-exist. Yet, it seems that the variants L0, L1 and L4 may be realised first in 5G deployments. In case high isolation is required (variants L0 and L1 in Figure 3-3), all RAN protocol stack functions can be tailored according to the slice requirements. In such cases, for instance, each slice can run its tailored dynamic scheduler as an intra-slice control function. In realisation variants, e.g., L4 in Figure 3-3, where the whole RAN protocol stack is shared by different network slices, the control functions are of the cross-slice form. Under the light of the above discussion, part of the cross-slice control functions, e.g., slice-aware RRM, can be implemented as intra-slice control functions when a high-isolation realisation variant is considered. It is worth re-emphasising that even though the whole RAN protocol stack is shared by different network slices, slice-specific performance requirements can be fulfilled with appropriate QoS enforcement, as discussed under the L4 variant above.

In a further dimension, especially slow-timescale RAN control functions can be implemented as applications running in the Controller Layer shown in Section 3.1 and further described in Section 3.3.1.

Such applications take into account already standardised protocols and can provide enhancements within a cell or for neighbouring cells, see, e.g., [XRAN][4].

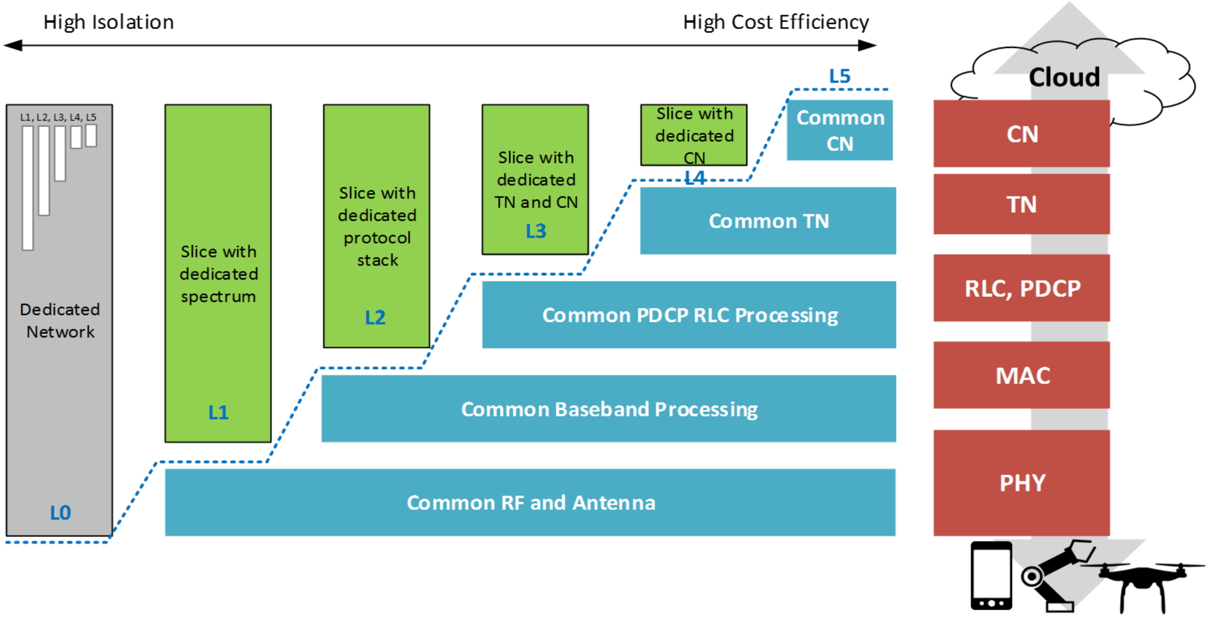


Figure 3-3: High-level slicing realisation variants affecting intra- and cross-slice control functions

3.2.2 Core network

The key technological components of the CN of 5G systems (5GC) are architecture modularisation, CP and UP separation and Service-Based Interface (SBI). These are reflected in the SBA (crystallised in 3GPP Release 15 specifications [3GPP TS23.501]) where the CP NFs are interconnected via the SBI. Each NF, if authorised, can access the services provided by other NFs via the exposed SBI. As a set of examples, the Network Exposure Function (NEF) is a NF included in the 5GC which allow each NF to expose its capability to other NFs; The Network Repository Function (NRF) is an NF included in the 5GC allowing each NF to discover which instance of another NF can be accessed to receive a required service. The AN CP is connected to the Access and Mobility Function (AMF) of 5GC in case of 3GPP Access, and is connected to the Interworking Function (N3IWF) in case of non-3GPP Access.

Compared to the traditional functional based network architecture design, SBA is expected to have the advantage of short role out time for new network features, extensibility, modularity, reusability and openness [NGMN18].

This reference architecture, as envisioned 5GC architecture for 5G-MoNArch, allows the definition and instantiation of flexible E2E networks, which can be customised by network operators' or vertical industries' requirements, in terms of performance, capabilities, isolation etc. In other words, 5GC reference architecture allows the support of network slices, i.e., independent logical networks, either sharing partly/entirely the infrastructure they are instantiated on, or isolated and deployed over separate infrastructures. 5G devices will be able to access 5GC and requiring services from a number of supported network slices. The Network Slice Selection Function (NSSF) is an emerging NF dedicated to select the proper NSI for the 5G devices. The reference architecture provides multiple options to customise network slices capabilities. For example, the Session Management Function (SMF) may allow the support of different UP protocol models, such as IPv4/IPV6, Ethernet, or unstructured data format. The Policy Control Function (PCF) may allow customising the policy framework on network slice basis. Finally, the Unified Data Management function (UDM) may enable different authorisation, authentication, and subscription management mechanisms upon network slice tenant needs. It should

[4] Meanwhile, xRAN Forum has merged with C-RAN Alliance to form the ORAN Alliance.

also be noted that, thanks to SBI, the reference architecture also provides third parties with the possibility to influence the network behaviour, extend and customise network slices capabilities via the inclusion in the system of proprietary non-standard Application Functions (AFs). Using the SBI, the AF is possible to access services provided by other NFs, as well as to expose theirs services to other NFs, e.g., via NEF.

Despite the foundations for 5GC have been successfully established, the general framework still appear not entirely mature and seems to be still susceptible to significant technical and conceptual enhancements. Some key examples of issues still offering a large number of design options and room for further improvements are:

- The instantiation and selection of NFs for different slices in the infrastructure;
- The specific functional customisation of NFs to address requirements of specific use cases;
- The functional interaction among different network slices.

The 5G-MoNArch core network architecture uses the 3GPP SBA based architecture and network functions currently defined in Rel. 15 as a baseline. The needed enhancement of the network functions e.g., AMF, PCF, NSSF, are studied to address several of the gaps listed in Table 2-1.

A separate distinguishing feature of 5GC, compared to previous generation networks, is network analytics capability embedded in the general framework, via the definition of the Network Data Analytics function (NWDAF). In short, as per 3GPP Release 15, NWDAF provides 5GC with the ability to collect and analyse *per slice aggregated data*, and to aid network optimisation via interaction with PCF. Albeit included in 3GPP release 15 specification, NWDAF description and capabilities are extremely rudimental. The exploitation of the full potentials of network analytics and Big Data technologies requires the clarification and investigation of a number of questions, including:

- What data should be collected by NWDAF and what feedback is expected from NWDAF;
- From which entities and how should the NWDAF collect the data;
- How NWDAF shall collect data on per PLMN and/or per slice and/or per user basis and/or per session basis;
- How NWDAF shall expose its services, and which NFs may benefit from them;
- How can NWDAF get the data from the NFs/NEs which are not connected to the SBI;
- The granularity of the optimisation to be enabled by NWDAF services, options being:
    - Per session basis;
    - Per user basis;
    - Per slice basis;
    - On Inter-slice basis.

5G-MoNArch is investigating the enhancement of the CP/UP procedure (e.g., slice alignment procedure between RAN and CN) and the architecture (e.g., interfaces and functionality extension of NWDAF, new functionality to support inter-slice coordination) to address the above issues and questions. The related innovation elements are described in Section 3.3.2 as InE#2 Inter-slice coordination and InE#3 Inter-slice context sharing and optimisation. The detailed solution and analysis of the innovation elements in the core network are included in Sections 4.2.1, 4.2.2, and 4.2.3, respectively.

One other aspect is the E2E slice view which needs the alignment of a network slice between the Network layer and M&O layer. The M&O layer looks at the network slice deployment in a longer time scale for one tenant/one group of services. The Network layer takes care of the individual user, connects them to the already deployed NSI by the M&O layer and controls the shorter time scale slice KPIs. Both layers need to work together to guarantee the Service Level Agreement (SLA).

In the real network deployment, not all network slices are supported over the complete PLMN network, especially when considering the E2E perspective. 3GPP defines the network slice availability as following:

"A Network Slice may be available in the whole PLMN or in one or more Tracking Areas of the PLMN. The availability of a Network Slice refers to the support of the NSSAI in the involved NFs. In addition, policies in the NSSF may further restrict from using certain Network Slices in a particular TA, e.g. depending on the HPLMN of the UE."

More specifically, the E2E slice availability is decided by the RAN slice capabilities, CN slice capabilities, the NSI management, network configuration, and also network policies. This brings up the following issues:

- Whether the current network layer slice selection mechanism in 3GPP is sufficient to address different deployment scenarios.
- How the Network layer interacts with management layer on individual network slices.
- How to map the customer services to the actual deployed network slice in the operator network.

Since end to end aspects of slice covers from service layer, management and orchestration and network layer, the enhancements are discussed in different sections e.g., context aware slice selection is covered in Section 4.2.3, CP/M&O layer per slice interaction is covered in Section 4.2.1, and service to slice mapping is captured in Section 4.2.2.

3.2.3 Management and orchestration

5G-MoNArch M&O system follow 3GPP guidelines using virtualisation and slicing to fill the identified gaps (cf. Table 2-1). VNF are aggregated into network slices and foresees automation and orchestration functions also considering Self Organising Network (SON) algorithms. E2E management and orchestration is performed at different levels in a coordinated manner. These levels are: service, network configuration, virtualisation, and transport. 5G-MoNArch M&O layer takes care of this job, interworking with Control layer and Network layer, to deploy the required NFs and to configure the appropriate interconnections according to the service and network requirements.

The 5G-MoNArch M&O layer complies with 3GPP specifications that foresee a management system that coordinates network and slice management and orchestration. Current 5G-MoNArch architecture explicitly takes into account the interaction with the 3GPP Management Entities dedicated to Network management and configuration (3GPP Network Management in Figure 3-4). For slice management the NSMF will implement 3GPP standards for slice management and orchestration.

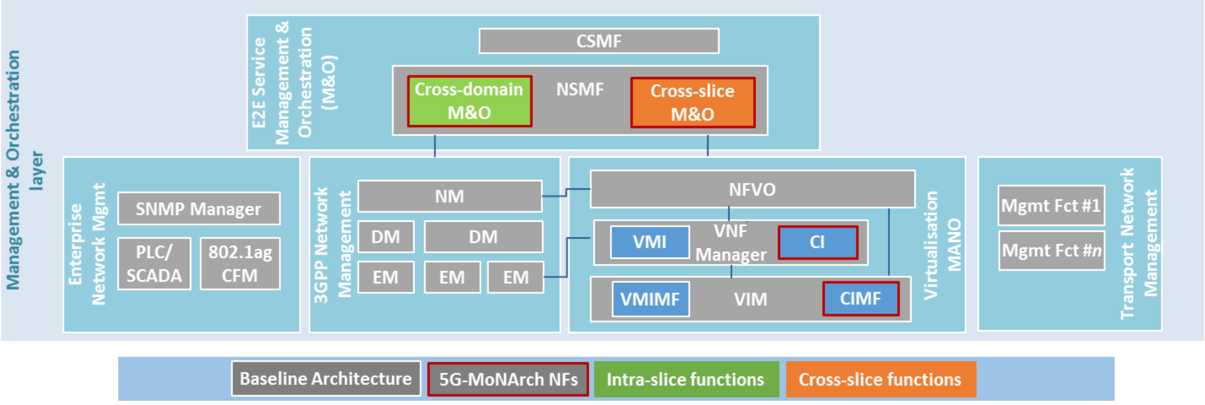


Figure 3-4: 5G-MoNArch Management & Orchestration layer

In the E2E Service Management & Orchestration sublayer, service requirements are translated into network requirements by the CSMF. The obtained network requirements are forwarded to the NSMF which is composed by sub-entities or micro-services, that address the management and orchestration of each slice (Cross-domain M&O) and the management according to the possible interaction among slices in terms of resources and features sharing (Cross-slice M&O).

The Management Function defined into 5G-MoNArch E2E Service Management & Orchestration sub-layer are needed to support E2E cross-slice optimisation allowing simultaneous operation of multiple network slices. The Management layer, with the interaction of NSMF and NFVO, fits the specific requirements of each covered service supporting Orchestration-driven elasticity. Analysing performance and assurance data the management layer orchestrates action at slice level and cross-slice level to support telco cloud resilience

The two service-level sub-entities then interact with Domain-Specific Application Management (e.g 3GPP Network Management and ETSI NFV MANO). To fill several of the identified gaps (cf. Table 2-1), the M&O layer has to:

(1) Identify the requested VNFs/PNFs that support the service requirements.
(2) Identify the forwarding graph that links the VNFs/PNFs.
(3) Identify the configuration and policies (e.g. for elasticity) to fulfil the required service and SLAs.
(4) Identify the most appropriate Network Slice Template (NST) (for network management) and Network Service Descriptor (NSD) (for VNF deployment).
(5) Identify KPIs for Performance Management (PM) to meet the requested SLAs.
(6) Orchestrate the deployment and activation of the NSI.
(7) Activate PM and Fault Management (FM).
(8) Run PM and FM comparing the data with the defined KPI for the slice.
(9) Activate orchestration to fulfil service changes requests or to meet the SLAs using FM and PM.
(10) Expose PM and FM data to the customer (if requested).
(11) Orchestration performs the LCM of VNFs and performs the requested action on the transport part.

The deployment and management of a network slice is performed to fulfil the request of a customer asking for a Communication Service, 5G-MoNArch M&O layer is coherent with some aspect specified by 3GPP in [3GPP TS 28.530]. In the following are reposted the 3GPP principles that 5G-MoNArch is following from [3GPP TS 28.530].

The 5G-MoNArch M&O layer takes care of the LCM of a NSI working with all the other Domain Specific orchestrators. When providing a communication service, 5G-MoNArch M&O layer has to use non-3GPP parts (e.g. Transport Network) in addition to the 3GPP managed network components. Therefore, in order to ensure the performance of a communication service according to the business requirements of the customer.

5G-MoNArch M&O layer has to coordinate with the management entities of the non-3GPP parts (e.g., ETSI MANO system) when preparing a NSI for this service. This coordination may include obtaining capabilities of the non-3GPP parts and providing the slice specific requirements and other resource requirements of the non-3GPP parts.

5G-MoNArch M&O layer has to identify the requirements for RAN, CN and non-3GPP parts of a slice by breaking down the customer requirements into different parts and sending them to the corresponding management systems, respectively. To support this capability, and according to 3GPP actors and roles, 5G-MoNArch M&O layer introduce the Communication Service Management Function (CSMF).

The coordination may also include related management data exchange between those management systems and 3GPP management system. As defined by 3GPP, 5G-MoNArch M&O layer manages NSIs using three new functions:

- Communication Service Management Function (CSMF): this function takes care of the management of the communication service and translates the requirements related to the communication service to network slice related requirements.
- Network Slice Management Function (NSMF): responsible for management and orchestration of NSI. Derives network slice subnet related requirements from network slice related requirements. Communicates with NSSMF and CSMF.
- Network Slice Subnet Management Function (NSSMF): responsible for management and orchestration of NSSI. Communicates with the NSMF. NSMF, according to 5G-MoNArch, could be useful to take care of specific management domains or to aggregate NF from a specific vendor.

5G-MoNArch approach on slice offering is coherent with the 3GPP definition of Network Slice as a Service (NSaaS) [3GPP TS 28.530]. NSaaS can be offered by a Communication Service Provider (CSP) to its Communication Service Customer (CSC) in the form of a communication service. As defined by

3GPP, 5G-MoNArch M&O comprises the option of exposing some management interface. For 5G-MoNArch this feature is important to let the customer to operate the slice applying custom LCM and optimisations.

5G-MoNArch approach on slice offering is also coherent with the 3GPP definition of “Network Slices as NOP internals” model. Network slices are not part of the CSP service offering and hence are not visible to CSCs. However, the NOP, to provide support to communication services, may decide to deploy network slices, e.g. for internal network optimisation purposes. 5G-MoNArch Deliverable D2.1 [5GM-D2.1] identified some gaps that require an improved management and orchestration (M&O) system in the 5G-MoNArch architecture. The compliancy and enhancement of what defined in 3GPP, for the management of 5G networks, is the chosen path to fill those gaps (cf. Table 2-1) related to management and orchestration.

5G-MoNArch ETSI MANO evolution

Network slicing, multi-tenancy and flexibility of supporting different services are the key requirements that novel 5G systems have to support. 5G-MoNArch architecture has to fulfil these requirements and provide mechanisms and framework that manage NFs that are shared between network slices or belonging to different management domains.

Mapping 3GPP network slicing concepts to ETSI NFV framework

5G-MoNArch architecture embeds ETSI NFV MANO orchestration framework besides 3GPP compliant modules. This includes:

- VIM: Responsible for control and management of NFV Infrastructure (NFVI) compute, storage and network resources.
- VNFM: Responsible for LCM of VNF instances.
- NFVO: Responsible for the orchestration of NFVI resources and LCM of NSs.

This section briefly describes the ETSI MANO concepts that are used and enhanced in 5G-MoNArch and how it can coexist along 3GPP compliant M&O modules [3GPP TR 28.801] to support E2E network slicing.

ETSI NFV Architectural Framework [ETSI NFV13] introduces a concept of NS (network service) as a set of NFs connected according to one or more forwarding graphs [ETSI NFV16]; it additionally adds the concept of nested NSs. The NFVO would use the NSD as a template with information used to manage the lifecycle of an NS. VNF Descriptor (VNFD), on the other hand, is a template describing the requirements of VNF. It is used by the VNFM for VNF instantiation and by NFVO to orchestrate the virtualised resources.

[3GPP TR 28.801] describes a model where a network slice contains one or more network slice subnets. Each network slice subnet can be composed of one or more NFs. Therefore, a NS can be considered as a network slice subnet in case it contains at least one VNF. Similarly, the network slice blueprint described by [ETSI NFV13] could be associated with nested NFV NSDs. Additionally, [3GPP TR 28.801] describes three management functions dealing with network slicing management as described in Section 3.3.3, i.e. CSMF, NSMF and NSSMF. In reference to the 5G-MoNArch overall architecture, Cross-domain M&O could be mapped to NSMF while Cross-slice M&O could be either NSMF or NSSMF as described in Section 3.1

Figure 3-5 shows how these functions could match the NFV MANO model using the Os-Ma-Nfvo reference point as a way of interaction between 3GPP slicing related management functions and NFV-MANO. The role of the NSMF and/or NSSMF would be to determine the type of NS, VNF and PNF that can fulfil the requirements for a NSI or NSSI.

As described in [5GM-D2.1], there are several gaps that need to be addressed in order to properly interface with NFV-MANO while slice-related management functions are still under definition in 3GPP SA5 regarding the interaction with NFV MANO.

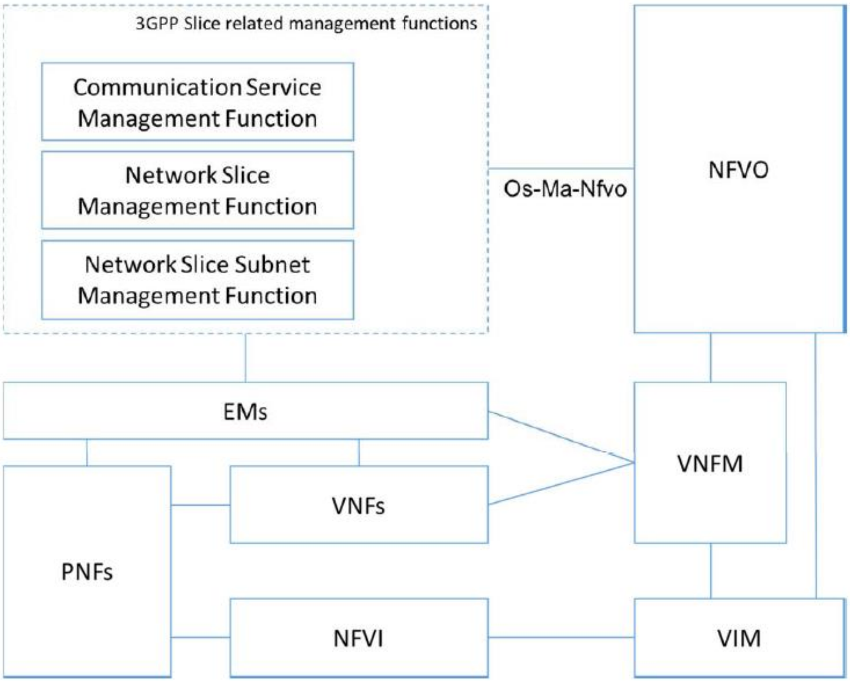

3GPP Slice related management functions
Communication Service Management Function
Network Slice Management Function
Network Slice Subnet Management Function
Os-Ma-Nfvo
NFVO
EMs
VNFM
VNFs
PNFs
NFVI
VIM

Figure 3-5: Network slice management in an NFV framework [ETSI NFV17]

Role of ETSI NFV MANO in NSI management

According to [3GPP TR 28.801] the lifecycle of a network slice is comprised of the four following phases. This will be further discussed in Section 4.3:

- Preparation;
- Instantiation, Configuration and Activation;
- Run-time;
- Decommissioning.

From an NFV perspective the role of NFVO in the preparation phase is to ensure the resource requirements for a NST. NFVO contains the NSDs that have been previously on-boarded and that can be used to create new NSTs that are created and verified in the preparation phase. The NSDs can be updated and created from the beginning if required, if a new NST is necessary.

During the instantiation phase the NFV MANO functions are only involved in the network slice configuration if parameters related to virtualisation are required for any VNF instance and can be called in the network slice activation step. During the activation the NSMF or the NSSMF functions can activate VNFs by means of Update NS sent towards NFVO. This operation could include adding, removing or modifying VNF instances in the NS instance.

During the run-time phase NFV MANO is responsible for PM, FM that could affect a VNF's functioning, and lifecycle of virtualised resources. This could include for example scaling of NS.

Use cases and impact on NFV architecture

[5GM-D2.1] described some of the M&O use cases from 3GPP perspective. [ETSI NFV17] additionally takes into account the NFV MANO architectural framework [ETSI NFV13] and evaluates the impact of network slicing, multi-tenant, and multi-domain scenarios on NFV architectural framework. Some of the evaluated use cases are:

- Single operator domain network slice.
- NSI creation.
- NSSI creation.
- NSI creation, configuration and activation with VNFs.
- NSI across multiple operators.

In case of single operator domain network slices, [ETSI NFV17] suggests that additional functionality may be needed to support configuring policies, access control, monitoring/SLA rules, and usage/charging consolidation rules. The specification proposes to add an external entity called Network Slice Manager that would be responsible of:

- Determining the requirements for NSIs from the description of applications and services by mapping appropriate features into NSD and VNFD.
- Management of network slice catalogue, network slice and/or sub-network blueprint, and lifecycle of network slices.

ETSI NFV-MANO system supports and manages the resources of the VNFs, as the NSI can be composed of VNFs and PNF. In NSI creation use case the MANO is responsible for management of virtualised resources while 3GPP application takes care of network applications. The NSD contains requirements for QoS and resources of a network slice. During the instantiation the deployment flavour is selected during the instantiation. Another use case is derived from [3GPP TR 28.801] and consists of NSSI creation that is done by NSSMF. This function specifies which NFs and resources are needed. The NFs can be either VNFs or PNFs. In this case, NFV MANO supports the management of the virtualised resources. If VNFs are included in NSSI, NSSMF triggers NFV-MANO to instantiate or configure the VNFs that are needed.

NFV in multi-tenant and multi-domain environment

5G-MoNArch M&O layer has to be extended in order to support multi-tenant and flexible E2E network slicing. The network slices have to by isolated between each other and capable to run on shared infrastructure without affecting each other.

Tenants manage the slices in their operative domains by means of NFVO. Each tenant has its own NFVO that is responsible for resource scheduling in the tenant domain. The resources can belong to different administrative domains in the infrastructure, so NFVO has to be able to orchestrate resources across different administrative domains. This is the role of Cross-domain M&O function in 5G-MoNArch. Cross-domain M&O function is in charge of managing and coordinating NSs between different management domains. On the other hand, Cross-slice M&O is responsible for common functions between different slices.

3.3 *Novel components and interfaces of the 5G-MoNArch architecture*

This section introduces the novel network functions and interfaces that 5G-MoNArch has introduced beyond state-of-the-art mobile network architectures.

3.3.1 Radio access network components

The 5G-MoNArch RAN architecture takes the baseline architecture [5GM-D2.1], which covers 5GPPP Phase 1 consensus and the 3GPP status from the publication time, and extends it with the latest 3GPP Release specification on NG-RAN [3GPP TS 38.300] [3GPP TS 38.401], e.g., addition of Service Data Adaptation Protocol (SDAP) layer and F1 interface with Central Unit (CU) - Distributed Unit (DU) split, and particularly with the 5G-MoNArch functional models emerging from the 5G-MoNArch innovations as outlined in Chapter 4 and Chapter 5.

The 5G-MoNArch extensions not only include the new functional enhancements on the CU and DU but also the F1 interface implications (see Chapter 4) as well as Controller Layer described herein for RAN. It is worth noting that, in 5G-MoNArch, the Controller Layer is envisioned only for RAN. The reason is that the framework of SBA (see Section 3.2.2 and Section 3.3.2) provides the needed flexibility to introduce application functions (AFs), while such an extension is not available for RAN. A high-level illustration of the 5G-MoNArch RAN architecture is given in Figure 3-6. Therein, the Controller layer is identified by XSC and ISC along with the corresponding applications (APPs) running on the northbound interface (NBI). The control commands and interactions with the gNBs take place via the southbound interface (SoBI).

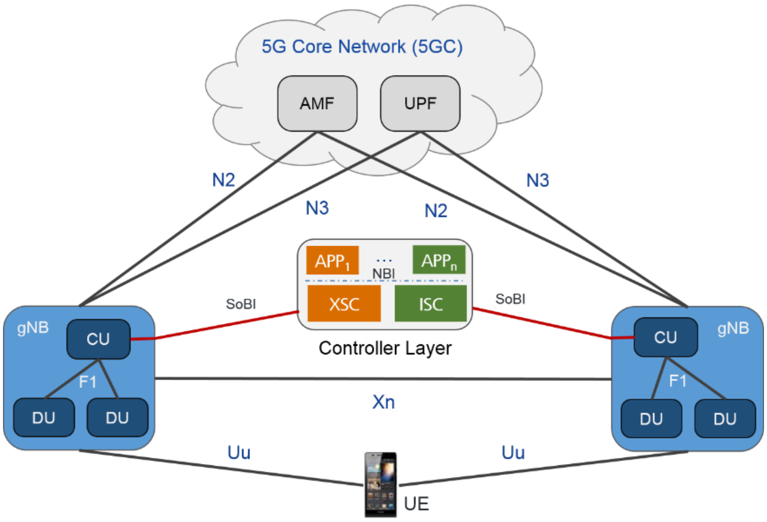


Figure 3-6: High-level 5G-MoNArch RAN architecture

Based on the high-level RAN architecture, a detailed illustration of the 5G-MoNArch RAN protocol architecture is given in Figure 3-7. The protocol architecture includes both the control plane (CP) and user plane (UP) functions at the Controller layer, CU, DUs and UEs. The extensions introduced by 5G-MoNArch innovations are highlighted and the associated descriptions are provided in the following. The interface implications are captured by Message Sequence Charts (MSCs) which are provided in Chapter 4 in accordance with the 5G-MoNArch innovations. A so-called RAN Controller Agent (RCA) is introduced in the CU to interface distributed and centralised VNFs to the logically centralised controller. The RCA is responsible for collecting monitoring information related to both UEs and RAN, such as Channel Quality Indicator (CQI), Power Level, Path Loss, Radio Link Quality, Radio Resource Usage, Modulation and Coding Scheme (MCS), Radio Link Control (RLC) buffer state information, etc. and sending them to controllers in the form of NBI applications (Slow Inter-slice RRM, Slice Aware RAT Selection, Elastic Resource Control, etc.) for further optimisation. RCA is also responsible for routing re-configuration information from controller to the respecting VNFs in the CU and DU of RAN.

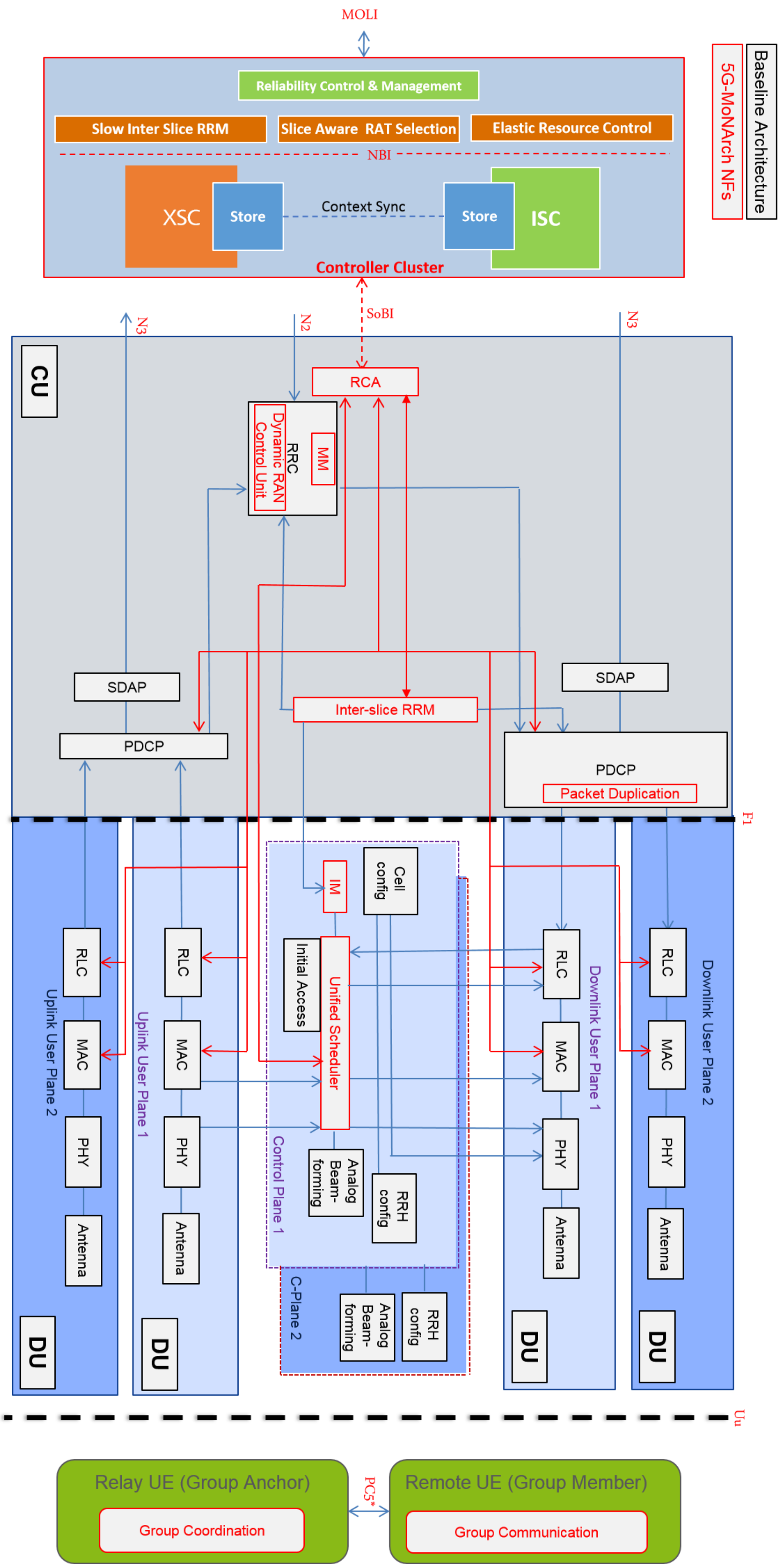


Figure 3-7: 5G-MoNArch RAN protocol architecture

3.3.1.1 Slice-aware RRM and RRC

The overall 5G-MoNArch architecture supports the isolation of NSIs, including resource isolation, OAM isolation, and security isolation. Resource isolation enables specialised customisation and avoids one slice affecting another slice. E.g. RAN needs to provide and enforce differentiation, and maintain isolation between slices where resources are constrained including RF resource, backhaul transport resource and computing resource. Each slice may be assigned with either shared or dedicated radio resource depending on RRM implementation and SLA. The amount of allocated resources can be scaled up or down for higher utilisation efficiency depending on the traffic load of each NSI. This section details Inter-Slice RRM approach followed in 5G-MoNArch to efficiently share and manage Radio resources between slices.

Inter-slice RRM

The network slice-awareness in 5G RAN will strongly affect the RAN design and particularly the CP design, where multiple slices, with different optimisation targets, will require tailored access functions and functional placements to meet their target KPIs. To this end, RRM is one of the key aspects which will be affected. Here to mention that the operation and placement of RRM will be strongly affected by the aforementioned slice realisation variants which correspond to the slice isolation at RAN level. In Slice-aware RAN, in order to offer the flexibility that multiple slices can meet diverse KPIs (e.g., data rate, latency, and reliability), some RRM functionalities will be required to be tailored for different slice requirements.

On the other hand, the RAN deployment may provide some limitations on the efficiency of RRM due to the wireless channel, traffic load, and resource availability constraints, which may affect the overall performance (assuming numerous slices re-using the same RAN deployment). In particular, in dense urban heterogeneous scenarios, the signalling and complexity of RRM will be higher due to more signalling exchanges needed for passing RRM information to different entities. Moreover, the distribution of RRM functions in different radio nodes will provide new dependencies between RRM functions, which should be taken care of in order to optimise performance. In addition, in case of HetNet RAN deployments, non-ideal backhaul between access nodes (macro and small cells) will put some limitations on the RRM decisions and placement options to meet certain KPIs.

In SotA literature, the distribution of RRM in different nodes is discussed as a way to meet capacity and coverage demands in dense RANs, where interference management (IM) is critical. There can be different levels of centralisation of RRM as proposed in literature, namely Centralised, Semi-centralised and Distributed. For centralised RRM, some solutions have been proposed that require controller for clusters of HetNets (Cloud-based Resource pooling and management (C-RAN)) [ODK16]. There, resource pooling and centralised management of resources can provide high gain in terms of capacity. Nevertheless, this can be realised using ideal backhaul / fronthaul and can be seen as challenging task for dynamic resource allocation in fast changing environments. Furthermore, other RRM splits are also discussed in literature, by grouping RRM to real-time and non-real time and distributing them in different nodes. In [iJOIN D3.3], a flexible C-RAN was proposed where RRM was centralised and in some scenarios with non-ideal backhaul, real-time RRM could be de-centralised in small cells.

In slice-aware RAN, the CP can be categorised in the following groups of functionalities based on the RAN Configuration Modes (RCM) framework[5]. RAN Slice or RAN configuration mode (RCM) has been proposed in literature; and is a composition of RAN network functions, specific function settings and associated resources (HW /SW, and network resources). These RCMs will multiplex the traffic to/from core network slices to ensure optimisation across slices. To ensure meeting the end-to-end slice requirements, assuming limited RCMs, which may be mapped to numerous slices, a CP functionality framework is introduced, which is required to allow for slice-tailored optimisation in RAN. In particular:

- **Intra-RCM RRM:** For slice specific resource management and isolation among slices, utilising the same RAN is an open topic which is currently investigated. In literature [YT16], the

[5] Further details on RCMs have been captured in 5G-MoNArch Deliverable 2.1 [5GM-D2.1].

conventional management of dedicated resources can be seen as intra-slice RRM, which can be tailored and optimised based on slice specific KPIs.

- **Inter-RCM RRM/RRC**: On top of Intra-RCM RRM, Inter-RCM RRM/RRC (which includes also Inter-slice RRM and slice-aware Topology RRM for wireless self-backhauling) can be defined as the set of RRM policies that allow for sharing/isolation of radio resources among slices or slice types to optimise the resource efficiency and utilisation, by flexibly orthogonalising them in coarse time scales. Inter-RCM RRM can be defined as an “umbrella” functional block which dictates the RAN sharing and level of isolation / prioritisation among network slices or slice types. In this direction, an Inter-RCM RRM mechanism is proposed in [PP17], where slice-aware RAN clustering, scheduler dimensioning and adaptive placement of Intra-slice RRM functions is discussed in order to optimise performance in a dense heterogeneous RAN. Given the requirement of new access functions which can be tailored for different network slices, the distribution of RRM functionalities in different nodes will be a key RAN design driver which can allow for multi-objective optimisation in a multi-layer dense RAN. The adaptive allocation of such functions is also envisioned as key feature to cope with the dynamic changes in traffic load, slice requirements and the availability of backhaul/access resources. To this end, one further Inter-slice/RCM RRM functionality is proposed in [SSC+17] which performs traffic forecasting of different slices and allocates resources to slices in a pro-active manner.
- **Topology RRM**: This can be seen as another category of Inter-RCM RRM, mainly for D-RAN, where the resource allocation of wireless self-backhauling is essential to allow for joint backhaul/access optimisation [LPL+17]. Thus, Topology RRM can be tailored for different slices [PSW+17] in order to allocate backhaul resources among RCMs in a slice-tailored manner in order to avoid backhaul bottlenecks.
- **Unified scheduler**: An overarching medium access control (MAC) Scheduler, where different slice types share the same resources and dynamic resource allocation and slice multiplexing is required on top of RCM-specific MAC.

Based on this categorisation, an interesting aspect which may define the CP functionality requirements and the interface / signalling requirements between the CP functions is the functional split which is dependent on the CU - DU split options. It is to mention that CU and DU split commonly refers to the split of the 5G base station (gNB, ng-eNB) protocol stack; however, it may also refer to functional splits involving cloud entities (e.g. central cloud - edge cloud split) when part of the RAN is virtualised.

Currently, in 3GPP, one split has been specified (from a set of introduced split options), namely Higher Layer Split (HLS) which is the splitting below Packet Data Convergence Protocol (PDCP)-level. For the HLS split Figure 3-8 presents the possible placement of Inter-RCM and Intra-RCM RRM and RRC functionalities. Depending on the placement the interface requirements might be different due to the time/resource granularity of the CP functionalities and their possible interconnections. The interface requirements and the required interactions between the slice-aware CP functionalities will be further analysed in future deliverables.

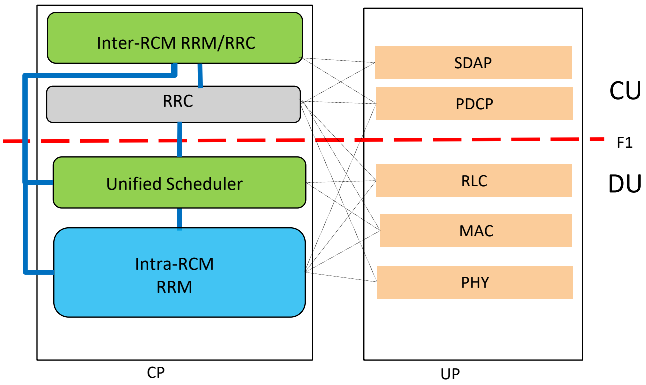


Figure 3-8: Exemplary slice-aware split for CU-DU (functional deployment and interactions)

Slow inter-slice RRM based on the Controller layer

The advantages of SDN such as centralised network abstraction and re-programmability can be used as an alternate solution to implement slice aware RRM. In such approach SDN controller modules along with centralised RRM function (as NBI application) will be deployed as a VNF on demand managing radio resources between slices. Slices in turn consist of chained VNFs to implement the E2E network and can be deployed in the same or physically separated cloud infrastructure. The major objective of using SDN framework for inter slice RRM is to achieve cross layer optimisation by using various network parameters such as radio resource status, current data-rate, buffer status, network latency, priority of slices, etc.

Though the radio resources usage can be better optimised by using centralised and joint optimisation techniques via SDN framework, there is an inherent latency added due to back and forth communication between RAN functions and the controller. The centralisation of RRM i.e., to have a radio resource allocation decision from the controller and send it to the RAN, every scheduling period (~1ms) is almost impossible due to various communication latencies (e.g., between controller and NB application, NB application and controller, controller and Scheduler, etc.). So, in order to better realise this centralised approach, 5G-MoNArch introduced the two-level approach based Inter-slice RRM, i.e., slow Inter-slice RRM from the controller (>1ms period) and native Inter-slice RRM from the CU (~1ms period).

Slice-aware functional operation

As introduced in D2.1 [5GM-D2.1], slice-aware functional operation can comprise multi-slice resource management on shared infrastructure resources as well as hard/physical network resources, namely, wireless access nodes. That is, the slice support may not only include the conventional radio resources like time and frequency resources, but it can also include the adaptation of the network topology considering the dynamic small cells (DSCs) available in a certain region. A DSC can comprise access nodes that are not bound to a fixed topology. For example, relays mounted on vehicles, aka vehicular nomadic nodes (VNNs), can be considered as DSCs, where VNNs can be activated and deactivated based on the traffic demand. Further, VNNs may change locations as in case of car sharing or taxi fleet and may be temporarily available, e.g., during parking time [5GM-D2.1] [BRZ+15]. Slice-aware functional operation can thus take into account network topology and slice requirements to determine the functional operation (see Section 4.3.2).

The functional operation can be determined by a dynamic RAN control unit (see Figure 3-7 and Figure 3-9). Depending on the functional operations of the DSCs and how frequently the functional operations are configured by the RAN control unit, the RAN control unit may reside at different NEs, as exemplified in Figure 3-9. Two example realisations are provided in the following, while more details are given in Section 4.3.2.

- In case of L1 functional operation (e.g., physical layer, PHY), L2 functional operation (e.g., {PHY, MAC}, or {PHY, MAC, RLC}, or {PHY, MAC, RLC, PDCP}), and amplify-and-forward modes, the DSC cell is part of the surrounding macro cell and the UE may be connected both to the DSC and macro cell. Then the configuration of the DSCs can be dynamically or semi-dynamically changed by a RAN control unit connected to and possibly residing at the RRC of the macro cell base station (BS)[6], as depicted in Figure 3-9 (a). This would necessitate additional signalling on the self-backhaul (e.g., Un*) interface between macro BS and DSC. This signalling can configure the reception and transmission modes of the DSC based on the network slice customer served by the DSC. The dynamicity of such configuration updates depends on the backhaul link quality and slice requirements. In particular for DSCs like vehicular nomadic nodes (VNNs) [5GM-D2.1] [BRZ+15], the backhaul link quality will depend on the position and, thus, at each location change, a new configuration for the functional operation can be needed. The frequency of such updates can range from minutes to hours.

[6] The set-up of the BS may determine the interface that may be impacted. In case of monolithic BS, the impacted interface would the wireless backhaul interface, while in case of disaggregated BS (i.e., CU-DU split), the impacted interface would be F1 [3GPP TS38.470].

Accordingly, having the RAN control unit at the macro cell BS enables more dynamic functional operation updates in case of dynamic radio topologies.

- In case of L3 functional operation (e.g., {PHY, MAC, RLC, PDCP, SDAP and RRC}), the DSC may have its own cell, e.g., with a physical cell ID (PCI), and the configuration of the functional operation may take place at a slow time scale. In this case, as shown in Figure 3-9 (b), in one implementation, the RAN control unit may have a Cross-slice M&O functionality that resides at the NSMF. In another implementation, RAN control unit may reside at the RAN, e.g., at RRC, and may communicate with the Cross-slice M&O functionality for configuring L3 DSC functional operation, where part of the configuration parameters (such as transmit power) may be obtained from this Cross-slice M&O functionality.

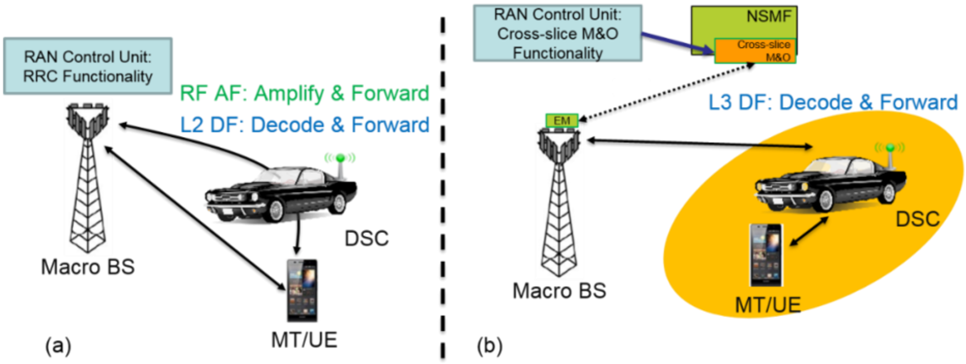


Figure 3-9: Example Illustration of the slice-aware functional operation with three different modes (RF-L1, L2, and L3), which are determined and configured by a RAN control unit. Note: Amplify-and-Forward and Decode-and-Forward are marked as AF and DF, respectively

Slice-aware RAT selection

As already mentioned, the efficient control of the available radio resources and technologies to satisfy the heterogeneous requirements of different slices is currently an important 5G research challenge. In the 5G RAN architecture, the 5G-MoNArch concept foresees that in the central unit a mobility management (MM) module is in charge to optimise the access of the users to a specific RAT, provided by a 5G distributed unit, according to the slice to which the user is associated. In contrast to classical association paradigms, this approach will enable to consider slice specific KPIs, like the reliability of the access technology.

D2D group mobility

Device to Device (D2D) communications facilitates an enabling innovation for further support of service continuity and smooth mobility (beyond the network edge). This can be realised via offloading some signalling at the RAN level (from direct signalling to the gNB to indirect signalling between anchor and remote UEs) as shown in Figure 3-7. As will be detailed in Section 4.1.3, a novel group mobility paradigm is established with floating mobility anchor as a Group Coordinator, not necessarily “pinned” to single Relay UEs. The above solution can be confined to RAN domain where the mobility management is handled by gNB. However, gNB needs to be aware of anchor assignment and associated remote UEs (i.e., Group Members) per group as will be outlined later.

3.3.1.2 Elastic resource management

Current trends on big data and its pervasiveness open an opportunity to exploit data analytics to improve the operation of different aspects of the mobile networks by means of data analytics. Although also previous generation of mobile networks incorporated monitoring data for basic network management, the extent of the new available data and the heterogeneity of the management decisions that shall be taken (e.g., radio and cloud resource assignment, per slice) bring this aspect to another level. Moreover, the increasing availability of machine learning / artificial intelligence algorithms make the data analytics based network management even more appealing. One of the innovations of 5G-MoNArch is to incorporate such data analytics into the architecture to improve the operation of certain functions, such as radio resource optimisation and slice selection. Such data analytics are fed with the data that can be gathered from the network as a whole (i.e., VNFs and PNFs composing a certain network slice and the attached UEs). Generally speaking, the more detailed the data is, the more accurate are the features that may be extracted from this data.

Indeed, data gathered from the RAN NFs is probably the most important kind of data that has to be gathered from a resource assignment perspective. The selected Modulation and Coding schemes (MCS) highly depend on the Signal-to-Interference-and-Noise Ratio (SINR) margin of a certain user and have a big impact on the computational effort induced by the decoding / encoding functions of the RAN.

Data gathering in the RAN could be achieved by means of a monitoring application running at the XSC that e.g. gets from the gNB DU information about the used Physical Resource Blocks (PRBs) by each tenant or the SINR of each user. Other probes can be placed directly on tenants controlled VNFs (cVNFs) (e.g. AMF, to keep track of registered users) or directly in the Orchestration.

Resource assignment to slices for radio purposes entails taking optimal decision on both the spectrum assignment to slices, but also on the computational capabilities needed by each slice to encode / decode data of user equipment (UE) using that spectrum. Therefore, by gathering such data, a Big Data analytics component such as the one defined by ETSI Experiential Networked Intelligence [ETSI ENI] could provide algorithms for the following enablers defined by 5G-MoNArch (see more details in [5GM-D4.1]):

- Characterisation of network slices load, in terms of used bandwidth, both in the spatial and in the temporal component. This can be leveraged for the correct dimensioning of the data centres, the slice admission control algorithms and intra-slice orchestration algorithms.
- Composability of Network Slices: in order to exploit multiplexing gains of elastic resources assignment, assessing the degree of complementarity on both the spatial and temporal dimensions will be leveraged by proactive cross-orchestration algorithms. That is, different network slices may provide high gains in statistical multiplexing, allowing thus for a higher efficiency in the resource assignment.

Possible examples of how this data can be leveraged for this purpose are available in [5GM-D4.1]. In there, the complementarity of mobile network services is investigated, showing the level of complementarity on both temporal and spatial dimensions.

While predominantly the data coming from the (core and access) VNFs has been addressed, UEs can have more prominent role for data preparation for the network based on past profile of intra-slice vs. cross-slice information they have gathered. As outlined earlier, network analytics can play a focal role in load balancing and radio resource optimisation at intra-slice and cross-slice levels. In order to establish UE access to analytics information, new signalling procedures to be devised between some cross-slice core associated network NFs related to mobility management and network slice selection and the RAN that can be communicated (e.g. via RRC messages at connection establishment and / or mobility procedures).

3.3.1.3 Reliability control and management

In order to achieve RAN reliability needed for URLLC services, 5G-MoNArch extends the architecture by a reliability control application in the control layer and a reliability sub-plane in the network layer, as will be further detailed in Section 5.2.1. RAN reliability can be improved by either data duplication or network coding functions. In order to support the data duplication reliability function, the introduction of Packet Data Convergence Protocol (PDCP) acknowledgments is envisioned. The PDCP acknowledgments operation is a new approach that was not included in LTE standards. In LTE standards, the packet acknowledgment feedback (ACK) sent from the receiver to the transmitter in order to indicate whether the transmission was correctly received is carried out in two layers: At the medium access control (MAC) layer by means of hybrid automatic repeat request (HARQ), and at the radio link control (RLC) layer by means of outer ARQ. Given that the RLC layers of the two links involved in data duplication procedure do not process the exact same packet sequence, in the data duplication case feedback should be sent with the PDCP packet numbering. As a result, duplicate packets can be coordinated via specially design mechanisms at the PDCP layer, ensuring thus that lost packets are recovered within a limited time interval.

3.3.2 Core network components

This section focuses on the 5G-MoNArch enhancements for the core network functions in the network layer (as shown in Figure 3-10).

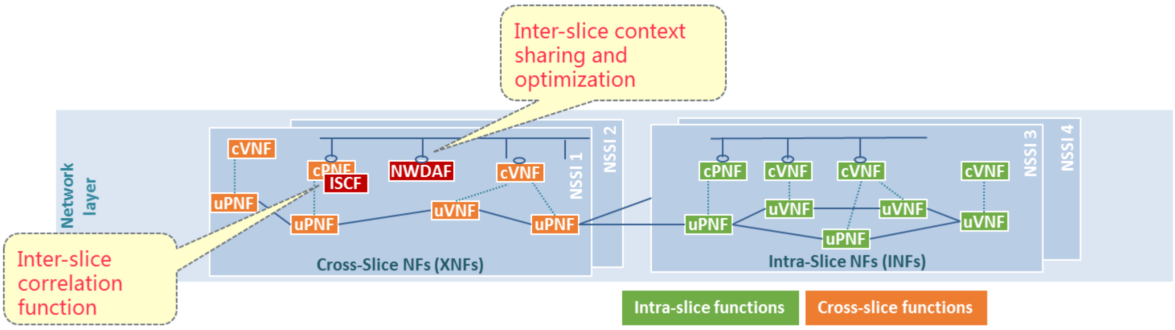


Figure 3-10: Functional enhancement in the Network layer

As outlined in Section 3.2.2, technical specification [TS23.501] of the 3GPP – Working Group SA2 (as standardisation body dealing with the 5G System Architecture) defines the service –based Network Functions (NF) and interfaces as illustrated in Figure 3-11. Here, also the NFs have been highlighted where enhancements to the Core Network beyond current developments in 3GPP (based on 5G-MoNArch studies) are envisioned, namely Inter Slice Correlation Function (ISCF), and possible enhancements at PCF, NSSF, and NWDAF.

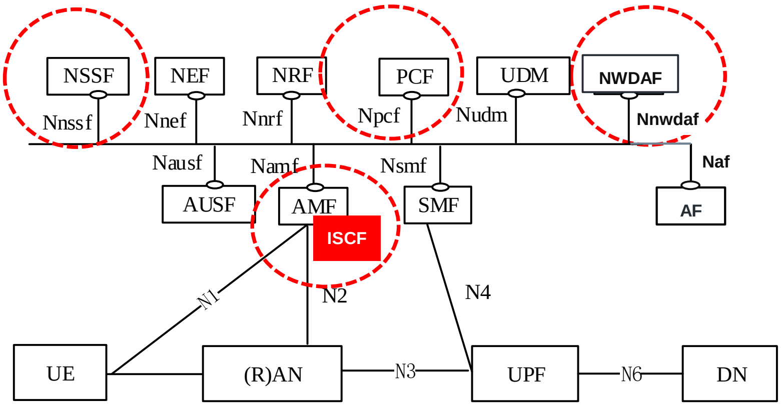


Figure 3-11: 3GPP 5G Architecture and functional enhancements in the core network

To fulfil targets on inter-slice context aware optimisation, the following enhancements are envisioned:

- Enhancement of NWDAF to collect and provide per slice/cross slice feedback information to the network functions.
- Optimisation for slicing and M&O layer based on context awareness:
  - Enable the Control Plane (CP) as well as the M&O layer to close the decision-making loop between the CP and M&O layer entities using context awareness in order to optimise the Mobile Core Networks (CN) operation.
  - Enhancement of NWDAF to collect information from M&O layer and maybe also provide feedback to M&O layer per slice/cross slice.
  - Enhancement of NWDAF, NFs, and M&O layer to coordinate the execution of changes in the 5G system based on the feedback provided by NWDAF in case of the CP / M&O layer joint optimisation cases.

Enhancement of NWDAF and/or NSSF to collect/ process terminal-driven analytics in order to improve slice selection and control.

A key network function here is the NWDAF. 5G-MoNArch envisions that this NF should be capable of collecting the data from the control layer (include the 5GC NFs, AFs) via SBI. It should also be able to collect information from and to provide analytics data to the management layer, RAN and UE where each layer may have its own implementation of a data analytics engine, which should be able to interact with NWDAF at 5GC to support end to end per slice service assurance.

Furthermore, on Inter-slice coordination, the CP CN architecture solution needs the following enhancements:

(1) Enhancement of network function to provide per service traffic flow binding.
(2) Enhancement of network functions to distribute the service traffic flow binding
(3) Enhancement of PCF to treat per service correlated QoS profile
(4) Enhancement of network performance exposure towards verticals
(5) Enhancement of network functions to perform cross slice optimisation.

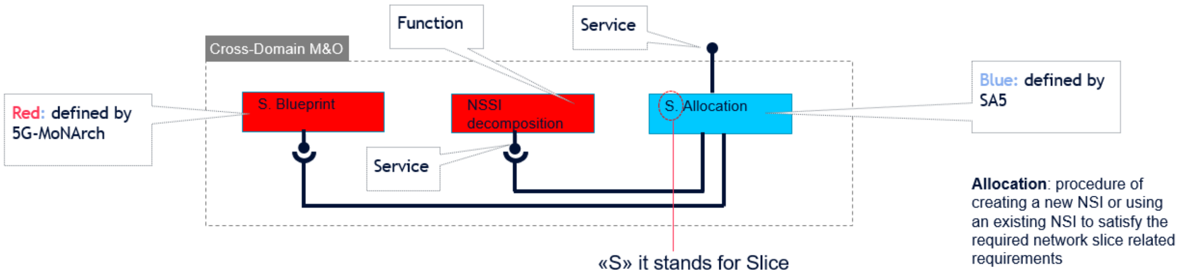
Parts of these enhancements, i.e., (1), (2), (4), are explained in Section 4.2.2, while the others, i.e., (3) and (5), are under further development. All these enhancements are in agreement with the current SA2 SBA architecture, functional framework and they align with the 3GPP 5GS control plane procedures.

Further, [TR 23.786] has defined a set of key issues that are directly addressed by 5G-MoNArch solutions (e.g., those detailed in Sections 4.2.1, 4.2.2, and 4.2.3), particularly “Key Issue #3: QoS Support for eV2X over Uu interface” and “Key Issue #7: Network Slicing for eV2X Services”.

3.3.3 Management and orchestration components

This section describes the novel Management and Orchestration (M&O) components introduced by the 5G-MoNArch architecture. In particular a functional split of the CSM/NSMF/NSSMF M&O entities is defined presenting several new components with respect to the SotA. The section further details the internal architecture and functions of the management entities that compose the overall M&O architecture. The proposed functional split is an enhancement with respect of what is currently standardised in 3GPP SA5, adding new functions according to 5G-MoNArch requirements.

This functional decomposition is intended to highlight 5G-MoNArch novelties that have been defined working on the enablers. In an SBA approach each function offers its functionality as a service to any authorised consumer anyway, in the practical implementation, some services are used locally and other are exposed to other management domains (cf. Figure 3-12).



Allocation: procedure of creating a new NSI or using an existing NSI to satisfy the required network slice related requirements

Figure 3-12: M&O functional split principle

The E2E Service Management and Orchestration sublayer, detailed with internal functions is depicted in Figure 3-13. The blue boxes represent the functions already defined in 3GPP SA5, while the red boxes represent the novelty functions defined by 5G-MoNArch.

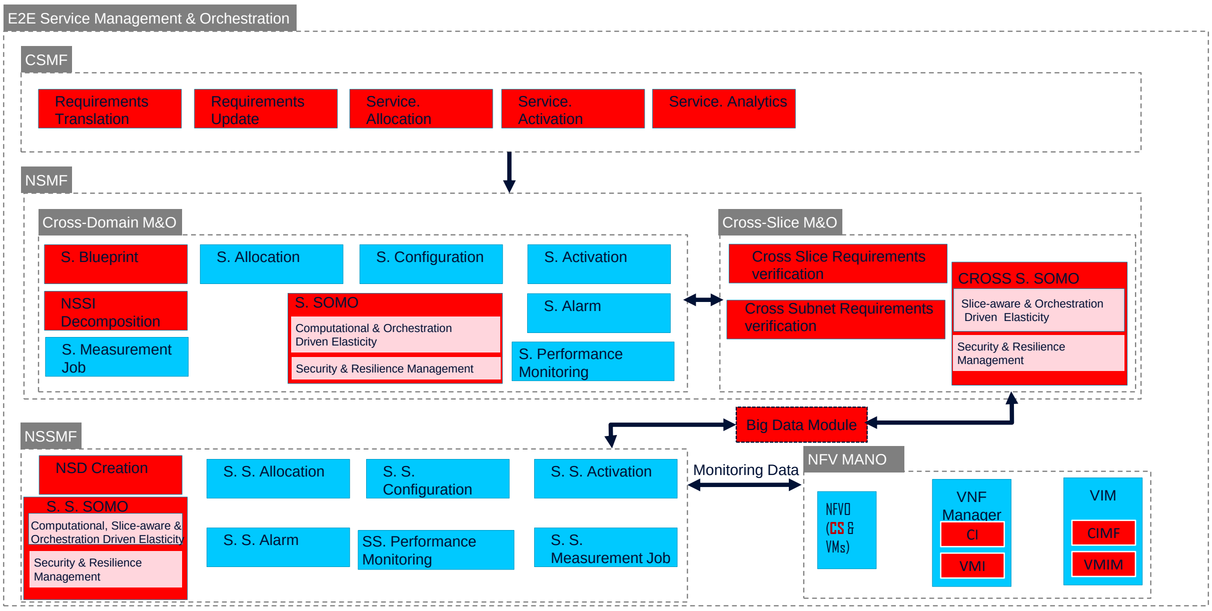


Figure 3-13: Breakdown of the E2E Service Management & Orchestration sublayer

In the following sections, each of the three management functions (CSMF, NSMF, and NSSMF) will be presented with its functional decomposition. The Big Data Module is explained in depth in Section 4.3.5.

3.3.3.1 5G-MoNArch communication service management

The Communication Service Management Function (CSMF) takes care of service allocation and management, also translating the service requirements into network requirements and offering a view on the service status and performance. Please note, that all the functions defined for the CSMF are new with respect to SotA defined in 3GPP SA5. The functions defined for the CSMF are described below:

- **Communication Service Allocation**: this function exposes a service to the tenant to request the allocation of a communication service. This request from the customer triggers a request to the NSMF for the allocation of a NSI. This function receives as an input the service requirement. Before asking for an NSI the service requirement has to be translated to network requirements that are the input for the request to the NSMF. The Service Allocation function also exposes a service for the update of the requirements. When a communication service has been requested, the tenant can modify it updating the service requirements. This function takes care of requirement management consuming the service exposed by the Service Requirement Translation.
- **Communication Service Requirements Translation**: this function translates service requirements into network requirements. This function is consumed by the Service Allocation function.
- **Communication Service Activation**: the allocation of a service is intended to setup all the required infrastructure to build up the service without exposing it to the end users. This function takes care of the actual service activation to have it exposed to the customers.
- **Communication Service Analytics**: performs network data analytics in order to obtain analytics at service level.

3.3.3.2 5G-MoNArch network slice management

With reference to the 5G-MoNArch M&O layer, the NSMF is divided into the cross-domain M&O and the cross-slice M&O.

The cross-domain M&O takes care of the management of a single network slice across the different management domains. The function split for this management entity is as described below:

- **Slice Allocation:** the slice allocation function takes as an input the network requirements provided by the CSMF and, also consuming the services exposed by the cross-slice M&O management entity, reuse an existing NSI or create a new NSI to satisfy the allocation request. To create a new NSI the network requirements has to be used to create the actual structure of the NSI in terms of NFs, topology, connectivity and configuration. These data are managed in the Network Slice Blueprint.
- **Slice Blueprint:** the function produces the slice constituents/attributes/configuration starting from the network requirements maybe with the support of predefined templates for specific well known or standardised slices. The 5G-MoNArch Slice Blueprint, that defines the Network Slice Instance in terms of network functions, their interconnection and configuration according to a specific service request, will be presented in Section 0.
- **NSSI Decomposition:** the function decomposes the network slice into slice subnets producing the network slice subnet blueprint for each required NSSI
- **Slice SOMO (S.SOMO):** Self-Organising Management & Orchestration (SOMO) functions dedicated to the slice life cycle optimisations as well as slice configuration and performance enhancements, such as resource scaling and NF dynamic deployment, (re-)configuration and troubleshooting (self-healing). It enables elasticity and the resilience/ security features in the Management & Orchestration layer.
- **Slice Configuration:** once the NSI is deployed, this function takes care of the configuration of slice. As an example, it configures (through the appropriate domains controllers) the connectivity among the NSSIs.
- **Slice Activation:** the allocation of a network slice is intended to setup all the required resources to build up the slice without having it up and running. This function takes care of the actual slice activation to have it exposed to the customers to support a communication service.
- **Slice Alarm:** alarms management at slice level, filtering and aggregating the alarms coming from the different slice subnets to provide alarm information and management for a specific network slice.
- **Slice Performance Monitoring:** performance data management at slice level, filtering and aggregating the performance data coming from the different slice subnets to provide performance data information and management for a specific network slice.
- **Slice Measurement Job:** measurement job management at slice level. This function transforms a request of measurement job for a slice into the appropriate measurement jobs for NSSIs that compose the NSI.

The cross-slice M&O takes care of the interaction and resource sharing among the deployed NSI. The function split for this management entity is as described below:

- **Cross slice requirements verification**: this function supports the allocation of a network slice evaluating if an existing NSI can also support the new requested communication service in terms of requirements.
- **Cross subnet requirements verification:** this function supports the creation of a new network slice evaluating if existing NSSIs can also support the requirement for the slice subnets that are constituents of the new network slice.
- **Cross Slice SOMO:** function dedicated to the Cross-Slice SOMO network algorithms.

The Slice Blueprint, the NSSI decomposition, the S.SOMO and all the functions defined inside the cross-slice M&O represent new elements with respect to the SotA defined in 3GPP SA5.

3.3.3.3 5G-MoNArch network slice subnet management

The NSSMF manages the network slice subnets that are constituents of a network slice. 5G-MoNArch architecture foresees multiple NSSMFs e.g. for different domains or technologies. Each NSSMF takes care of a groups of NFs collected into a management entity name sub network slice that can be shared among NSIs for resource optimisation.

The functions defined for the network slice subnet are described below:

- **Slice Subnet Allocation:** the slice subnet allocation function takes as an input the network slice subnet requirements provided by the NSMF and, also consuming the services exposed by the cross-slice M&O management entity, reuse existing NSSIs or create new NSSIs to satisfy the allocation request.
- **Slice Subnet Configuration**: once the NSSI is deployed, this function takes of the configuration of the NSSI. As an example it activates the configuration of the application part of the VNFs through the network management domain.
- **Slice Subnet Activation:** the allocation of a network slice subnet is intended to setup all the required resources to build up the slice subnet without having it up and running. This function takes care of the actual slice subnet activation to provide the requested network service.
- **NSD Creation:** creates the Network Service Descriptor for MANO.
- **Slice Subnet SOMO (SS.SOMO):** function dedicated to the SOMO algorithms for slice subnets.
- **Slice Subnet alarm:** alarms management at slice subnet level, filtering and aggregating the alarms coming from the different NFs to provide alarm information and management for a specific network slice subnet.
- **Slice Subnet Performance Monitoring:** performance data management at slice subnet level, filtering and aggregating the performance data coming from the different NFs to provide performance data information and management for a specific network slice.
- **Slice Subnet Measurement Job:** measurement job management at slice subnet level. This function transforms a request of measurement job for a slice subnet into the appropriate measurement jobs for the NFs that compose the NSSI.

The NSD Creation and the SS.SOMO functions represent new elements with respect to the SotA defined in 3GPP SA5.

4 5G-MoNArch Enabling Innovations

Deliverable D2.1 [5GM-D2.1] has provided a gap analysis with respect to ongoing 5G system architecture design efforts in the industry and academia, as perceived from the 5G-MoNArch perspective, cf. Table 2-1. The project's so-called innovation elements and enablers[7] as outlined in the following sections aim at enhancing, extending, and modifying the state-of-the-art 5G architecture concepts in order to close these gaps[8]. Each section will therefore detail the innovation element, highlight the novelties of the concept, describe the involved network functions (NFs) of the overall architecture (existing and novel NFs, cf. Chapter 3) and describe the work flow (using, e.g., message sequence charts) to realise the innovations. Table 4-1 depicts an overview of the innovation elements and enablers, as well as their mapping to involved NFs and layer(s) of the overall architecture.

Table 4-1: Mapping of innovation elements/enablers to the 5G-MoNArch overall architecture layers

Innovation elements/enabler	**Involved/affected network domains, NFs and layers of the 5G-MoNArch overall architecture**
Telco-cloud-enabled protocol design	Controller layer functions, selected UP VNFs in Network layer
Telco-cloud-aware interface design and requirements analysis	RAN-level UP (and CP) VNFs, Xn and F1 interfaces, Network layer
Terminal-aware protocol design	RAN-domain CP VNFs and interfaces incl. F1
Inter-slice context sharing and optimisation	CN-level UP and CP NFS, M&O layer functions
Inter-slice coordination	CN-domain CP NFs, service-based interfaces, Network layer
Terminal analytics driven slice selection / control	CN-domain CP NFs (AMF, NSSF, NWDAF), interfaces to UE and Itf-X to M&O layer
Inter-slice RRM for Dynamic TDD Scenarios	RAN (Inter-slice RRM, IM, and Unified Scheduler)
Context-aware relaying mode selection	RAN (Dynamic RAN Control Unit at RRC), M&O Layer (Cross-slice M&O)
Slice-aware RAT selection	RAN-omain CP NFs, Network, Controller and M&O layer as well as associated interfaces
Inter-slice RRM using the SDN framework	RAN-domain NFs, XSC/ISC and applications, Network layer, Controller layer, interfaces: NBI, SoBI, MOLI
Big data analytics for resource assignment	CN (NWDAF), M&O layer (Cross-slice M&O)
Framework for slice admission control	NSMF (Cross-slice M&O), NFVO, M&O layer and respective interfaces (e.g., Os-Ma-Nfvo)
Framework for cross-slice congestion control	NSMF (Cross-slice M&O), NFVO, M&O layer and respective interfaces (e.g., Os-Ma-Nfvo)
Slice admission control using genetic optimisers	NSMF (Cross-slice M&O), NFVO, M&O layer and respective interfaces (e.g., MOLI, Os-Ma-Nfvo)

[7] As illustrated in Chapter 1, a 5G-MoNArch enabling innovation consists of one or more innovation elements, where an innovation element can be constructed by one or more enablers depending on the needed level of granularity for designing the innovation element.

[8] A detailed description of the gaps is provided in Appendix A.

ML-based optimisation using an extended FlexRAN implementation	RAN-domain VNFs (CP and UP), Network layer
Computational analysis of open source mobile network stack implementations	RAN-domain VNFs (CP and UP), Network layer
Measurement campaigns on the performance of higher layers of the protocol stack	Higher-layer RAN VNFs (CP and UP), Network layer

The presentation of the innovation elements is structured using the three enabling innovations *telco-cloud-enabled protocol stack* (Section 4.1), *experiment-driven optimisation* (Section 4.5), and *inter-slice control & management*, where the latter is split into three sub-groups each representing an innovation element, namely inter-slice context-aware optimisation (Section 4.2), inter-slice resource management (Section 4.3), and inter-slice management & orchestration (Section 4.4).

The two enabling innovations *telco-cloud-enabled protocol stack* and *experiment-driven optimisation* have a special role since they do not follow the classical approach of designing a network function for a specific purpose, e.g., optimisation of resource utilisation. Rather, they propose a completely new approach to system architecture design. While the former focuses on minimising cross-functional dependencies (e.g., telco-cloud-ready function and interface designs in the RAN), the latter uses observations and results from operational networks to enhance the architecture and the behaviour individual NFs (e.g., resource orchestration algorithms used in the M&O layer). Therefore, these innovations do not always have an immediate representation in the functional architecture.

4.1 *Telco-cloud-enabled protocol stack*

The expected advantages brought by a cloud-enabled protocol stack design are backed by the relative maturity of current software initiatives (such as, Open Air Interface [OAI] or SRS LTE [SRSLTE]) and the recent increase in the pace of their updates. Moreover, this also provides the motivation and the means for researchers to investigate possible enhancements of technologies that have only been available in rather proprietary manner in the past, such as, cellular radio protocol implementations.

In future, fully softwarised and cloudified mobile networks will necessarily build on cloud-aware protocol stacks. Both network management and the resulting overall performance will benefit from making VNFs aware of being executed on shared resources by means of virtualisation environments such as virtual machines or containers. In this section, the main challenges to achieve this vision are discussed, while and describing possible implementations of functionality that builds on this cloud-awareness.

This approach entails two main challenges, namely (i) redefining the interactions between VNFs, relaxing as much as possible their temporal and logical connections, and (ii) support an elastic operation, to efficiently cope with changing input loads while running in an infrastructure of resources that is not over-provisioned. The functional requirements of these novel design strategies are detailed in what follows, before discussing why they will also require the formal definition of novel Key Performance Indicators, cf. [5GM-D6.1].

Given the high flexibility provided by the NFV approach, the deployment of such cloud-aware protocol stack does not have a direct negative implication on the provided telecommunication service per se. The re-definition of the interactions among VNFs allows for a more flexible service orchestration, while the re-design of VNF internals may be easily provided by a code refactoring in a much faster way than the current tightly coupled HW-SW PNF approach. While having a cloud-aware protocol stack will benefit any kind of telecommunication service, this may be particularly relevant for the extreme ones. For example, a mission critical VNF can be optimised to reduce its memory footprint, while low latency services may exploit especially tailored orchestration patterns involving edge computing facilities.

4.1.1 Telco-cloud-aware protocol design

Concept

Future network architectures will heavily rely on the flexible function decomposition and allocation. That is, the former monolithic PNF are split into interconnected modules that can be concatenated to provide the same functionality: e.g., a physical eNodeB is split into PHY, MAC, RLC and PDCP SW implementations running in different execution containers, which can be located in different nodes of the cloudified network.

This approach provides several advantages, as it allows heterogeneous deployments for different services (i.e., mMTC, eMBB), which are tailored to their specific requirements. For example, depending on the latency, bandwidth, and/or computational requirements of the service, it may be better to locate certain VNF towards the edge of the cloud rather than in a central location. How to place VNF across the cloud is a network orchestration problem, which is constrained by the split into modules described above. However, this typical NF decomposition for the RAN protocol stack was not designed for its cloudification, and therefore the potential gains are limited. This issue is discussed in more detail in the following. Also, the deployment of VNF in computational resources constrained environments, such as edge clouds, takes advantage of this enabler.

One key assumption of network stack designs is that certain functions are implemented in the same physical space, e.g., within the same chip. (maybe on a different chip, but surely on the same HW). So, non-ideal links with non-negligible delays are a problem for physical network elements that need to be decomposed into several network functions. Interfaces among them, thus, were designed considering communication links spanning some microns of silicon, and not several miles of fibre as in the case of, e.g., C-RAN.

In this way, the possible inter-dependencies between these functions are overlooked, as the delivery of information between them is practically immediate. However, as argued above, to fully benefit from a network-wide orchestration of a cloudified stack, VNF should support their execution on different nodes. But the design of traditional protocol stacks does not support such flexible placement of VNF, as those with heavy inter-dependencies may introduce very high coordination overheads, or may not be even possible due to infeasible network requirements. These limitations severely constrain network orchestration, which compromises the overall gains obtained from the flexible function allocation. This is flagrant for e.g., the introduction of centralised RAN functions, where long delays in the information exchange between radio access points and the central cloud result in serious performance deterioration.

Position in 5G-MoNArch architecture

Because of the above, the full protocol stack (and, in particular, the RAN) has to be re-designed with the goal of leveraging the benefits of the flexible function decomposition and allocation, so as to cope with non-ideal communication (i.e., non-zero and varying delay, limited throughput) between the nodes in the cloud. Specifically, a cloud-aware protocol stack should relax as much as possible, or even completely remove, the logical and temporal dependencies between VNF, such as very tight timing constraints for the HARQ, to enable their parallel execution and provide a higher flexibility in their placement.

One of the most immediate and appealing advantages of a cloudified network is the possibility of reducing costs, by adapting and re-distributing resources following (and even anticipating) temporal and spatial traffic variations. However, it is also likely that in certain occasions the resource assignment across the cloud cannot cope with the existing traffic due to some peaks of resource demands. This is particularly true for C-RAN deployments, that have to deal with demand loads known to be highly variable. In this scenario, allocating resources based on peak requirements would be highly inefficient, as this design jeopardises multiplexing gains in particular when cloud resources may be scarce (e.g., a "flash crowd" at an edge cloud): here any temporal shortage might result in a heavy congestion or even a system failure. VNF, instead, shall efficiently use the resources they are assigned with. Thus, they have to become elastic, i.e., adapt their operation when temporal changes in the resources available occur, in the same way they have a long-established manner of dealing with outages such e.g. channel errors. Therefore, to fully exploit the benefits of softwarising the network operation, the NF design has to take the potential scarcity into account and be prepared to react accordingly.

This enabler does not have a direct implication on the 5G-MoNArch architecture per-se, but it will provide the fundamental building blocks (i.e., cVNFs and uVNFs) on the network layer, that will be used by the controllers and M&O to achieve elasticity or resilience.

Evaluation and analyses

In the context of wireless communications, the concept of elasticity usually refers to a graceful performance degradation when the spectrum becomes insufficient to serve all users. However, in the framework of a cloudified operation of mobile networks that has to deal with elasticity under resource shortages, also other kinds of resources need to be considered that are native to the cloud environment such as computational, memory, and storage assets available to the containers the VNF are bound to. This has hardly been a problem for traditional NFs, that were designed to run over a given HW substrate with exclusive access to the resources and requires the definition of novel interfaces that will provide the amount and type of available cloud resources at a given point in time, just like, e.g., the accessible spectrum is a parameter for a RAN function.

Elasticity has also been considered by non-VNF cloud operators, but the presented concept deviates very much from theirs: the time scales involved in RAN functions are significantly more stringent than the ones required by, e.g., a Big Data platform or a web server back-end. Another key difference is that resources are way more scattered in the presented scenario (e.g. they are distributed across the "edge clouds"), which reduces the possibility of damping peaks by aggregating resources.

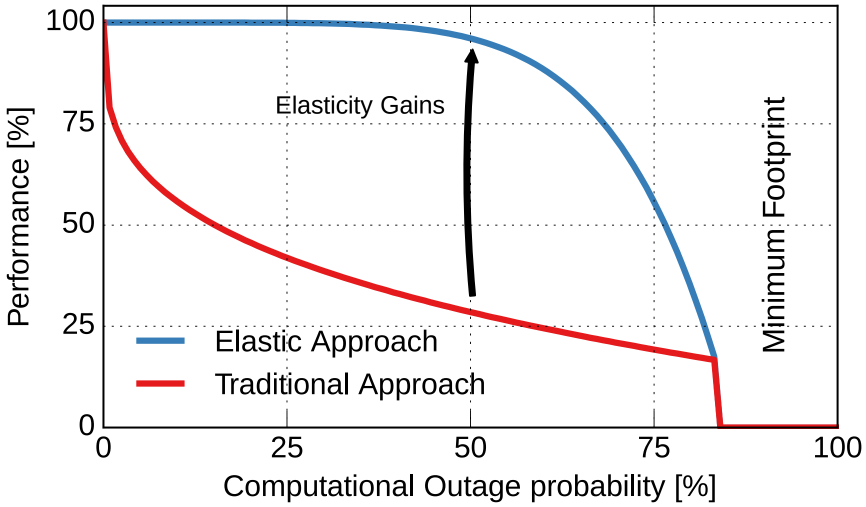


Figure 4-1: Telco-cloud-aware (elastic) VNF operation (illustrative)

To better illustrate the benefits of elasticity in the cloudified mobile network operation context, firstly the notion of “computational outage” is considered, i.e., the unavailability of the required resources to perform the expected operation. In a traditional, non-elastic operation, there is a 1-to-1 mapping between outages and performance loss, as Figure 4-1illustrates: if the resources are not available 20\% of the time, there is a 20% performance degradation, as the function is unable to operate under any shortage. In contrast, an elastic design supports what hereafter is referred to as graceful performance degradation, which causes that the VNF would still work under a resource shortage (with reduced performance, though), this resulting in the "gains" qualitatively illustrated in the Figure 4-1. Making a protocol stack cloud-aware through elastic VNF requires hence a paradigm shift in their design, moving away from the tight HW-SW co-design as discussed before, to a flexible operation in which the amount of available resources is an additional parameter.

To fully take advantage of elastic VNF, a detailed analysis of their operation is required: first, a thorough assessment of the resources consumed during execution, including statistics about temporal variations over time; second, a characterisation of the correlations between VNF operations, to serve as input for the orchestration algorithm, so it could e.g. dynamically assign resources to resilient VNFs and quickly "rescue" them when outages happen. Indeed, the quest for cloudification will end up with novel orchestration algorithms. Specific algorithms are defined in WP4, but the overall operation can be generalised as depicted in Figure 4-2.

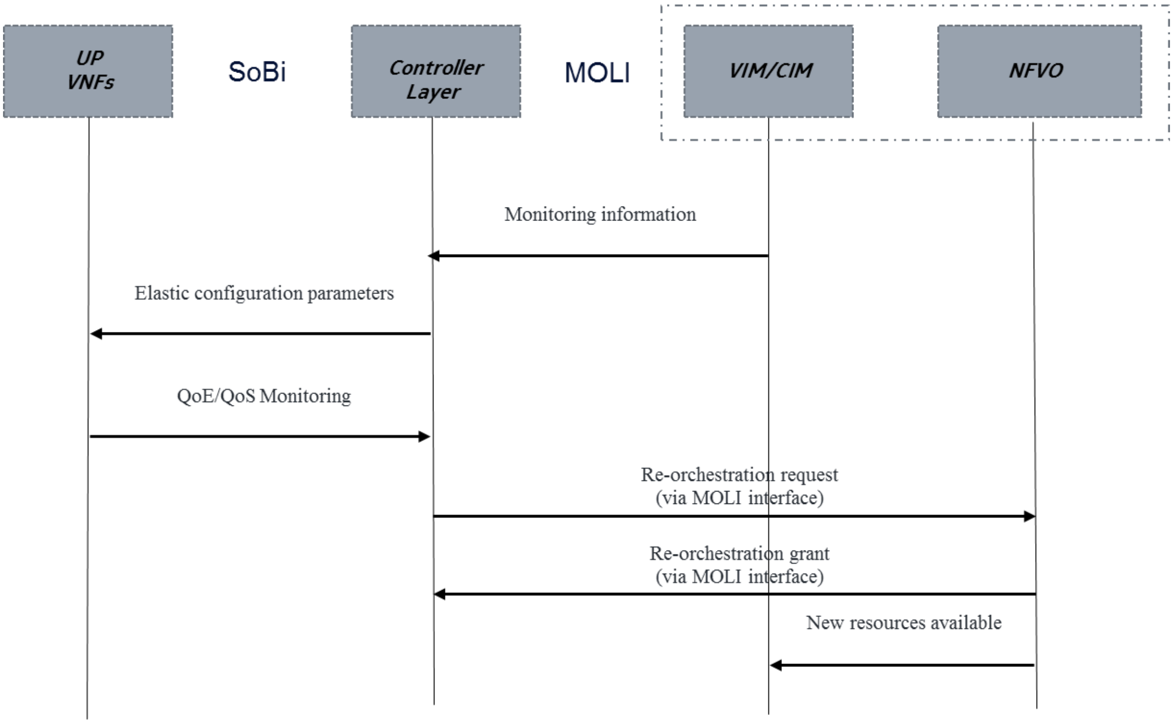

UP VNFs
SoBi
Controller Layer
MOLI
VIM/CIM
NFVO
Monitoring information
Elastic configuration parameters
QoE/QoS Monitoring
Re-orchestration request (via MOLI interface)
Re-orchestration grant (via MOLI interface)
New resources available

Figure 4-2: Telco-cloud-aware protocol stack operation for elasticity

4.1.2 Telco-cloud-aware interface design and requirements analysis

Concept

Besides the novel design of elastic VNFs, one of the most challenging tasks to introduce a cloud-enabled RAN protocol stack is to derive requirements regarding the interface among VNFs which include separated RAN functionalities such as the MAC scheduler, or PHY layer procedures. It is also for further study to what extent the RAN protocol stack can be cloudified. Especially in the MAC and PHY layer delay requirements and interdependencies among functions are critical.

A first study related to these targets and challenges is presented in [5GM-D4.1]. The basic architecture to introduce a cloud enabled protocol stack is illustrated in Figure 4-3. On the one hand, an extension to 3GPP’s Xn and F1 interfaces to provide much higher flexibility is required as well as extensions regarding the transport protocol to interconnect multiple, e.g., containers among multiple physical machines is needed. The yellow boxes represent the virtualised environment of the either CP or UP functionality illustrated as blue boxes. One of the major upcoming tasks is to derive subgroups of functionalities dependent on the limitations defined by acceptable additional delay and interdependencies of functionalities which then will be virtualised.

Position in 5G-MoNArch architecture

Telco-cloud-aware interface design affects the 5G-MoNArch RAN functions and interfaces. It mainly analyses UP functions, but also potential interdependencies of CP sub-functions are covered. Moreover, the proposed concept affects the interfaces Xn and F1 as defined by 3GPP for Release 15. In the 5G-MoNArch context, both interfaces reside in the Network layer.

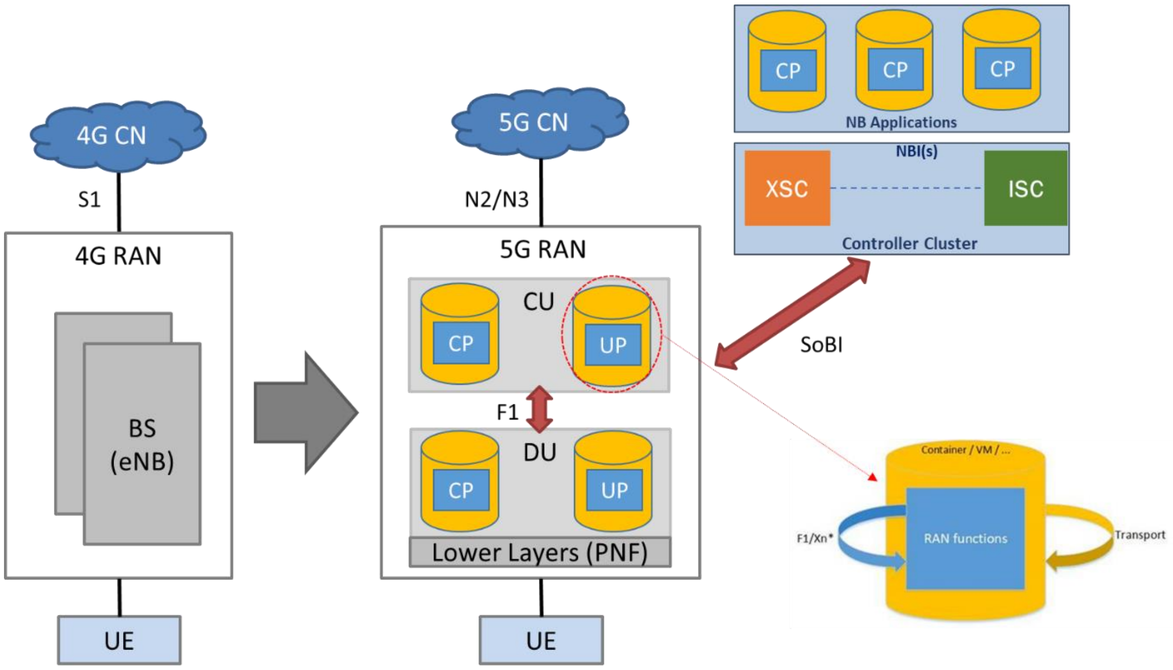
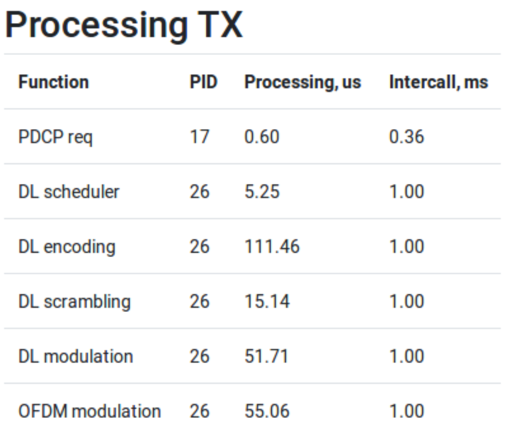


Figure 4-3: Cloud-enabled protocol stack architecture

Evaluation and analyses

In a first step, it is necessary to evaluate the required processing times of distinguished BS functions under influence of parameter adaptations, such as bandwidth and modulation and coding scheme. Additionally, it is necessary to understand what are additional delays and computational overhead introduced by the virtualisation techniques, such as Docker Container. First example results regarding the processing times of individual RAN functions are illustrated in Table 4-2. The table shows the separated functions, by now in a non-virtualised manner. As an example, especially the increased processing time of the DL encoding under full load conditions generated with one active UE, could be observed. The total sum of processing time to create the TTI in this example is approx. 239µs without any additional delay by virtualisation techniques or transport.

Table 4-2: Evaluation of RAN functions considering required processing times



Processing TX

Function	PID	Processing, us	Intercall, ms
PDCP req	17	0.60	0.36
DL scheduler	26	5.25	1.00
DL encoding	26	111.46	1.00
DL scrambling	26	15.14	1.00
DL modulation	26	51.71	1.00
OFDM modulation	26	55.06	1.00

In future steps, the parameters above will be changed to study the effect of on the processing time and to propose a novel design of elastic VNFs.

4.1.3 Terminal-aware protocol design

Concept

Flexible Group Mobility via floating mobility anchors

D2D communications facilitates an enabling innovation for further support of service continuity and smooth mobility (beyond the network edge). This can be realised via Group Mobility, an area currently under study in standards (mainly for wearable devices) where a Relay UE acts as the surrogate of handover signalling messages for Remote UEs when they move along together. In practice, the linkage between a group of Remote UEs and a Relay UE may not be exclusive or permanent due to, e.g. non-uniform mobility patterns followed by them. Therefore, different mobility scenarios can be envisioned beyond those followed in current standard discussions. For example, in case of stationary Internet of things (IoT) devices, Remote UEs do not necessarily move along a Relay UE through which they communicate. Hence, a new mechanism to efficiently handle group mobility in such scenarios is required.

A novel group mobility paradigm is proposed with floating mobility anchor as shown in Figure 4-4, not necessarily “pinned” to a single Relay UE. Instead, the anchor and corresponding mobility group can be dynamically changed based on the mobility patterns, relative channel quality fluctuations and the level of support needed.

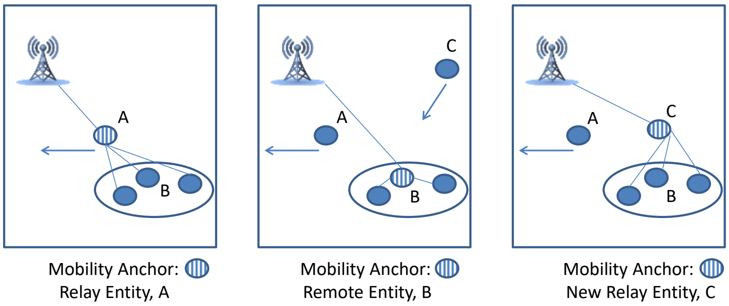


Figure 4-4: Concept of proposed floating mobility anchor

The above concept can enhance telco grade support in a group of Remote UEs (e.g. from scalability perspective) in line with Gap #4 and facilitate offloading some signalling at the RAN level (from direct signalling to the gNB to indirect signalling between anchor and Remote UEs) in line with Gap #5 (cf. Table 2-1).

Position in 5G-MoNArch architecture

Mobility and handover can be seen as a cross-slice NF (as part of AMF) within 5G-MoNArch architecture which should be commonly supported for all the sessions of a specific UE. The above solution can be confined to RAN domain where the mobility management is handled by a gNB. However, the gNB needs to be aware of anchor assignment and associated Remote UEs per group. Furthermore, further coordination is needed if an anchor and / or part of the Remote UEs leave the group for example due to changes in neighbourhood / mobility pattern. Enhancements could be envisioned on carried information over F1 interface (in CU/DU functional split) to update information as above between gNB-CU and anchor (e.g. over an enhanced F1 termed as F1*) in case of group status change or mobility at RAN-level.

Evaluation and analyses

The detailed description of Flexible Group Mobility is as follows:

- Group anchor assignment / Group formation: Define is a group as a set of UEs or other entities (in either Remote or Relay modes) that can be bundled together based on proximity, good inter-entity channel quality, similarity and correlation in supporting cell, mobility pattern, service profile or slice-driven characteristics. A group anchor is defined per group taking into account multiple criteria (good intra-group connectivity to maximum number of group members, good link connectivity towards mobility management function/ entity, sufficient power limit or processing capability). In presence of a Relay entity within a group, the Relay can be the natural group anchor as it will satisfy the relevant criteria. A UE or any other entity may participate in multiple groups assuming multiple-service/ slice profiles. As a result, a Remote entity in one group can be a Relay entity in another group. The exclusivity or generality of the groups is subject to network operator's decision. A group anchor aggregates individual group member signalling messages related to mobility management (anchor change or handover) towards/ from a gNB or relevant gNB-CU based on the level of support needed.

- User Update: should a group member leave the group, the gNB-CU and the group anchor send an updated list of associated Remote UEs to each other to coordinate on the changes.
- Anchor change: If the current group anchor leaves the group (e.g. due to changes in mobility pattern, channel quality or service/slice profile), a reassignment procedure is triggered so a new group anchor is designated by the network (gNB-CU) and the old anchor is released. Therefore, the anchor role can dynamically float across candidate members.
- Group handover: If a handover procedure is triggered via group anchor (e.g. due to the changes of channel quality to the gNB), the gNB or relevant gNB-CU decides on remote UEs to be shifted to another anchor (via anchor change procedure) or alternatively Remote UEs to be handed over (along the old anchor) to another gNB. The anchor change or handover of Remote UEs should precede any old anchor handover. Afterwards, the old anchor handover can be followed.

Figure 4-5 shows the Message Sequence Chart for the proposed concept for different stages, in particular for anchor change and group handover as described above.

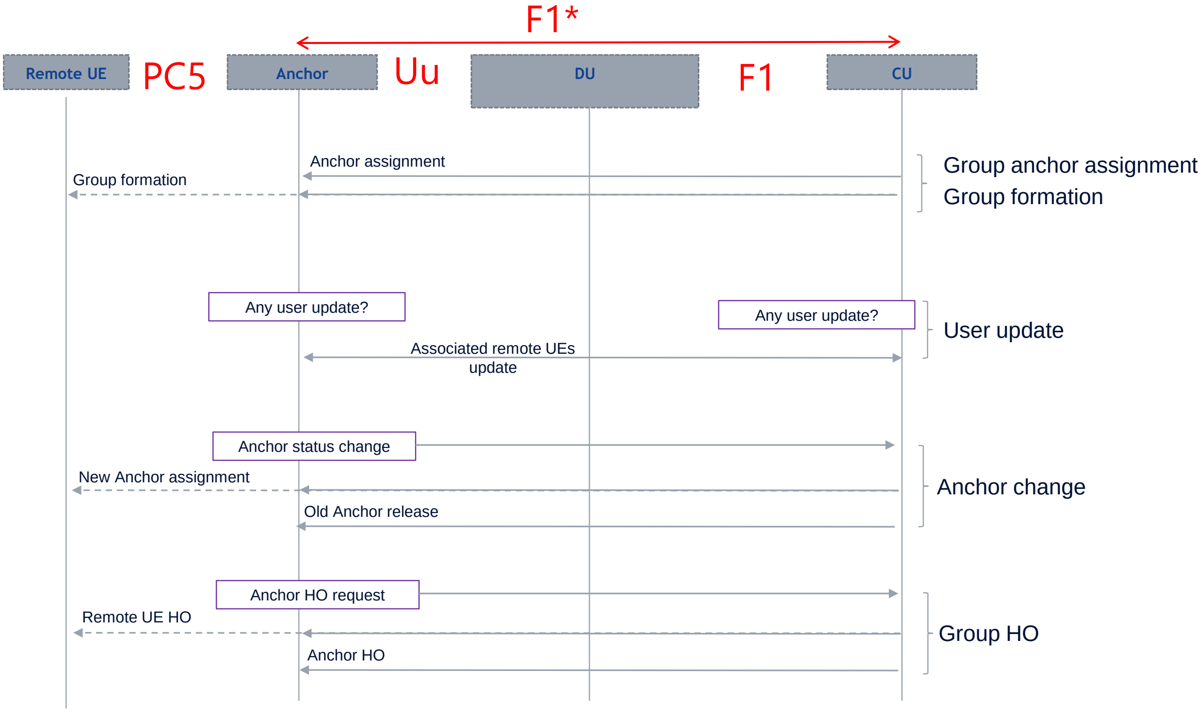


Figure 4-5: Message sequence chart of the anchor change / group handover concept

4.2 *Inter-slice context-aware optimisation*

4.2.1 Inter-slice context sharing and optimisation

Concept

5G Systems Phase 1 (i.e., Release 15) defines NWDA function in the network layer to perform per slice data analytics for service assurance. While cross slice context sharing and E2E cross-slice optimisation is not fully supported. This work focuses on defining entities in a mobile network that can operate with context awareness to close the loop of decision-making between entities of the Network layer and M&O layer in order to optimise intra and inter network slice operations. The work covers the following aspects:

- Enable information about status of entities of the system kept in the M&O layer to be considered in the decision making of control plane (CP) functions in the Network layer
- Reduce the chances of unnecessary or multiple changes at M&O layer and CP for solving a situation involving related entities, or entities in the same geographical region.
    - For instance, if PCF, SMF, O&M consume the same data analytics about prediction of probably reduction on throughput in a certain area of the network slice, how to prevent that SMF triggers UPF relocation, PCF triggers changes in policies to reduce traffic, and M&O layer triggers auto scaling of NFs, when these actions are affecting the same area of the network slice.
- Potential to reduce the need for long term capacity planning and pre-provisioning of infrastructure resources in order to guarantee the expected performance of mobile network services
    - In 4G, the QoS Class Identifier (QCI) has a budget of delay that is expected to be provisioned at the infrastructure by the M&O layer. This means that today it is first necessary to understand which are the characteristics of the mobile traffic and then dimension and pre-provision the network up front for such demand. This can lead to over- or under-provisioning of the network and this will impact the service performance. The presented enhancements tackle this problem by using context awareness to assure E2E QoS and at the same time improve the usage of the mobile network from the point of view of the operators.

Position in 5G-MoNArch architecture

5G-MoNArch reference architecture will be updated to enhance the Network layer and M&O layer, and provide enablers for inter-slicing optimisation (e.g., inter-slice context sharing and optimisation by enhanced NWDAF).

5G-MoNArch reference architecture will be updated to enhance the coordination of slice and cross slice optimisations and M&O layer optimisations, and provide enablers for coordination of Network layer and M&O layer optimisation (e.g., cross-slice and M&O layer context sharing, and optimisation by enhanced NWDAF).

Evaluation and analyses

Main analysis required towards the definition of mechanism for 5G Phase 2 (i.e., further 3GPP release introducing significant changes beyond Release 15) for inter-slice context sharing and optimisation are:

- Analysis of required inter-slice interfaces and procedure enhancements (i.e. Phase 1 gap analysis), relating to CP, UP, and M&O layer, NWDAF function enhancements.
- Inter-slice interfaces and procedure solutions design.
- Analysis of required context information, information source, information format, to be collected and used for optimisation.
- Analysis of the potential applications and optimisation for NWDAF.
- Scenario and requirements analysis for inter-slice coordination of optimisations as well as coordination of optimisations across Network layer and M&O layer.
- Architecture analysis on the conflicts of parallel actions performed by network layer and M&O layer.
- Analysis on the related interface/procedure enhancement mapping to the current standards and 5G-MoNArch high level architecture.

Figure 4-6 illustrates examples of enhancements to be included into NWDAF functionalities to support the mechanisms listed above. The enhancements of NWDAF proposed to tackle the issues of coordination of slice/cross-slice optimisation and M&O layer optimisations is illustrated in Figure 4-7.

Proposed is a solution where NWDAF can generate feedback and coordination notifications. These coordination notifications are messages sent by NWDAF in order to inform, NFs and OAM of situations in which a generated feedback consumed by a certain entity might generate effects on another entity. The entity suffering the effects becomes aware that it might not trigger changes, before just triggering actions, the entity suffering the effects might trigger some back off time to avoid unnecessary changes in the system. In addition to NWDAF, the NFs and M&O layer functions are enhanced in order to support such coordination triggered by the NWDAF.

Defined is the minimal set of types of contexts that can be generated by the NWDAF. Furthermore, defined is a format for describing a context type as a tuple (<Entity#1> - <Entity#2>), where the first entity indicates who enforces a certain change in the operation of the system, and the second entity indicates which entity might be influenced by consequences of the enforced changes. For instance, if CP changes the gateway from the users, M&O layer will see a reduction of traffic in a part of the network and an increase in another part. This is represented as a CP-M&O layer type of context.

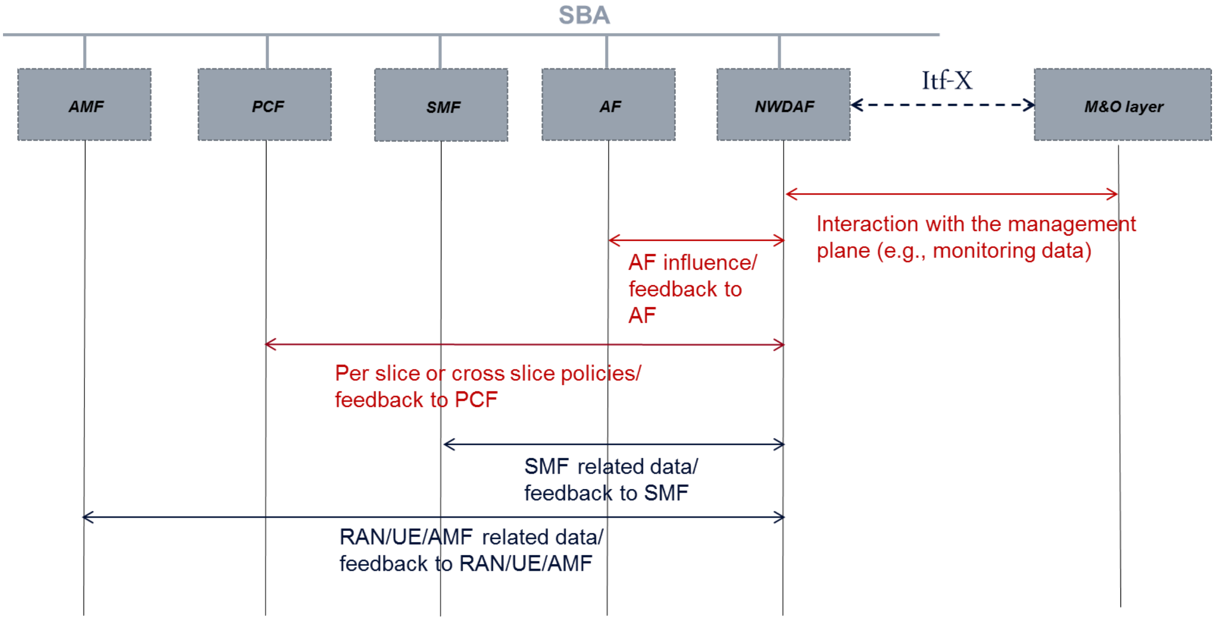

SBA
AMF
PCF
SMF
AF
NWDAF
Itf-X
M&O layer
Interaction with the management plane (e.g., monitoring data)
AF influence/ feedback to AF
Per slice or cross slice policies/ feedback to PCF
SMF related data/ feedback to SMF
RAN/UE/AMF related data/ feedback to RAN/UE/AMF

Figure 4-6: 5G-MoNArch enhancements of NWDAF (red-coloured parts)

The minimal set of types of contexts are described as follows:

- **CP only:** related to changes to be enforced in CP with minimal or no effect in M&O layer; trigger no notification
- **CP-M&O layer:** related to changes in CP that probably will affect M&O layer; trigger notification message to M&O layer functions
- **M&O layer-CP:** related to changes in M&O layer that will probably affect CP; triggers notification message to CP functions

Figure 4-7 shows the interactions among NWDAF, NFs, and M&O layer for coordination of actions due to the generation of the proposed types of contexts.

- Step 0: NFs and OAM register to receive feedback from NWDAF
- Step 1: NWDAF collects data from NFs and/or M&O layer in order to generate feedback
- Step 3: NWDAF generates feedbacks and determine the type of context associated with each feedback
- If CP Only type of feedback:
  - Step 4a: NWDAF notifies NF with the feedback it registered to receive
  - Step 5a: NF that received a feedback will decide if changes need to be triggered based on the received feedback
- If CP-M&O layer type of feedback:
  - Step 4b: NWDAF notifies NF with the feedback it registered to receive
  - Step 5b: NF that received a feedback will decide if changes need to be triggered based on the received feedback
  - Step 6b: NWDAF will generate a coordination notification message to M&O layer about the generated feedback that might affect M&O layer operation

  - Step 7b: M&O layer upon receiving the coordination notification message decides whether a back-off timer for changes should be triggered (to avoid conflicting or unnecessary changes) or not.
- If M&O layer-CP type of feedback:
  - Step 4c: NWDAF notifies M&O layer with the feedback it registered to receive
  - Step 5c: M&O layer upon receiving a feedback will decide if changes need to be triggered based on the received feedback
  - Step 6c: NWDAF will generate a coordination notification message to NFs about the generated feedback that might affect their operation
  - Step 7c: NFs upon receiving the coordination notification message decide whether a back-off timer for changes should be triggered (to avoid conflicting or unnecessary changes) or not.

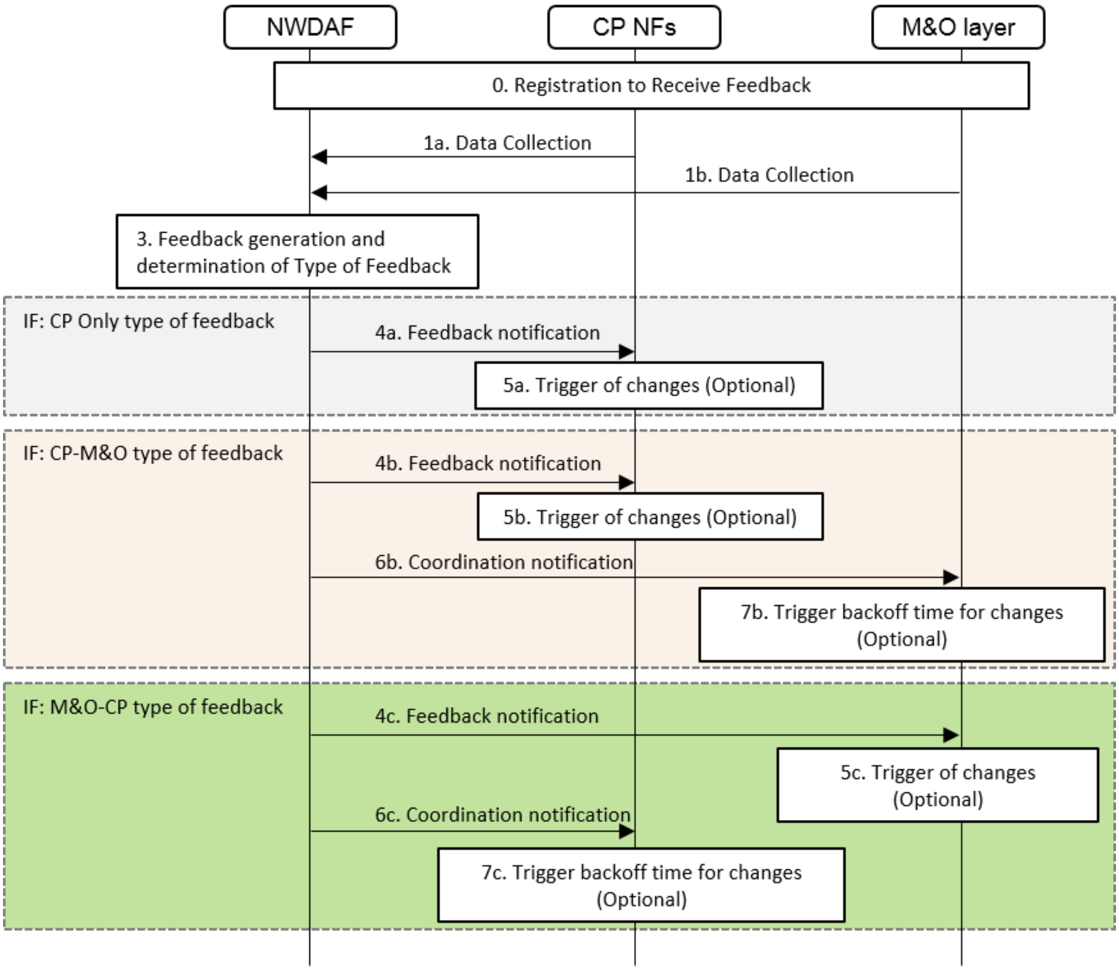

NWDAF
CP NFs
M&O layer
0. Registration to Receive Feedback
1a. Data Collection
1b. Data Collection
3. Feedback generation and determination of Type of Feedback
IF: CP Only type of feedback
4a. Feedback notification
5a. Trigger of changes (Optional)
IF: CP-M&O type of feedback
4b. Feedback notification
5b. Trigger of changes (Optional)
6b. Coordination notification
7b. Trigger backoff time for changes (Optional)
IF: M&O-CP type of feedback
4c. Feedback notification
5c. Trigger of changes (Optional)
6c. Coordination notification
7c. Trigger backoff time for changes (Optional)

Figure 4-7: NWDAF enhancements for coordination of feedback usage between network layer and M&O layer

The specific interfaces between NWDAF, NFs, and M&O layer, are currently under discussion at the SA2 study item on enhanced Network Automation [3GPP TR 23.786]. The discussion includes the type of services offered and consumed by NWDAF, NFs, OAM to enable both the data collection as well as the consumption of feedback generated by NWDAF. In addition, the actual parameters to be considered by these interfaces is included in this discussion.

4.2.2 Inter-slice coordination

Concept

3GPP defines some basic network slice types, e.g., eMBB, mMTC, URLLC, where each network slice type is designed for a group of services sharing similar service requirements. However, some applications/services may require multiple service flows. Such multiple service flows can be implemented by different QoS flows, different PDU sessions or even different network slices. For instance, in remote driving case (cf. Figure 4-8), the High Definition (HD) video requires high throughput which is supported by eMBB slice. While, the on-vehicle sensor data and vehicle control signalling requires low latency and high reliability which is supported by URLLC slice. Similarly, in Touristic City scenario the VR/AR application may require an eMBB slice to transfer HD video contents from the video server, meanwhile a URLLC slice maybe needed to exchange the haptic interaction between the tourist and the guide [5GM-D6.1].

For services using multiple slices, different slices can be fully isolated and their performance are independent to each other. However, the actual performance of individual independent slice will be affecting the same service. This results in the correlation between requirements of different network slices for the same service/applications, more specifically:

- Performance of one slice affects the required KPIs of another slice. For instance, in remote driving/AR/VR, long latency of video control (direction of view) signal makes the transmission of HD streamed video from the vehicle site useless.
- The KPI (e.g., Latency) budget is actually shared between different slices. The user experience is affected by the summary of the latency from multiple slices (i.e., the latency of the control signalling to the vehicle and the latency of the video/sensor report from the vehicle).

Obviously, exploring the service correlation of different service flows can help to increase network efficiency and improve user experience.

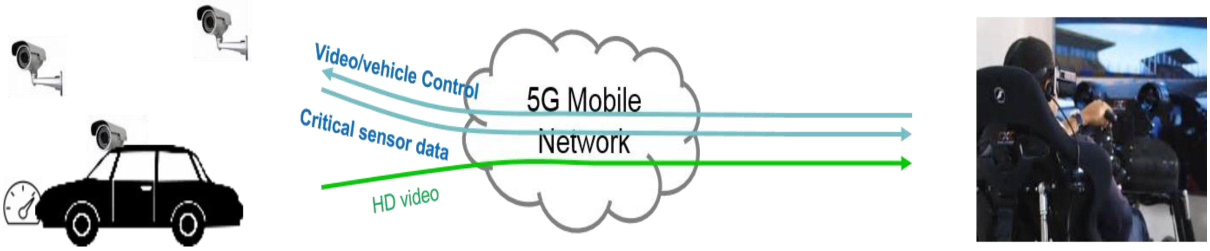


Figure 4-8: Remote driving use case

Position in 5G-MoNArch architecture

This work proposes a CP network function ISCF in 5GC to bind the services flows from the same application/service. There are two options to implement this function: 1. At the AMF 2. At the PCF. In option 1, ISCF binds the service flow of the applications by intercepting the session establishment requests from the UE. In option 2, ISCF gets the service flow binding information from the AF, i.e., via interactions with verticals/applications.

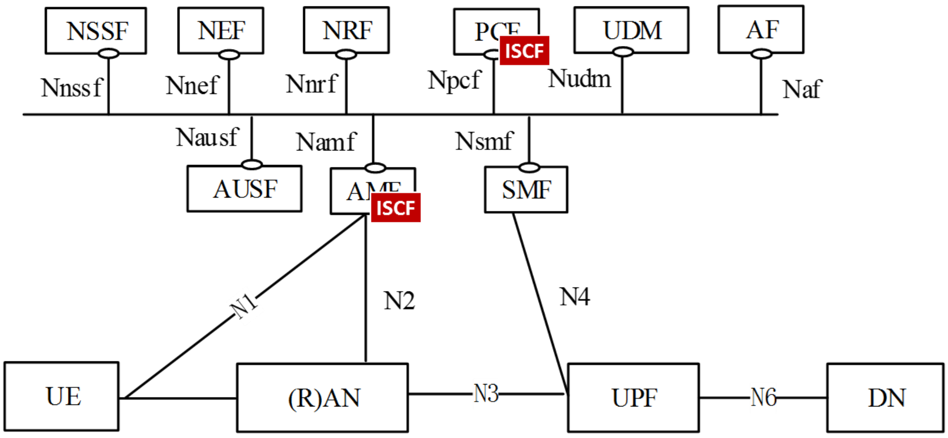


Figure 4-9: Two options of ISCF implementation in SBA

Evaluation and analyses

Except for the bind of services flows, such binding information should be distributed to the NF or management layer where such information is used for network optimisation. When ISCF gets the service flow binding information, it can provide it via SBI to other network functions for optimisation purpose (e.g., SMF, PCF), or perform data analytics (e.g., NWDAF), or RAN via N2 interface, or further exposure to the management layer (e.g., via NEF).

Meanwhile, network optimisation needs to be based on the correlated KPIs of the bind services flows. This information can either come from the CSMF in the management layer and stored at PCF as correlated QoS profile of different traffic flows. This information can also come from the AF via influencing the QoS profile at PCF.

The following figure shows the procedure in case the ISCF is located at AMF (cf. Figure 4-10):

(1) Network Slice Selection Policy (NSSP) at the UE maps one service/application into multiple network slices (S-NSSAIs). Trigged by an application, UE will send the session establishment request with multiple PDU session each indicate the PDU session ID and correspondent S-NSSAI to the AMF via NAS message.
(2) AMF marks down related PDU session IDs, S-NSSAIs for this request and also the related SMFs. It sends the binding information of the PDU sessions to the related SMFs.
(3) The related SMFs decides on the QoS flows of these bind PDU sessions and further bind the QoS flows.
(4) SMFs indicate the PDU session/QoS flow binding to PCF (or other network functions where such information is needed, or via other network functions to RAN, UE, management layer, etc.)
(5) PCF decides on per QoS flow/per PDU session policy and send to the related network functions.

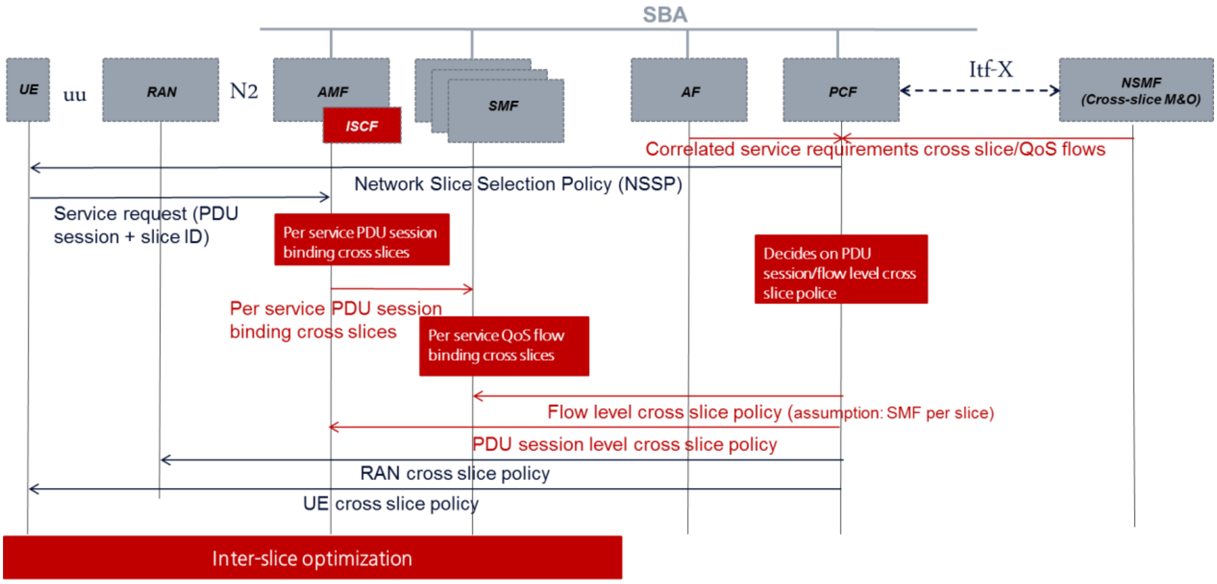

SBA
UE
uu
RAN
N2
AMF
ISCF
SMF
AF
PCF
Itf-X
NSMF (Cross-slice M&O)
Correlated service requirements cross slice/QoS flows
Network Slice Selection Policy (NSSP)
Service request (PDU session + slice ID)
Per service PDU session binding cross slices
Decides on PDU session/flow level cross slice police
Per service PDU session binding cross slices
Per service QoS flow binding cross slices
Flow level cross slice policy (assumption: SMF per slice)
PDU session level cross slice policy
RAN cross slice policy
UE cross slice policy
Inter-slice optimization

Figure 4-10: Example Message Sequence Chart for inter-slice service correlation (5G-MoNArch enhancements are indicated in red colour)

4.2.3 Terminal analytics driven slice selection and control

Concept

There are already established services within next generation service-based CNs (as outlined in 3GPP SA) to access operator-specific analytics (NWDAF). The current defined services are mainly envisioned to share such information within CN between different NFs of the same slice.

UEs are natural data collection points to gather more localised analytics within the network. Examples of data that the UE can provide are positioning information (e.g. collected from inertial sensors of the UE, geo-referenced radio data from wifi) or user profiling info (e.g. when a UE changes environment from outdoor to indoor or from vehicular to pedestrian mode). Such information may help the NWDAF to make more intelligent decisions on slice selection (e.g. to switch from a slice with more flexible resources to a resilient one or vice versa).

As UEs can simultaneously connect to or switch across different slices (e.g. in case of mobility), they can have more prominent role for data preparation for the network to provide relevant localised contextual information and to identify earlier any changes in the network compared to the past intra-slice and/or cross-slice information they have gathered. The outcome processed information can also be used for network slice selection for the UEs. This can be utilised to address Gap #6 (cf. Table 2-1) to further optimise cross-slice operations.

As an example, the UE may cause the network to change the set of network slices it is using by submitting the value of a new NSSAI in a mobility management procedure. However, the final decision is up to the network. This will result in termination of on-going PDU sessions with the original set of network slices. Change of set of slices used by a UE (whether UE or network initiated), may lead to common NFs change subject to operator policy.

Position in 5G-MoNArch architecture

As captured above, there are intra-slice services (i.e., NWDAF) for sharing analytics between NFs within 5GC. PCF and NSSF at cross-slice level can be seen as the consumer of such services. New mechanisms and procedures can be defined on RAN-level to provide user access to that information via e.g. NSSF (with possibility to provide update/amendment reports to the network, subject to operator's policy).

In one variant of the proposed scheme, NWDAF services may be kept intact and mainly act as collection point of analytics data. In this variant, NSSF may have extra service and active role to cross-check localised terminal analytics coming via RAN versus global network analytics from NWDAF. The outcome of such post-processing can be used for slice selection within UE in coordination with original AMF instance as shown in Figure 4-11.

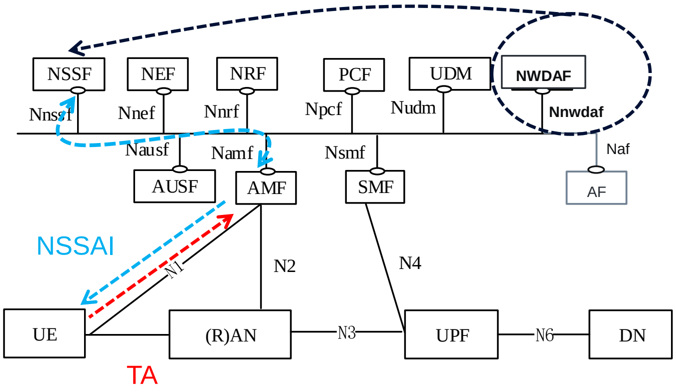


Figure 4-11: Possible flow for Terminal Analytics (TA)-driven slice selection and control

In another variant of the proposal, a new service can be defined for NWDAF to actively interact with – terminal-driven data analytics coming via RAN so then NWDAF services would not be only limited to monitoring type services. In this scenario, via a loopback interface to M&O layer, similar information may be used to update network analytics data at the Operator side.

Evaluation and analyses

Figure 4-12 shows an example Message Sequence Chart for supporting terminal driven local analytics and subsequent slice information update.

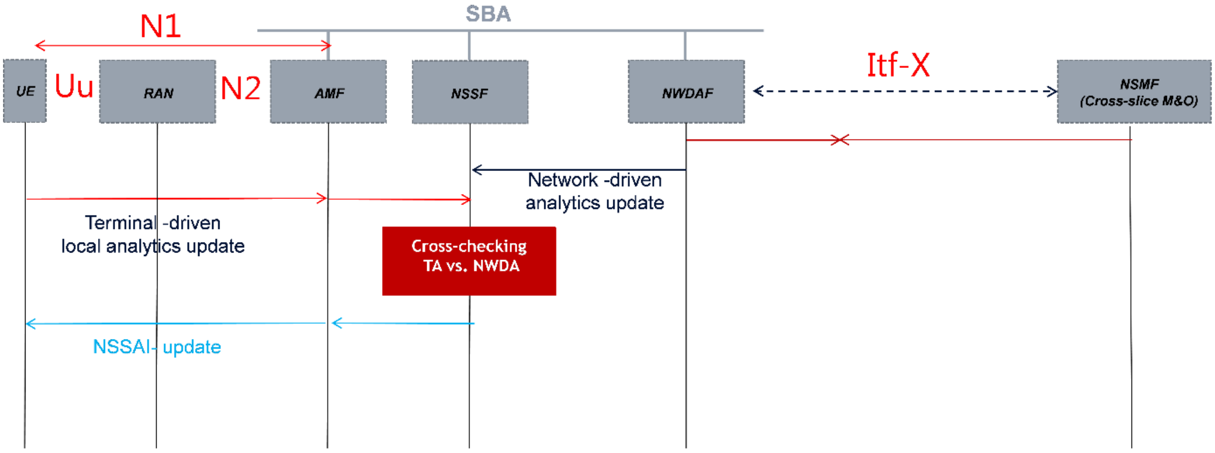


Figure 4-12: Example Message Sequence Chart for TA-driven slice selection (Variant 1)

4.3 *Inter-slice resource management*

Inter-slice resource management is a key innovation enabler in 5G-MoNArch architecture for optimising performance by allocating resources among slices which may share the same spectrum bands in access networks. This section presents some enabling resource management solutions to accommodate various use cases and with different dynamicity requirements.

4.3.1 Inter-slice RRM for dynamic TDD scenarios

Concept

This enabler introduces the notion of network slicing in 5G TDD networks, considering a multi-service environment with asymmetric traffic conditions. Network slices are formed on-demand with the allocated resources being dynamically adjusted with the objective to enhance the resource utilisation efficiency. Each network slice is customised to accommodate distinct service types by allowing each tenant to adopt a different TDD frame enabling a distinct UL/DL ratio, which can be re-configured independently reducing the loss of multiplexing gain. Although such TDD oriented network slicing framework is analysed in [SSS+16] considering an SDN-based architecture that enables multi-service and multi-tenancy support, the allocated slices have a fixed resource size for the entire duration of the service request, occupying only specific isolated sub-carriers.

This enabler builds on top of this slicing framework considering more dynamic slice allocations for dynamic radio topologies (addressing identified Gap #6 in Table 2-1 (E2E cross-slice optimisation not fully supported)), where slice resources can be adjusted during the time of a session request introducing the following planned contributions.

Initially, the generic optimisation problem for multi-slice multi-user and multi-cell UL and DL resource optimisation is formulated. The problem will be translated to two sub-problems (P1 and P2) to allow for solving it with lower complexity and enhanced modularity. P1 involves the link activation selection per time instance, given the slice / traffic requirements and the TDD patterns given dynamic radio topologies. In addition, P2 takes as input the link selection and per time-slot aims to optimise performance by allocating resource blocks to the active links, in a way that the KPI is optimised.

A graph-based solutions framework will be proposed for both problems to optimise slice performance while keeping the signalling overhead and complexity. For P1 a constraint-based greedy algorithm is provided, whereas for P2 the problem is solved by a novel bi-partite graph-colouring based solution, which aims to perform adaptive frequency partitioning per time slots in a way that interference due to resource conflicts is avoided and at the same time resource utilisation efficiency remains in high level. Initially, a bi-partite graph is translated to a line colouring graph, where each node is a combination of link and transmission time interval (TTI) (edge of the bi-partite graph). The edge between two nodes in the line colouring graph appears only if a conflict exists at the receiving end of the bi-partite graph, which is equivalent of having two or more links being assigned to the same TTI. The graph-colouring algorithm assigns a different colour to a node only in case of a conflict, which means that different sub-bands will be scheduled to avoid interference. Based on this algorithm, the output is a time-table where each link is assigned to different bands (e.g. F1,F2,..F6), within distinct TTIs to ensure interference-free transmission/reception. In fact, this algorithm provides a flexible dynamic adaptation, where different parameters like number of users, slice KPIs and resource availability can be altered accordingly.

Solution to P1: Slice-aware TDD pattern Activation: For P1 a heuristic solution is provided as illustrated in Algorithm 1 (Figure 4-13) for activating the links in a time window based on the slice demand and aforementioned constraints. Initially in Step 0, a list of permitted timeslots for UL and DL is introduced per slice considering the TDD configuration pattern where a link can be activated only for a given Transmission Time Interval (TTI). A weight $f(e,s)$ is also defined based on the slice traffic demand and a list of conflicting links, taking into account the half duplex constraint. In Step1, a random link is chosen to be included in a Candidate List (CL) for the first TTI and then the next link is identified with the minimum demand, provided that it does not violate the above rules. Once selecting a link, in Step 3 it is added to the CL and reduce its weight by 1. This is repeated in Step 4 and Step 5, till no more links exist for this TTI and then this process is repeated till all TTIs are considered (Step 6).

```
Step 0: ∀ slice (s):
  - Set list of allowable timeslots per slice for
    DL: AM_DL (s, TTI) based on confDL(s) and
    for UL: AM_UL (s, TTI) based on confUL(s).
  - Set vectors of Links (E) and Traffic Demand
    per link: fe,s
  - Set List of conflicting links for each link e:
    Conf (e, s) and CL={}
Step 1: Start from random link e0 , add to CL={e0}
Step 2: Add the link e* with the lowest f(e*,s) to CL list $\forall e^*: e^* \notin AM\_DL, AM\_UL$ or $\forall e^*: e^* \notin Conf(\{CL\})$ → CL=CL+{e*}
Step 3: Reduce f(e*,s) by 1. If f(e*,s)  is 0, remove e* from E list
Step 4: Go to Step 2 till E={} or no link can be added
Step 5: Store CL as FL(i) and reset CL={}. i=i+1 and repeat Steps 1-4
Step 6: Stop when i=T
```

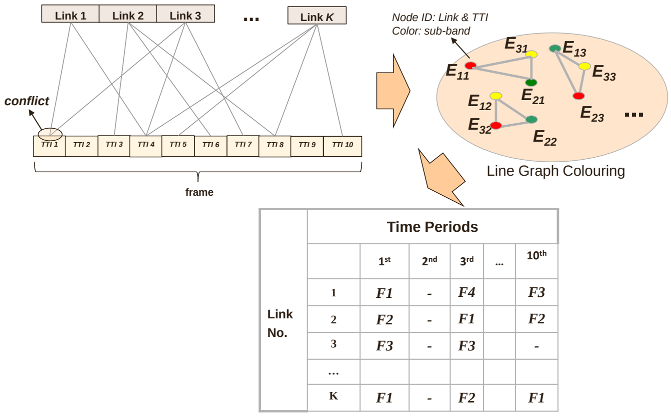
Figure 4-13: Algorithm 1: slice-aware TDD pattern activation for inter-slice RRM

```
- Set FL as [#Links x #TTI] matrix from Algorithm 1
- Set a color set Color and maximum number of colors Cmax and Clist={}
for TTI=1:T
   if FL(1:links, TTI)==y≤ $Cmax$
      Set randomly $y \in Colors$ different colors for the links
      connecting to TTI
   end if
      Store color indices for all links for TTI in a matrix as:
      Coloring(Link, Color Index, TTI)
end for
for color_index=1:Cmax
    CList(color_index) =Coloring (1:links,color_index,1:T)
end for
for bands=1:RB and color_index=1:Cmax
    Map bands to CList(color_index) that maximizes weighted sum-rate
end for
end for
```

Figure 4-14: Algorithm 2: graph-based resource allocation

Solution to P2: Graph-based Resource Allocation: For P2 a graph theoretic approach is considered. The outcome of the solution to P1 gives an allocation of links to TTIs. However, it is still unknown how many and which resources can be assigned to these links in order to avoid inter-cell and cross-link interference assuring the desired slice performance. The proposed P2 solution is illustrated in Algorithm 2 (Figure 4-14).

Initially, a bi-partite graph is created including the set of links and the set of TTIs. Based on this bi-partite graph, the resource allocation problem is translated into a time-tabling problem, where a number of activate links are required to occupy a number of different TTIs. A small cell Access Point (aka s-AP) has to create a time-table according to its availability in a way that no collision occurs in each slot. A graph-colouring is adopted to assign different colours, so as to restrict the allocation of links to conflicting TTIs in distinct sub-channels. As shown in Figure 4-15, a bi-partite graph is translated to a line colouring graph, where each node is a combination of link and TTI (edge of the bi-partite graph).



	Time Periods					
		1st	2nd	3rd	...	10th
Link No.	1	*F1*	-	*F4*		*F3*
	2	*F2*	-	*F1*		*F2*
	3	*F3*	-	*F3*		-
	...					
	K	*F1*	-	*F2*		*F1*

Figure 4-15: Graph colouring algorithm overview

Position in 5G-MoNArch architecture

- A common RRC functionality will be required which configures TDD patterns in a slice-aware manner and the link activations in long term. The placement of this functionality will depend on the dynamic radio topology and on the functional operation/capabilities of the unplanned small cells.
- Inter-slice RRM functionality at MAC or Unified Scheduler (which can be interpreted as an overarching layer on top of MAC for inter-slice dynamic scheduling) will be considered for dynamic resource allocation among slices based on the configured TDD patterns. The placement of this functionality will depend on the dynamic radio topology and on the functional operation/capabilities/supported split of the DUs (which can be planned / unplanned small cells).

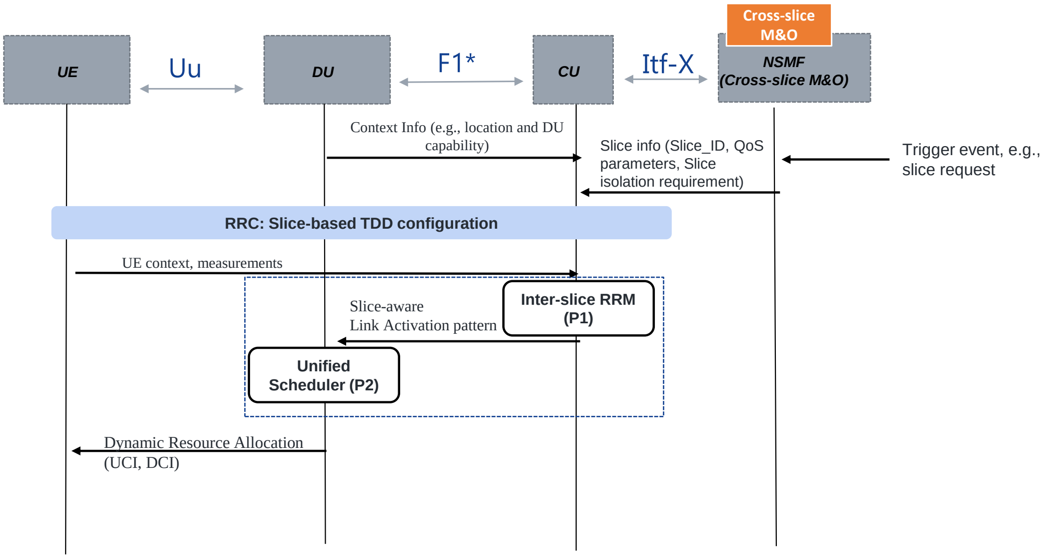

UE
Uu
DU
F1*
CU
Itf-X
Cross-slice M&O
NSMF (Cross-slice M&O)
Context Info (e.g., location and DU capability)
Slice info (Slice_ID, QoS parameters, Slice isolation requirement)
Trigger event, e.g., slice request
RRC: Slice-based TDD configuration
UE context, measurements
Slice-aware Link Activation pattern
Inter-slice RRM (P1)
Unified Scheduler (P2)
Dynamic Resource Allocation (UCI, DCI)

Figure 4-16: Message sequence chart for Inter-slice RRM in dynamic TDD scenario

Evaluation and analyses

Monte Carlo system level simulations will be provided for a 5G Ultra Dense Networks (UDNs) where resources can be shared by multiple slices with diverse KPIs (example for throughput, reliability). The evaluation study focuses on an outdoor small cell deployment of 4 s-APs covering a hotspot area, using the 3GPP as baseline for simulations (24 users uniformly distributed, 3GPP UMi channel, ideal backhaul). In each s-AP the corresponding users (6 users per cell) are randomly distributed. Matlab Monte Carlo simulations and random user drops for 500 snapshots are run. Assumed are 4 slices, whereas each slice has different TDD pattern as slice requirement (Slice 1: 80/20, Slice 2: 70/30, Slice

3: 60 /40, Slice 4: 50/50). At each snapshot, randomly 6 users are selected out of 4 cells to be connected to each slice, and a random traffic demand (1-10Mbps per user for both UL and DL) is applied. For the simulation comparison are considered:

- **Benchmark 1** is the cell specific dynamic frame re-configuration (CSDR) [SKE+12] without slicing where each s-AP can adopt a different TDD pattern, while using the same spectrum resources, with inter-cell and cross-link interference potentially deteriorating performance.
- **Benchmark 2** is the service-oriented TDD slicing [CSS+16], where slices are assigned a constant amount of resources (¼ of resource blocks in the simulations) and different TDD patterns are used independently for each slice. This solution provides a high spectral efficiency due to the interference isolation, but at the cost of lower resource utilisation, which can limit the peak throughput.
- **Algorithms 1 and 2** are used to select links and allocate resources over the entire range of resource blocks, while keeping interference at low levels.

Figure 4-17 shows the comparison of CDF curves of DL throughput per user as well as for UL throughput respectively (averaging it over the allocated TTIs) for all snapshots. In Figure 4-17 left it can be observed that the proposed solution outperforms Benchmarks 1 and 2 since it better addresses the trade-off between interference isolation vs resource utilisation. Benchmark 1 shows the worst-case interference scenario, whereas Benchmark 2, uses orthogonal resources for different slices. For Benchmark 2, the DL rate for all slices is aggregated collectively and it is shown that for the median and the 90th percentile of the CDF, the average throughput can be increased by more than 150%. The proposed solution shows a significant gain even over the second Benchmark, due to the fact that it achieves higher spectral efficiency with more resources being allocated to DL links based on the corresponding demand (in Benchmark 2, some resources may be wasted). In Figure 4-17-right, a similar trend is observed for the CDF of the UL throughput. The proposed solution shows similar performance at the 10th percentile of the CDF (cell-edge performance), whereas at median and 90th percentile (cell-centre) it outperforms both Benchmarks 1 and 2 respectively. This gain is mainly due to the fact that a better UL spectral efficiency can be achieved, and at the same time allocate more resources to links based on the actual demand, so as to maximise the total performance.

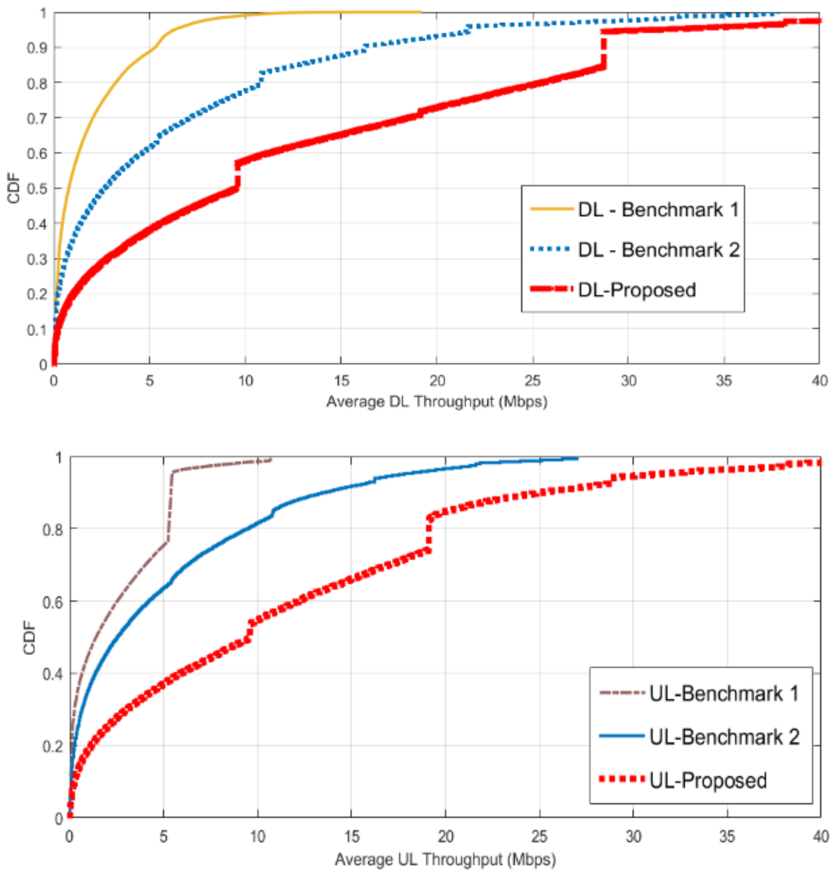


Figure 4-17: CDF of average user throughput illustration (DL and UL)

4.3.2 Context-aware relaying mode selection

Concept

As highlighted in [5GM-D2.1], for the fulfilment of network slice SLAs, an extended notion of a resource shall be taken into account, where the availability of wireless access nodes and the network topology shall be jointly considered along with the network slice requirements. This becomes particularly important when the network topology is changing as in case of self-backhauled DSCs, e.g., VNNs. The dynamic network topology can be exploited to better adapt to changing traffic conditions over time and space in cost-efficient way.

The wireless backhaul link of the DSCs can be reached by employing a relaying functionality. A fixed relay can be typically deployed as fixed radio frequency (RF) amplify-and-forward /repeater or layer 3 (L3) decode-and-forward (DF) node [3GPP TS 36.300]. As opposed to fixed functional operation in the SotA, slice-awareness and 5G tight KPIs can necessitate on-demand flexible SC operation. Slice-based target KPIs can comprise throughput / spectral efficiency for eMBB communications, high reliability and low latency for URLLC, and connection density for mMTC. Network slices may have different requirements in terms of throughput and latency, which necessitate enabling different operations for different types of traffic to meet certain KPIs. To this end, additional context can be utilised, such as, the position of the DSCs at different parts of the cells and the associated channel link qualities. Furthermore, different functional operations of DSCs can have different E2E latencies (e.g., amplify-and-forward relaying imposes less latency compared to DF relaying thanks to fewer processing steps of the signals). On this basis, as illustrated in Figure 4-18, the rational of this enabler is to analyse and determine the appropriate relaying mode (i.e., functional operation) of DSCs, based on, e.g.,

- Slice requirements, such as latency and required data rate;
- Resultant performance of selected mode (e.g., throughput and latency);
- Location of DSCs in the target service region (e.g., cell edge and cell centre).

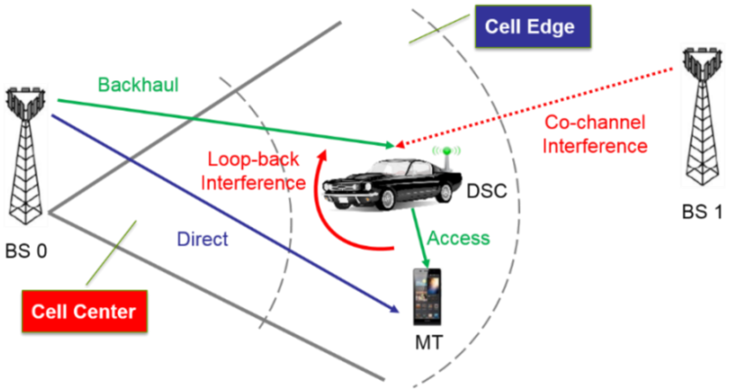


Figure 4-18: Example factors that can influence the functional operation of the DSCs

Different example functional operations (also referred to as modes) are depicted in Figure 4-19. As mentioned above, different possible functional operations can be identified given the per-slice requirements, the backhaul channel (between macro and small cell) and the RAN conditions. In this context, the first option is the L3 DSC with full functionality, i.e., the L3 DSC can control the cell under its coverage, e.g., with a physical cell ID. In case of L2 DSC there may be 2 different functional operations (PDCP/RLC split and RLC/MAC split). The PDCP/RLC split could be more applicable in cases of frequent fast handovers (e.g. high mobility users) between the macro and small cells, since PDCP re-transmissions would be required more often and PDCP should be centralised for fast traffic forwarding. On the other hand, RLC/MAC split could be more applicable to cases with better backhaul conditions (e.g., ideal backhaul) and cases where the RLC buffering needs to be centrally performed. An exemplary scenario of RLC/MAC split is the case of having large packets (e.g., eMBB traffic) and per segment ARQ is needed at the macro cell to avoid redundant re-transmissions of the entire packets. Another functional operation option is the L1 DSC which requires good backhaul and very low latency requirements. In that case, the real-time scheduling would be performed at the macro cell site and may have some resource pooling gains (e.g., Coordinated Multi-Point operation (CoMP) might also be used). Another option is the DSC to act as Radio Remote Head (RRH) which requires fronthaul between the macro cell and DSC, and can mainly be applicable to C-RAN physical deployment. These functional operations may not be confined to protocol stack layers, i.e., some of the functionalities at each protocol stack layer may also be split. For example, MAC functionality of HARQ may be at the DSC, while another MAC functionality multiplexing/de-multiplexing may reside at the macro cell BS.

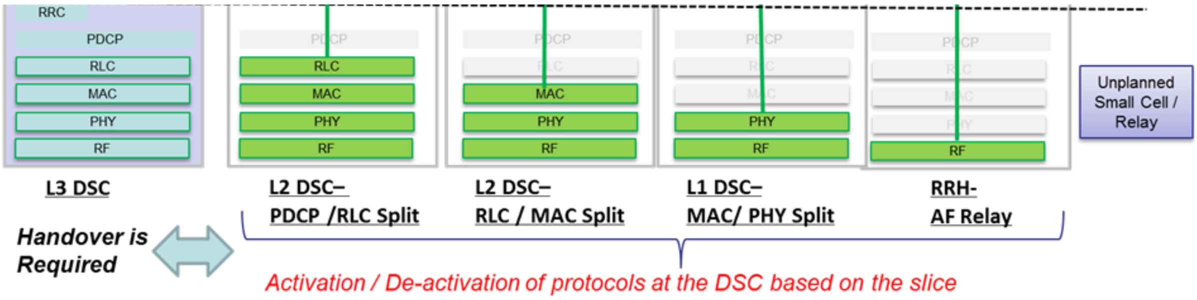


Figure 4-19: Example illustration of various functional operations/modes at DSC

This enabler is part of the 5G-MoNArch enabling innovation Inter-slice control and management. It targets the identified Gap #3 (The functional operation of small cell networks is fixed) and Gap #6 (E2E cross-slice optimisation not fully supported), cf. Table 2-1.

Position in 5G-MoNArch architecture

The mode selection can be based on a **dynamic RAN control unit** which can be located at the donor BS (e.g., CU) to which the wireless backhaul link connection is established. It is worth noting that the dynamic RAN control unit can take into account the information and/or commands provided by the slow Inter-slice RRM App in the controller layer (see Figure 3-6 and Figure 3-7). Such a control functionality can be considered as an extension to RRC protocol layer, as highlighted in Section 3.3.1. In addition, network slicing management functions (e.g., Cross-slice M&O function) can also be considered, which are responsible from RAN configuration. An example operation is depicted by a MSC in Figure 4-20.

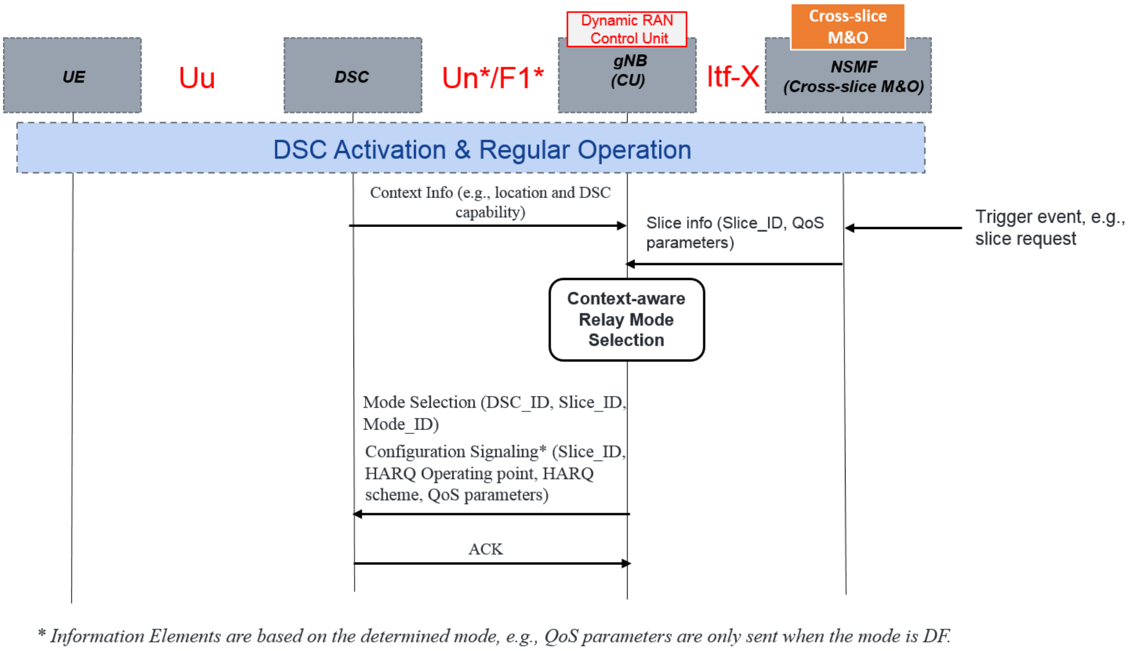

UE
Uu
DSC
Un*/F1*
Dynamic RAN Control Unit
gNB (CU)
Itf-X
Cross-slice M&O
NSMF (Cross-slice M&O)
DSC Activation & Regular Operation
Context Info (e.g., location and DSC capability)
Slice info (Slice_ID, QoS parameters)
Trigger event, e.g., slice request
Context-aware Relay Mode Selection
Mode Selection (DSC_ID, Slice_ID, Mode_ID)
Configuration Signaling* (Slice_ID, HARQ Operating point, HARQ scheme, QoS parameters)
ACK
* Information Elements are based on the determined mode, e.g., QoS parameters are only sent when the mode is DF.

Figure 4-20: Message sequence chart for the operation of the context-aware relay mode selection

Evaluation and analyses

The evaluation of this enabler will comprise a joint optimisation of the achievable data rate and the induced protocol processing delays considering different relaying modes and the location of the DSC in a macro cell. For the protocol processing delays existing standard specifications are to be utilised, e.g., LTE-A, and NR depending on the availability of the ongoing specifications. Accordingly, the overall performances of the different modes can be compared with the network slice requirements and the selection of the relaying mode can be justified. Such and similar evaluations will be presented in the final deliverable D2.3.

4.3.3 Slice-aware RAT selection

Concept

Network slicing enables to tailor a network instance to the specific requirements of a future 5G service. In this context, RRM will be a complex task, because the 5G network will integrate different RATs, each one with its specific characteristics in terms of e.g. coverage and capacity (see Figure 4-21). The appropriate configuration of the RAT and the management of the associated resources is a challenging task, when considering the heterogeneous requirements of the diverse 5G services.

In LTE system, cell range expansion has been used as a way to offload traffic from macro cells to small cells and boost the network capacity [ONY+11]. The concept foresees a similar scheme to balance traffic across multiple RATs, where biased received powers related to different RATs are compared at the UEs in order to select the most appropriated RAT to use.

In LTE, the same bias is used at different UEs to compare the received powers and associate to a nearby small cell or the macro cell, accordingly. However, although some UEs may benefit of the improved capacity offered by small cells, other UEs may rather require reliable coverage, offered by the macro cell signal. In addition, when considering millimetre-wave (mmW) small cells in future 5G networks it is of paramount importance to take into account their propagation characteristics, high path loss and sensibility to blockages, which can be detrimental for the user performance. This is particularly true for URLLC and Vehicle to Everything (V2X) communications. Therefore, this study focuses on Gap #5 of Table 2-1.

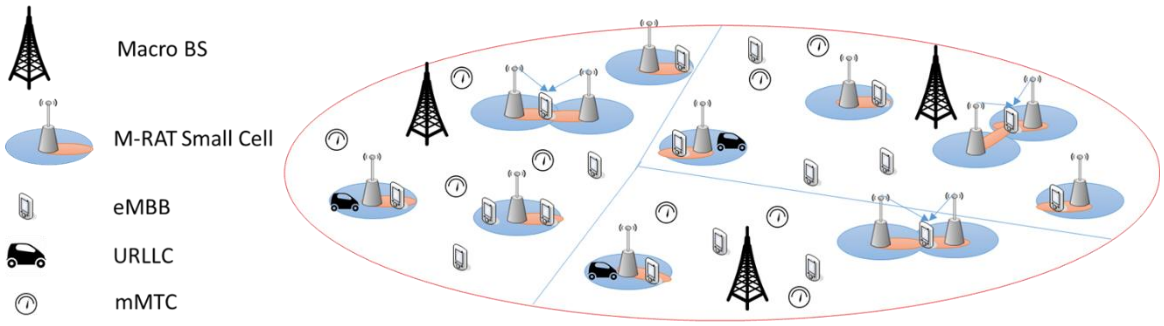
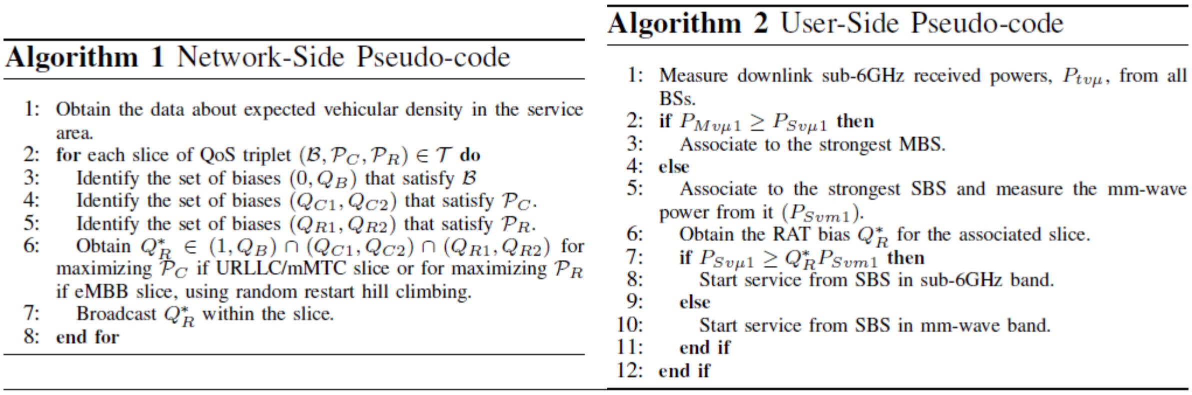


Figure 4-21: 5G multi-RAT deployment for heterogeneous service provisioning

An exemplary pseudo code for the implementation of the proposed approach is shown in Figure 4-22. In this example, with consider a multi RAT network deploying, eMBB, URLLC, and mMTC slides, each one characterised by different constraints in terms of SINR ($\boldsymbol{P_C}$) and data rate ($\boldsymbol{P_R}$) distribution, as well as for blocking probability. Based on context-aware related information (network deployment density, user density, and vehicle traffic in the area), the CU computes, by using stochastic geometry [GDC18] tools, the value of the RAT selection biases that satisfy these constraints, and then selects the appropriate slice-related bias accordingly. The bias is the transferred to the end users attached to each slice, and finally used to connect to the optimal RAT.



Algorithm 1 Network-Side Pseudo-code

```
Obtain the data about expected vehicular density in the service area.
for each slice of QoS triplet $(\mathcal{B}, \mathcal{P}_C, \mathcal{P}_R) \in \mathcal{T}$ do
    Identify the set of biases $(0, Q_B)$ that satisfy $\mathcal{B}$
    Identify the set of biases $(Q_{C1}, Q_{C2})$ that satisfy $\mathcal{P}_C$.
    Identify the set of biases $(Q_{R1}, Q_{R2})$ that satisfy $\mathcal{P}_R$.
    Obtain $Q_R^* \in (1, Q_B) \cap (Q_{C1}, Q_{C2}) \cap (Q_{R1}, Q_{R2})$ for maximizing $\mathcal{P}_C$ if URLLC/mMTC slice or for maximizing $\mathcal{P}_R$ if eMBB slice, using random restart hill climbing.
    Broadcast $Q_R^*$ within the slice.
end for
```

Algorithm 2 User-Side Pseudo-code

```
Measure downlink sub-6GHz received powers, $P_{tv\mu}$, from all BSs.
if $P_{Mv\mu 1} \geq P_{Sv\mu 1}$ then
    Associate to the strongest MBS.
else
    Associate to the strongest SBS and measure the mm-wave power from it $(P_{Svm1})$.
    Obtain the RAT bias $Q_R^*$ for the associated slice.
    if $P_{Sv\mu 1} \geq Q_R^* P_{Svm1}$ then
        Start service from SBS in sub-6GHz band.
    else
        Start service from SBS in mm-wave band.
    end if
end if
```

Figure 4-22: Slice-aware RAT selection pseudo-codes

Position in 5G-MoNArch architecture

A shared NF located at CUISC is defined, which will control the load balancing and the user association in the RAN, such that the slice requirements are taken into account. Such a control functionality can be considered as an extension to RRC protocol layer, as highlighted in Section 3.3.1. The slice related network requirements are signalled to the CU from the M&O layer, through an interface that is currently under definition in 5G-MoNArch. The MSC of the proposed solution is shown in Figure 4-23.

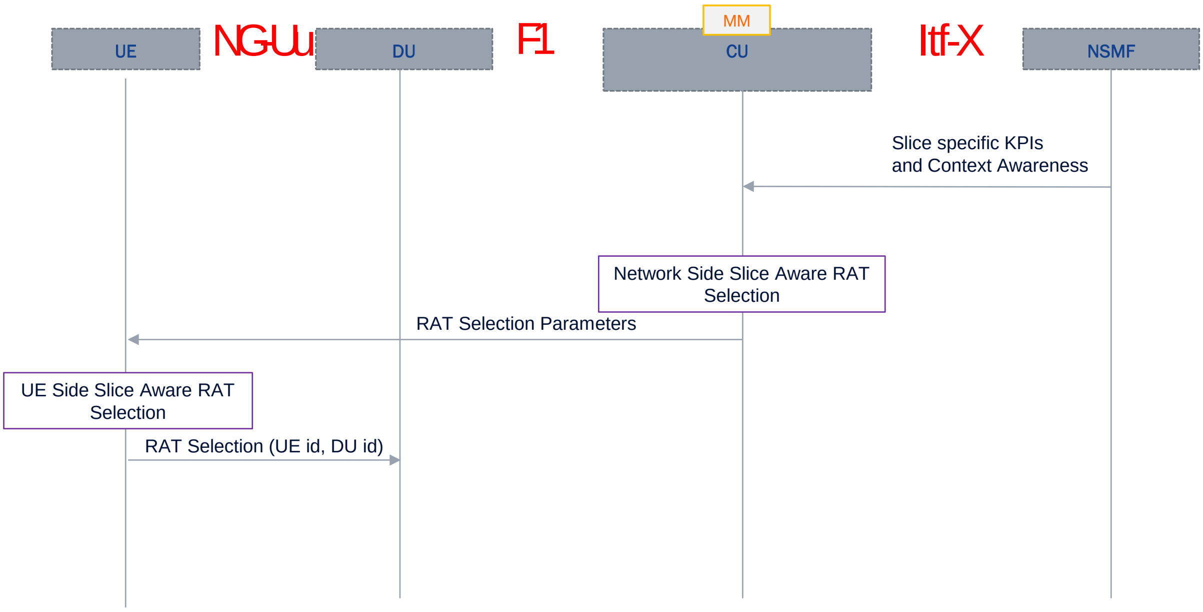

UE
NGUu
DU
F1
MM
CU
Itf-X
NSMF
Slice specific KPIs and Context Awareness
Network Side Slice Aware RAT Selection
RAT Selection Parameters
UE Side Slice Aware RAT Selection
RAT Selection (UE id, DU id)

Figure 4-23: Proposed slice-aware RAT selection mechanism

4.3.4 Inter-slice RRM using the SDN framework

Concept

In order to realise the concept of network slicing, it is important to design and validate an appropriate RRM strategy to share stringent radio resources between slices that have different SLAs. There is a lack of propositions in the current literature for enabling such strategies in the SDN/NFV driven 5G architecture (Gap #12, cf. Table 2-1). The inter-slice RRM strategy in the 5G-MoNArch architecture needs to consider the two layers of control, i.e., Controller layer and M&O layer and needs to identify and separate the strategical decisions to be deployed in those layers. As an example, the RRM decisions between slices deployed in the same domain can be from the Controller layer and those across different domains need to be from the M&O layer. The advantage of SDN such as E2E network abstraction, programmable user plane and centralised control plane benefits mobile network architecture by designing and deploying applications/algorithms that can control/manage stringent resources from the centralised vantage point. The adaptability of such solutions into mobile network infrastructure requires further study, especially on the extension of functions, protocols and algorithms for performance improvement (to address Gap #5).

The proposed inter-slice RRM approach as depicted in Figure 4-24 is a cross layer optimisation technique to improve the overall utilisation of radio resource between slices by considering SLAs of slices, current back-haul network latency, current radio resource usage and RLC buffer status information. In this framework, the proposed approach is the “slow inter-slice RRM” approach in addition to the fast-inter-slice RRM approach typically in the Network layer. This is due to the fact that it is impossible for the SDN controller to interact with the RAN scheduler for every scheduling period (~1ms) with new optimised parameters (latency in communication and processing). In summary, the proposed approach is the cross layer as well as two level inter-slice RRM technique.

Position in 5G-MoNArch architecture

As shown in Figure 4-24, the Inter-Slice RRM can be deployed as NB application on top of the controller framework in the 5G-MoNArch architecture. The controller collects matrices such as RLC buffer status, network latency and radio resource status information via SB interface and update the dynamic network topology in the controller. Inter-Slice RRM application uses that information available in the controller data-store along with SLAs of those slices under consideration by interacting with M&O layer via a dedicated interface. The MSC in Figure 4-13 explains the interaction between various functions during the operation of inter-slice RRM application in the SDN framework.

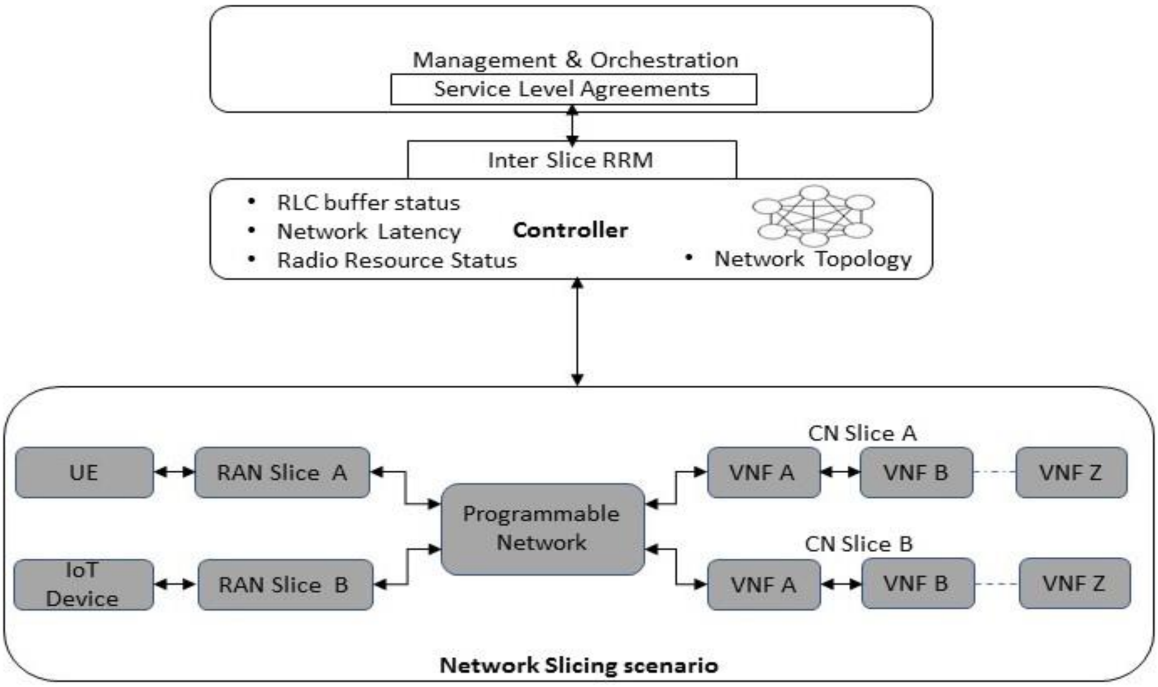


Figure 4-24: Inter-slice RRM using SDN framework

Evaluation and analysis

In this study, RRM strategy is evaluated by using SW emulators that are capable to emulate E2E mobile network managed/operated by open source SDN/NFV controllers along with commercial UEs. The user experience along with performance of the system with and without RRM strategy will be measured and compared to validate such approach.

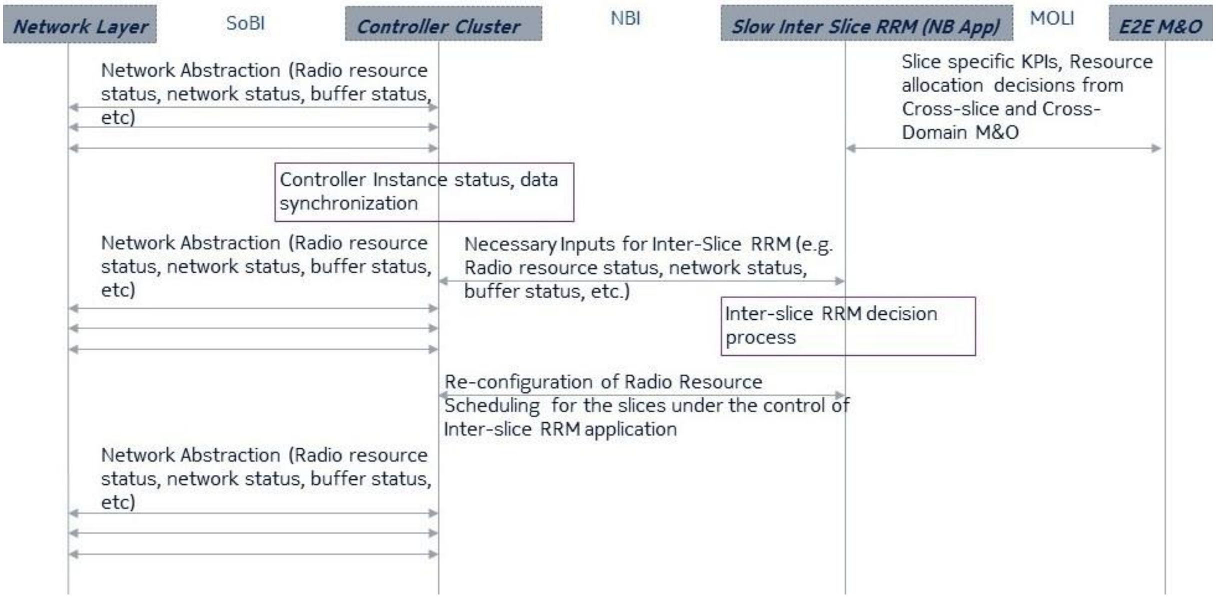

Network Layer
SoBI
Controller Cluster
NBI
Slow Inter Slice RRM (NB App)
MOLI
E2E M&O
Network Abstraction (Radio resource status, network status, buffer status, etc)
Slice specific KPIs, Resource allocation decisions from Cross-slice and Cross-Domain M&O
Controller Instance status, data synchronization
Network Abstraction (Radio resource status, network status, buffer status, etc)
Necessary Inputs for Inter-Slice RRM (e.g. Radio resource status, network status, buffer status, etc.)
Inter-slice RRM decision process
Re-configuration of Radio Resource Scheduling for the slices under the control of Inter-slice RRM application
Network Abstraction (Radio resource status, network status, buffer status, etc)

Figure 4-25: Message sequence chart of the proposed inter-slice RRM using SDN framework

4.3.5 Big data analytics for resource assignment

Concept

Chapter 3 described an overall architecture for instantiating multiple network slices, along some possible optimisations of the interactions among the functions in a VNF chain. However, when setting up a slice without stringent service requirements, one of the key desired features will be that of elasticity; this is needed in all cases where resource overprovisioning is not a valid option either due to the actual resource availability (e.g., in the edge of the network) or due to the dynamic nature of network load, which makes an efficient network slice dimensioning difficult. In those cases, temporal and spatial traffic fluctuations may require that the network dimensions resources such that, in case of peak demands, the network adapts its operation and re-distributes available resources as needed.

These load fluctuations usually characterise each slice. In this context, statistical multiplexing gains can be improved by applying elasticity to simultaneously serve multiple slices using the same set of physical resources (in conjunction with the cloud-aware protocol stack described in Section 4.1.1). This has a direct impact on the number of network slices that can be hosted within the same infrastructure and, in turn, allows to exploit complementarities across slices, yielding larger resource utilisation efficiency and high gains in network deployment investments (as long as cross-slice resource orchestration is optimally realised).

Position in 5G-MoNArch architecture

This behaviour is implemented by orchestration algorithms implemented in the Cross-slice M&O module. NFV-Os orchestrate VNFs on the available resources according to the available resources and their elasticity. For example, resources may be equally shared initially, then, in case of peak demands, the Cross-slice M&O can re-assign resources taking advantage of different distributions of loads. In this case, resources are borrowed from slices in trough load. The behaviour of the various elastic slices when the resources needed to accommodate their peak demands exceed the originally assigned ones is driven by the elastic operation.

Big Data engines can be used to perform the operation described above in an automated fashion. By studying the past load of different network slices, this engine can identify the most usual time interval and locations in which a network slice experience higher peak demands or, on the other hand, lower activities. Summarising, the foundation of this work lies in the network slice characterisation.

An accurate characterisation of traffic demands over a given area supports a more efficient planning of network resources. For example, in case of capacity-limited deployments, accurate characterisation supports a very efficient deployment of resources over time. Therefore, this kind of analysis will be beneficial also for the economic feasibility of multi service deployments. As depicted in Figure 4-26, the resource assignment procedure takes into account inputs coming from data monitoring modules deployed in the core network (such as the NWDAF).

Evaluation and analyses

The evaluation performed for this activity will be performed in two steps. Firstly, using a large-scale dataset, the activity patterns of different network slices will be evaluated, identifying possible complementarities in the load they impose on the network. Besides the network metrics, also other metrics such as cloud resources consumption and the related costs will be evaluated. Secondly, based on these finding, it will be assessed what would be the needed interfaces towards the orchestration and the network control layers that a Big Data driven resource assignment algorithm needs.

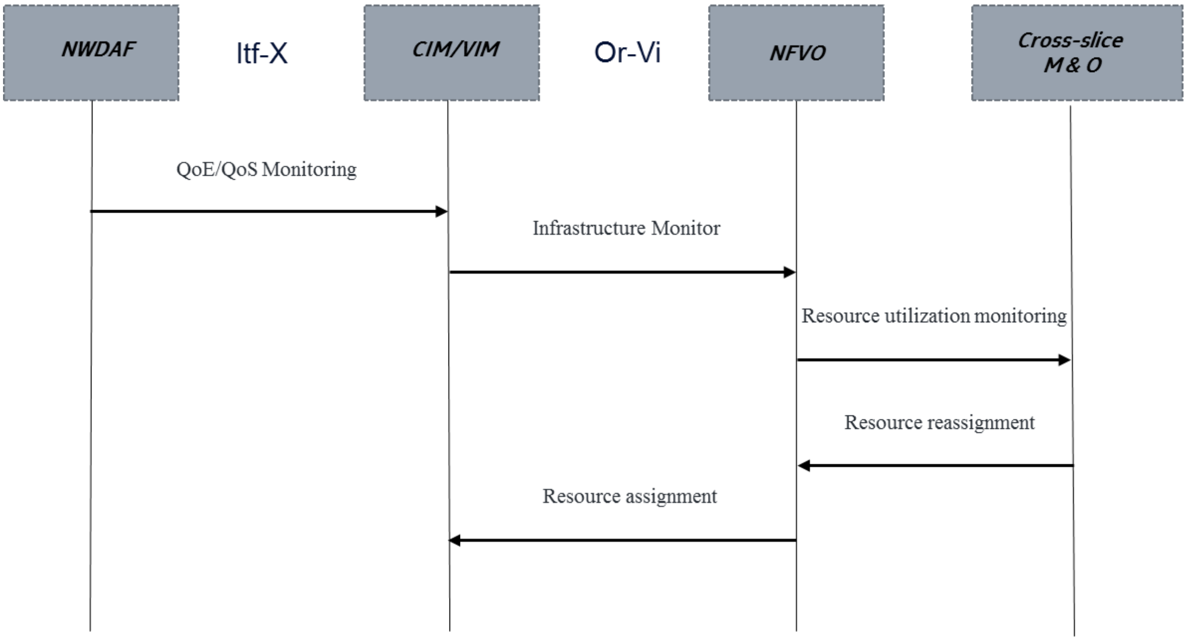


Figure 4-26: Big data resource assignment operation

4.4 *Inter-slice Management & Orchestration*

This section describes the two general frameworks for slice admission control and cross-slice congestion control. Both cover the phase of setting up and commissioning a new network slice instance and therefore are closely related. Further, a concrete implementation for slice admission control using genetic optimisers is presented. Moreover, Section 5.2 depicts how the slice congestion control is executed within the 5G-MoNArch architecture for deploying multi-slice networks.

4.4.1 Framework for slice admission control

Concept

The emerging technology of network slicing in 5G networks provides opportunities for new business by enabling multi-tenancy support. But this emerging technology introduces new technical challenges, since novel resource allocation methods must be developed to accommodate different business models. Specifically, infrastructure providers must implement new admission control policies in order to decide on network slices requests based on different SLAs. This section presents a *Framework for slice admission control* that will render the slice admission procedure easier, by analysing the available infrastructure resources and their remaining capacity for the accommodation of a new slice. The ultimate goal is the answer to the question: "*Can a new slice be served efficiently using the current resources?*". The proposed method differs from the approach proposed in Section 4.4.3, in that it uses an existing enabler proposed in WP4, namely the *Multi-objective Resource Orchestration* enabler, instead of a genetic optimiser as proposed in Section 4.4.3.

The implementation of slice admission control must ensure that after the admission of a new NSI, the resource allocation methods can optimise the network utilisation while also meeting the SLAs of each NSI. Towards this end, multiple factors must be taken into account, such as: slice SLA constraints, service requirements per slice, demand of the slices, computational resources, and requested demand for the new slice. The architectural diagram of the proposed approach is shown in Figure 4-27**.** Given the aforementioned factors as input, as well as a resource orchestration module (developed in the context of WP4), the framework decides if the new NSI can be deployed or not.

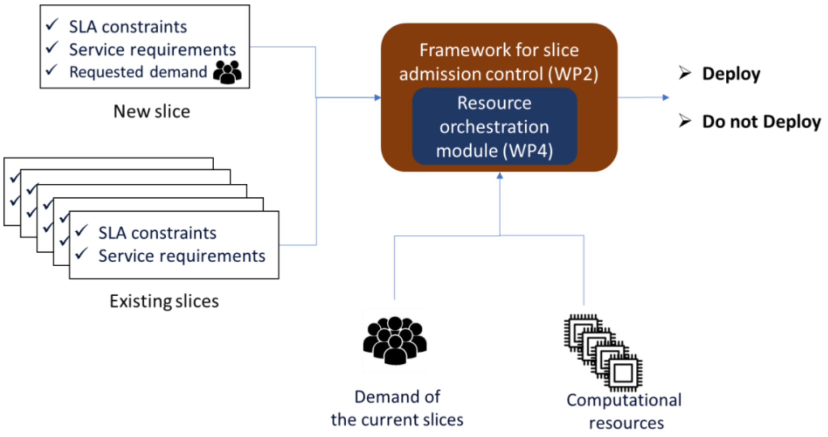
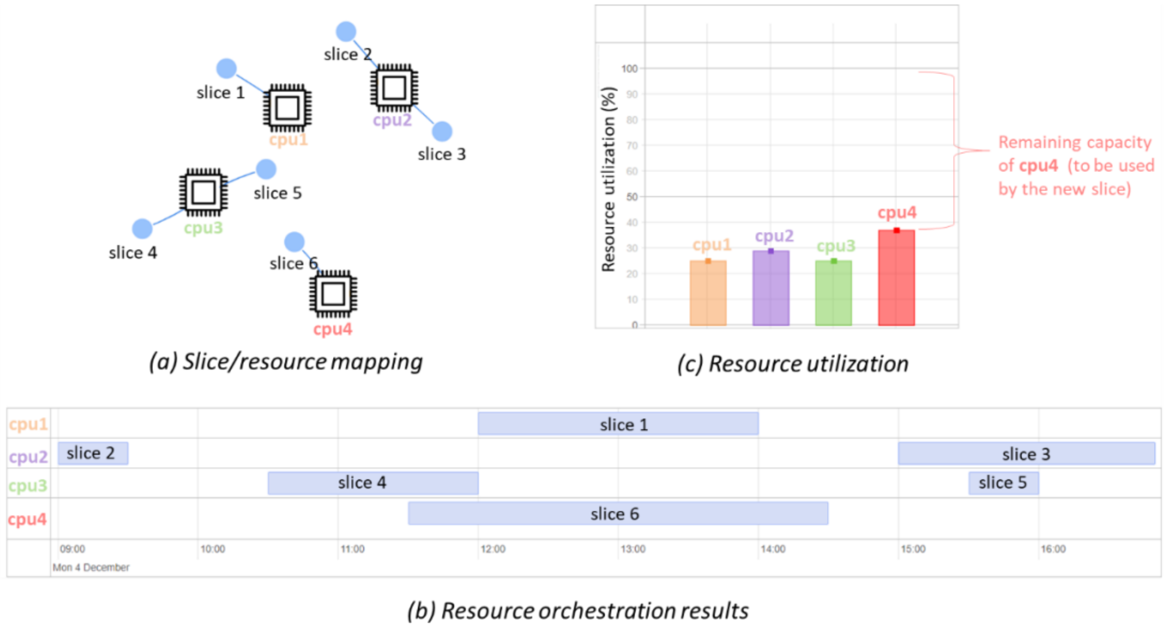


Figure 4-27: The architectural diagram of the proposed framework for slice admission control

Figure 4-28 shows the details of the proposed Framework for slice admission control. It should be noted that Figure 4-28 is just an example of how the propose method will work. Actual evaluation results and the setup used for the implementation will be provided in D2.3. For simplicity of presentation, and without loss of generality, only the computational resources are considered in this figure, illustrated by cpu1-4. Specifically, for the specified period of time (e.g. 09:00 to 17:00 on 4 Dec) each slice is executed on a subset of the computational resources (in this case only one CPU), as decided by the resource orchestration algorithm. The mapping of the slices to the computational resources without considering the exact time in which they are executed is shown in Figure 4-28(a) in a graph form, i.e., slices 2 and 3 are executed on cpu2, and thus connected by an edge. Figure 4-28(b) presents the actual mapping of the slices to the computational resources over time as computed by the resource orchestration algorithm, i.e., slices 2 and 3 are executed on cpu2 from 9:00-9:30 and from 15:30-16:00 respectively. Finally, Figure 4-2828(c) illustrates the resource utilisation for each computational resource, and the remaining capacity that can be utilised by the new slice. All the resources are less than 50% occupied, and given the resource demand of the new NSI (e.g. 20% CPU power) there is enough remaining capacity to accommodate its efficient deployment.



(a) Slice/resource mapping

(c) Resource utilization

(b) Resource orchestration results

Figure 4-28: Example analysis of the capacity of the computational resources and their availability to accommodate a new slice instance

Position in 5G-MoNArch architecture

The “Framework for slice admission control” will use as part of the method a resource orchestration module proposed in WP4. Specifically, the resource orchestration module will be utilised in order to identify how much of the resources are utilised by the current slices and how many resources are free on average, so as to take the decision of if the new slice can be served efficiently using the current resources. This means that the "Framework for slice admission control" will be implemented at the orchestrator level, and in particular in the CROSS S.SOMO module inside the NSMF (see Section 3.3.3), in order to manage virtual resources across different slices and make sure that the requirements of accepted slices are satisfied.

Evaluation and analyses

As mentioned in the previous paragraph, the "Framework for slice admission control" will use as part of the method a resource orchestration module proposed in WP4. Specifically, the resource orchestration module that will be used is the "Multi-objective slice-aware resource orchestration". This module takes into consideration multiple objectives in the form of KPI constraints regarding either the entire network, or specific slices based on their SLAs. Thus, given a current state of the network, the resources that are on average free, and a new slice with specific requirements, the algorithm can answer the following question with a yes/no response: *Can a new slice be served efficiently using the current resources?* An example of this approach is provided in Figure 4-28. Actual evaluation results will be presented in D2.3.

4.4.2 Framework for cross-slice congestion control

Concept

Network slicing is realised by deploying a set of VNFs requiring resources such as radio, computing, and storage resources. The Cross-slice Congestion Control (CSCC) function shown in Figure 4-29 is responsible of accepting or dropping a new slice request by controlling resource availability, slice priorities, and queue state.

The CSCC may decide, based on the service level requirements of a class, to scale down the allocated resources to one or multiples slices in order to accept a larger number of requests, which have high priority. The proposed CSCC has to be able to foresee the impact of a decision on the overall system performance [PJD+15]. This intelligence is ensured by using reinforcement learning (RL) techniques that allow to make the optimal decisions maximising resources utilisation [GBL+12]. Therefore, this study focuses on Gaps #5, #6, and #12, cf. Table 2-1.

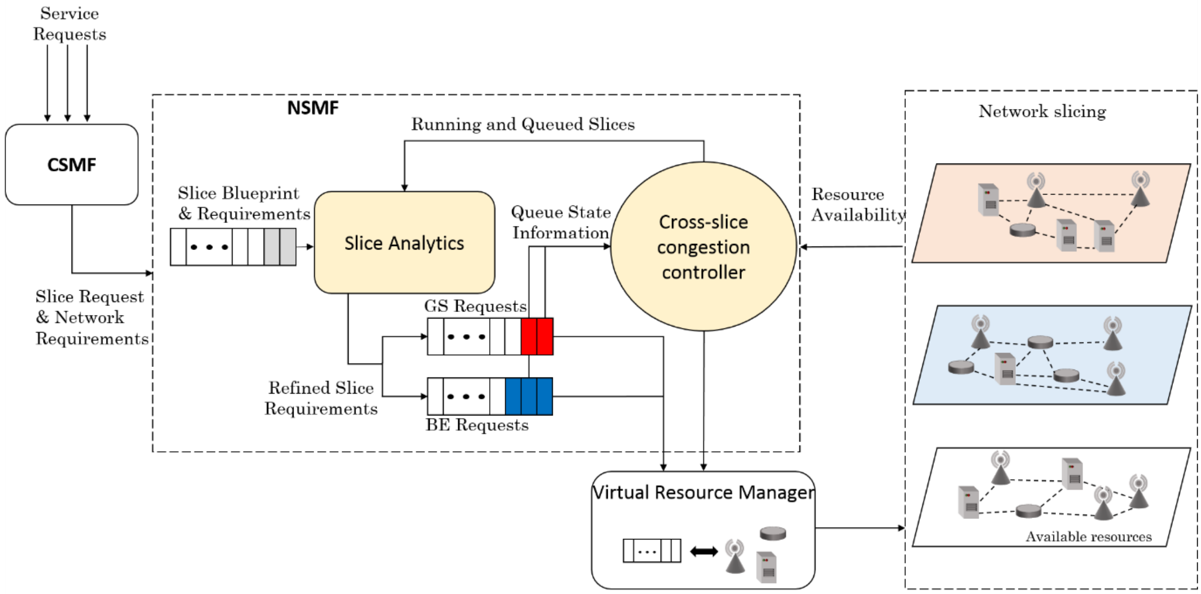


Figure 4-29: Proposed Cross-slice Admission and Congestion Control framework

Position in 5G-MoNArch architecture

The CSCC will be implemented at the orchestrator level, and in particular in the CROSS S. SOMO module inside the NSMF (cf. Section 3.3.3.2) as it enables to manage virtual resources across different slices such that the overall resource utilisation efficiency is maximised, dropped slices are minimised, and the requirements of accepted slices are satisfied. For more details on its implementation in the 5G-MonArch architecture, see Section 5.2.3.

Evaluation and analyses

At this stage, two slice classes are defined: best effort (BE) and guaranteed service (GS). In order to prioritise the deployment of GS requests, a higher reward is assigned for accepting their requests. It is important to note also that negative rewards will be considered when dropping a GS request so that the policy is pushed toward deploying more GS requests rather than BE slices. In this first study Q-learning is used to learn to optimal strategy to implement at the CSCC [GBL+12]. In the future months, more complex algorithms will be implemented that can take into account more realistic environment. In the results shown in Figure 4-30, the proposed solution is compared with a greedy policy in term of accepted and dropped slice requests. The results show that the proposed solution is able to improve the resource utilisation enabling to increase the percentage of accepted slice request without negatively affecting the performance at the GS slices.

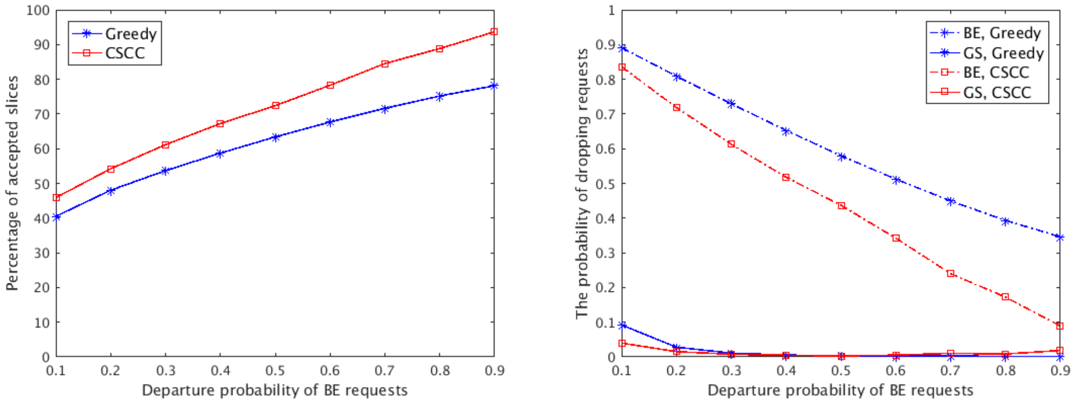


Figure 4-30: Percentage of accepted slices for Greedy and the proposed QL-based CSCC as a function of BE departure probability (left), and dropping probability for Greedy and QL-based CSCC as a function of BE departure probability (right)

4.4.3 Slice admission control using genetic optimisers

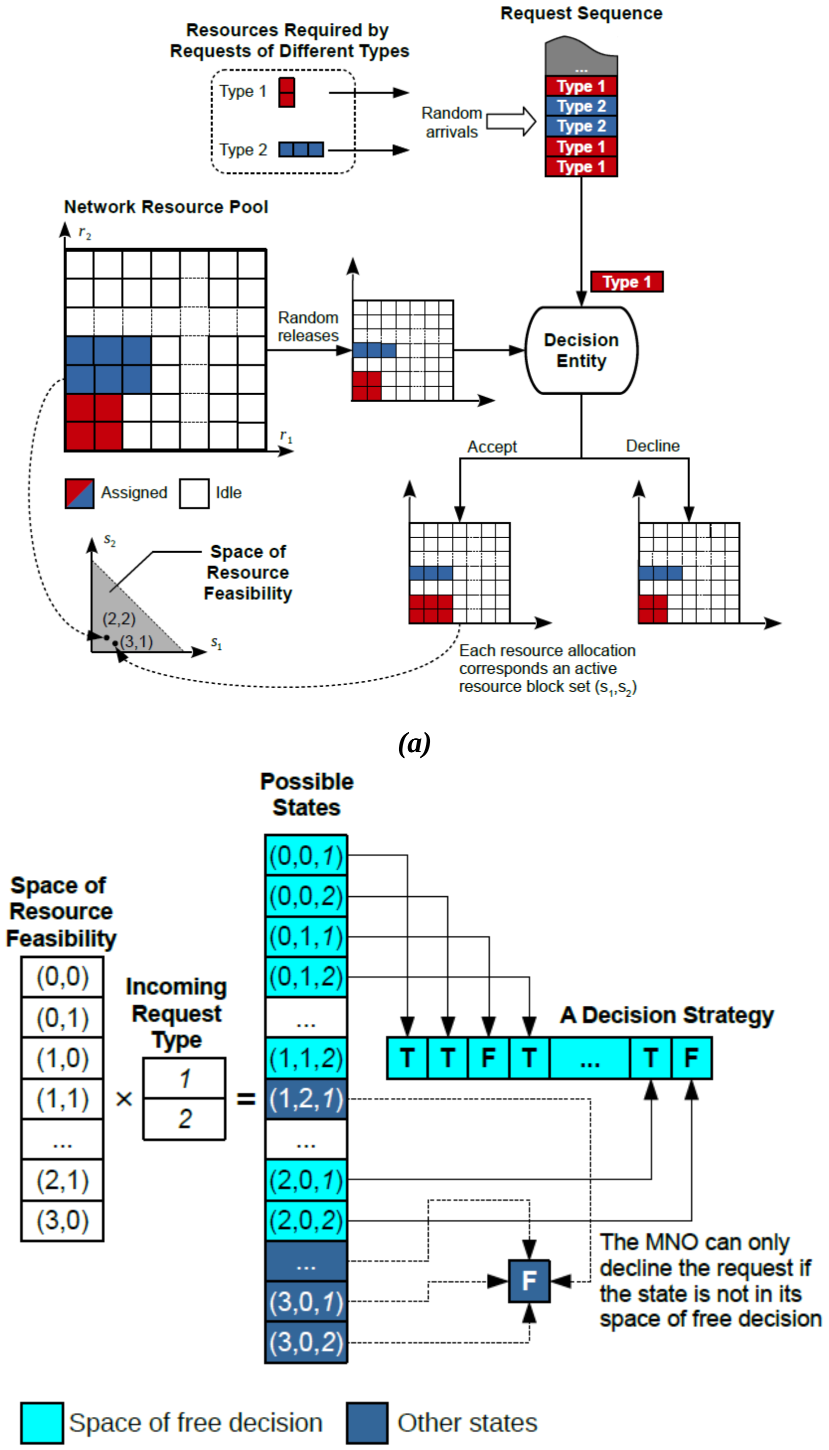
Concept

Inter-Slice Control Based on Tenant Request and Binary Decision:

As a specific form of public cloud service in context of sliced 5G telecommunication networks, Slice-as-a-Service (SlaaS) improves the sharing efficiency and the resource utilisation rate. Generally, network resources (both physical and logical) are bundled by the MNO into slices of different predefined types. Depending on the slice type, different slices have various utility efficiencies and periodical payments. Tenants can propose requests to create new slices upon their specific demands for network resources. The MNO, according to its current idle resource pool and the network's overall utility statistics, makes an individual binary decision to every arriving request, i.e. if to accept or to decline the request. Once a request is accepted, a new slice will be created to serve the requesting tenant. The corresponding portion of network resources remain occupied to maintain the created slice, until the service level agreement (SLA) is terminated and the network slice is released. The mechanism is briefly summarised in Figure 4-31(a).

Concept and Optimisation of Admission Decision Strategy:

A consistent decision strategy is defined as a binary decision function $d = (\mathbf{s}, n)$, where $\mathbf{s}$ is the set of current reserved resource bundles for active slices under maintenance, and n denotes the type of requested resource bundle. d=0 means the MNO will decline the request, and $d = 1$ stands for acceptance. By adjusting the decision strategy, the MNO is able to statistically optimise the overall utility rate of the entire network in long term. Every consistent decision strategy can be encoded into a binary sequence, where every bit represents the decision that the MNO can freely make, given a certain combination of current network resource pool status and incoming request. An example design of such encoders is illustrated in Figure 4-31(b).



(a)

(b)

Figure 4-31: Inter-slice control based on requests and binary decisions:
(a) the admission and resource allocation mechanism; (b) a codec design for decision strategies

Mechanisms to Handle Declined Requests

Declines to requests can be caused by two different kind of reasons: 1) hard constraint of the MNO's resource pool; and 2) low estimated utility rate (especially revenue rate) of the requested slice with respect to the opportunity cost (the utility of slices that may potentially be created in the future with the network resources required by the current request).

In the first case, it is impossible to immediately satisfy the tenant's demand without upgrading the resource pool. To mitigate rejecting the tenant and therefore losing the client, the MNO can offer a delayed service. Possible approaches to implement this include:

- A random delay protocol where the tenant resends its declined request after a random delay (similar to the random-access procedure in RAN);
- A queuing mechanism where the declined requests are buffered in a queue (or a pool) to wait for released resources.

In the second case, besides the delayed service, a bidding mechanism can be integrated where a tenant can keep increasing the payment it offers for the requested slice until it exceeds an upper bound or eventually gets accepted by the MNO.

Position in 5G-MoNArch architecture

The Genetic Slice Admission Control particularly affects the 5G-MoNArch M&O layer. The overall procedure involves the NFV MANO functions, Cross-slice M&O function within NSMF, XSC in the Controller layer as well as BSS functions, applications, and services of the Service layer. The call flow for slice admission control using genetic optimisation is depicted in.

Evaluation and analyses

A genetic method is proposed, where each feasible slicing strategy is encoded to a binary sequence. A population of randomly generated strategies are initialised and parallel evaluated in real-time with respect to their long-term network utility rate. A genetic algorithm (GA), which includes the three steps of reproduction, crossover and mutation, then applies to the current population, so that a new generation of candidate strategies will be created. This process runs in iterations so that the entire population evolves to a good set of strategies with high utility rates, and the best strategy in the population approaches to the global optimum through a winding process. The overall procedure is illustrated in Figure 4-32 Figure 4-33. The proposed method is model-free, can be flexibly applied to different (and even heterogeneous) constructions of utility function. It was verified to be effective, fast-converging and robust against inconsistent environment. Figure 4-34 shows the performance evolution of the entire population of strategies. Figure 4-35 shows the performance of the best (deployed) candidate in non-consistent network traffic scenario, three "naïve" strategies and a static optimum are also tested as benchmark. More details about the proposed method, the simulation design, more evaluation results, and further analysis can be found in [HJS18].

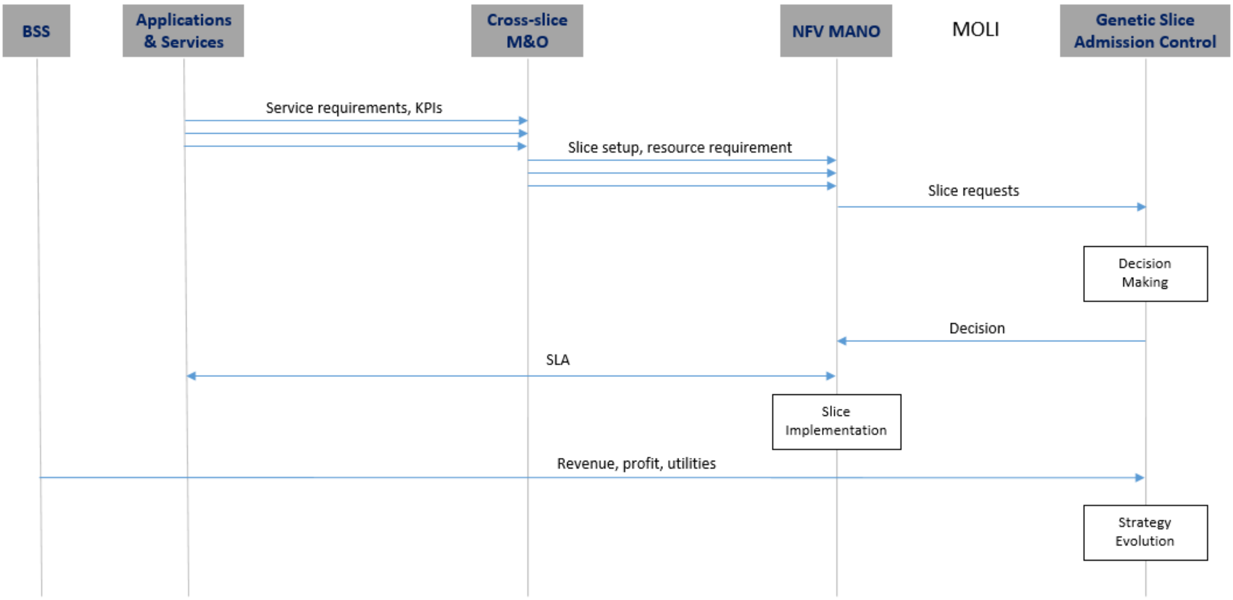


Figure 4-32: Message flow chart of deploying genetic slice admission control

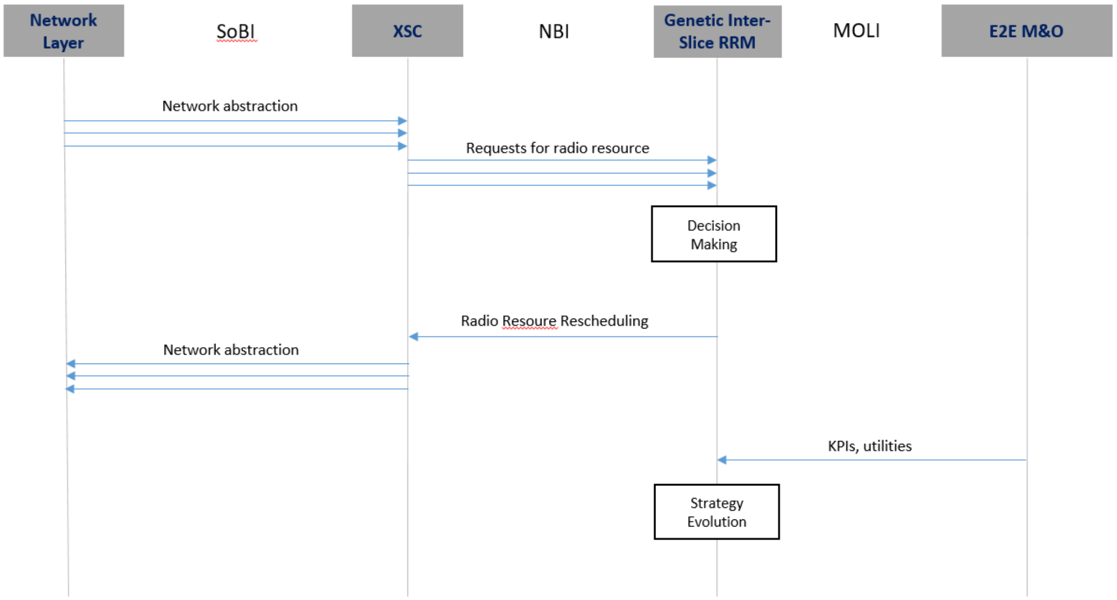


Figure 4-33: Message flow chart of deploying genetic inter-slice RRM

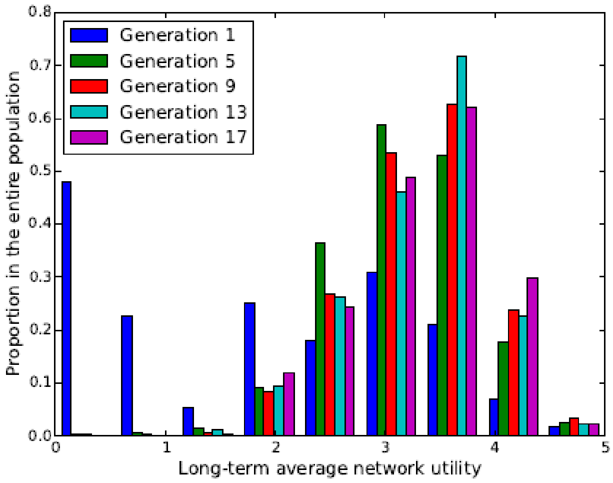


Figure 4-34: A population of 50 randomly selected slicing strategies evolves over 17 generations

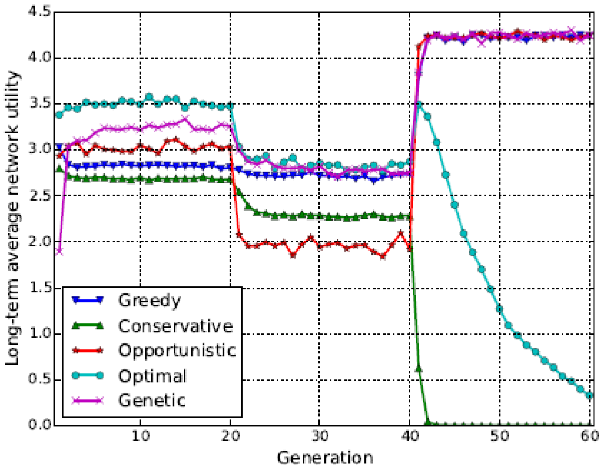


Figure 4-35: Proposed genetic optimiser remains on an almost-optimal performance level in inconsistent service environment, outperforming all "naïve" benchmarks and the static reference optimum

4.5 *Experiment-driven optimisation*

Experimental optimisation is one of the key elements in the designing and implementation of the next generation of mobile networks. Having different functionalities being virtualised the cloud infrastructure providers have to develop an experimental procedure to be able to meet the QoS requirements of each VNF optimally. Scaling and elasticity decisions (either vertical or horizontal) cannot be made without having a practical experimental optimisation approach. Experiment-driven optimisation is enabled through measurement campaigns (i.e., a monitoring process). The measurements from these campaigns feed a modelling procedure, which models the VNF behaviour regarding their computational, storage and networking resource demands. The resulted models may facilitate the overall resource management of the cloud infrastructure. Algorithms and functions that apply upon the 5G protocol stack can improve their performance by exploiting experiment-driven insights and, thus, taking more intelligent decisions. In contrast to importance of this issue, it was not the focus of many studies so far. In this context, the experiment-driven modelling and optimisation is a key innovation enabler for the 5G-MoNArch project filling the current gap on experiment-based E2E resource management for VNFs. However, it is expected that all 5G-MoNArch innovations can benefit from the experiment-driven modelling and optimisation; therefore, this innovation element can be inter-related to all other identified gaps (listed in Table 2-1). From a more general perspective, the innovation element mentioned above brings a new paradigm in network management and orchestration. The two other enablers of the project (telco-cloud-enabled protocol stack and inter-slice control & management) as well as the functional innovations of the project (resource elasticity, resilience) are fed and optimised with experiment-based inputs. That is, the orchestration can be tailored with very accurate models of the real VNF consumption in terms of CPU.

4.5.1 ML-based optimisation using an extended FlexRAN implementation

The aim of this experimental optimisation is to develop a Machine Learning (ML) based approach to manage the network functions, which are virtualised and implemented on the Commercial Off-The-Shelf (COTS) computers or data-centres. The two main steps are (i) profiling the network function computational complexity in bare-metal (i.e., without virtualisation) and container-based environment (since containers have relatively lower computational overhead and are more suitable for VNF in RAN with tight processing delay budget), (ii) developing ML agent(s) optimising the network based on the real-time reports and measurement.

Step 1 - Profiling of bare-metal container-based implementation of RAN:

Studying the complexity of RAN network complexity in terms of processing time is the focus of this step. The OAI Software Alliance [OAI] provides a comprehensive development environment for software defined radio incorporating concepts such as SDN and NFV. The intention of the OAI project is the development of a fully real-time 5G protocol stack for running on COTS hardware using open source software.

The processing time for functional blocks of PHY layer given different load configurations, the number of PRBs and MCS is measured. The same profiling profile in the next step extended for the FLexRAN branch, an example implementation and extension of an interface between CU and DU [3GPP TS 38.211]. FlexRAN [FNK+16] is an open source project that provides a flexible and extensible SDN-based RAN platform as a reference platform for researchers and developers. For that purpose, the framework basically extends the OAI implementation with SDN functionality

It provides an extensible framework for SDN-based RAN concepts that are well in line with the proposed 5G-MoNArch architecture introducing a controller, such as XSC/ISC. The second part of the performance study addresses an initial evaluation of the impact of containerisation of OAI eNBs with Docker [Doc].

Evaluation and development environment

The performed profiling is based on OAI emulator to measure the processing time of the LTE PHY layer given different load configurations, the number of PRBs and MCS. The used physical machine for profiling experimentation has an Intel® Core™ i7-4790 CPU @ 3.60GHz and 16 GB RAM. The machine is operated using Kubuntu 16.04 LTS with Kernel version 4.4.0-96 generic. Virtualisation is conducted using docker 17.06.1-ce. The CPU above has 4 physical cores and 8 logical threads. The processor also has 8 MB of Cache Memory and supports instruction set extensions SSE4.1/4.2, AVX 2.0.

Also, to measure the gain introduced by utilising AVX 2.0 instruction set, brief experimentations on a bare metal OS on an Intel® Core™ i7-2600 CPU @ 3.4 GHz (no AVX 2.0) are conducted and the results are compared to the primary testbed. Using AVX 2.0 instructions shows significant improvements in the individual functions and the overall processing time of the baseband unit. The results show that the utilisation of CPUs with AVX 2.0 can reduce the processing time into half. The profiling results are presentation in Section 4.1 of [5GM-D4.1].

The test setup that has been used for the FlexRAN performance study without Docker-based containerisation is shown in Figure 4-36. It consists of three computers with 4 x 4 GHz cores for evolved packet core (EPC), FlexRAN Agent (FR-A), and FlexRAN Controller (FR-C), respectively. All computers run with Ubuntu 16.04 and Linux kernel version 4.10.0-28-low-latency. The computers are interconnected via Gigabit Ethernet. The software-defined radio (SDR) device is a National Instruments USRP (Universal Software Radio Peripheral) 2944R [NI] which is connected via a ten Gigabit Ethernet connection to the computer that is running the FR-A with the embedded eNB implementation.

The ten Gigabit Ethernet connection is required to guarantee sufficient stability for the transfer of I/Q samples between eNB and USRP in both UL and downlink (DL) direction. This directly reflects the challenges faced by fronthaul implementations for lower layer splits in C-RAN architectures as discussed in detail in [ATM18]. The testbed architectures used for the performance study with Docker is shown in Figure 4-37. In this case, only one computer (Docker host) is used, and all elements of the network (eNB, MME, etc.) are running in individual Docker containers (marked as grey boxes in the figure). The results and analysis of this and further work using machine learning algorithms are comprehensively presented in [5GM-D4.1].

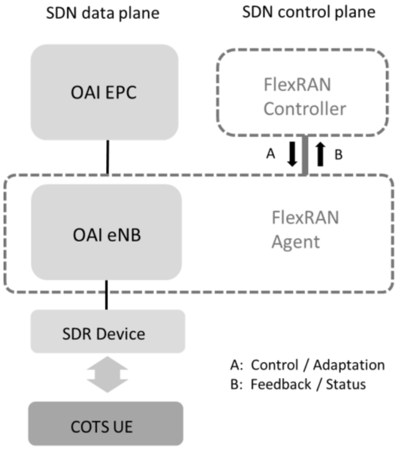


Figure 4-36: Experimental testbed based on FlexRAN

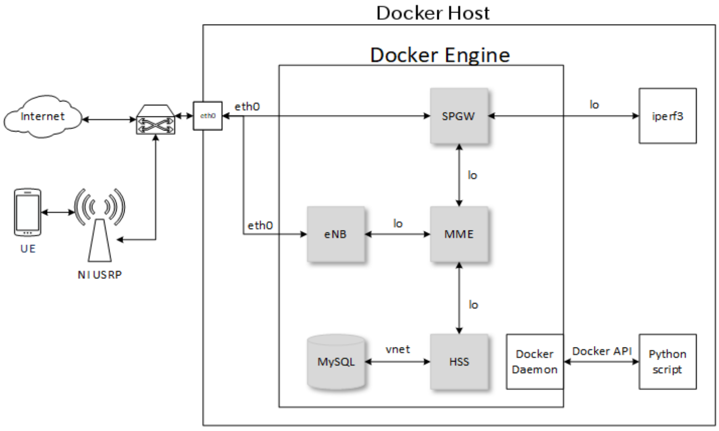


Figure 4-37: Experimental testbed for running OAI in Docker containers

Step 2: Developing Machine Learning Algorithm

In the next step, the reports and measurements from the experimental setup will be fed to the machine learning agent. The aim is to first update the models with the measurement and report on the run-time. The processing time of a specific function is highly dependent on the implementation techniques (e.g., number of memory access). Hence, the ML-based approaches are needed to adopt the complexity models of NFs to the reports and measurements. These models can be used later for optimisations and improvement of networks or used by other ML agents. In addition, ML-approaches are one of the candidate solutions for the elastic allocation of resources (radio or computational) to different network slices with different requirements.

4.5.2 Computational analysis of open source mobile network stack implementations

Experiment-driven optimisation necessarily builds on top of thorough measurements of software modules. 5G-MoNArch will use, especially for the testbeds, a mixture of open source and ad-hoc developed solutions. Therefore, some well-known implementation of the RAN: OAI [NMM+14] and srsLTE (SRS) [GGS+16] are measured.

All reported experiments are conducted using an eNB built with the Ettus USRP-B210 radio frontend boards connected using USB 3.0 to a Linux-based host computer that runs the different software suites considered. The frontend's up- and down-link interfaces are multiplexed on a single 2dB dipole antenna through an RF Diplexer compatible with LTE band 7. The host PC runs Ubuntu 16.04 and is equipped with an Intel Core i7-7700K CPU with four cores clocked at 4.2GHz, which is powered by an ASUS Z270-A motherboard and 16GB of DDR4 memory. Note that a configuration with such high computing power is required to be able to run effortlessly the different used software solutions, since baseband processing is particularly CPU expensive.

Using the configuration described above, the experiments are conducted with two types of eNB software, namely OAI version 0.6.1 and SRS version 2.0-17.09 of the srsENB application.

During the experiments, a single UE was connected to the eNB, and the radio was shielded to reduce interference. Both, CPU consumption and throughput, have been obtained with different eNB / UE configurations. Three different UEs were used: A Nexus 5 mobile phone, a Huawei USB dongle and the srsUE software.

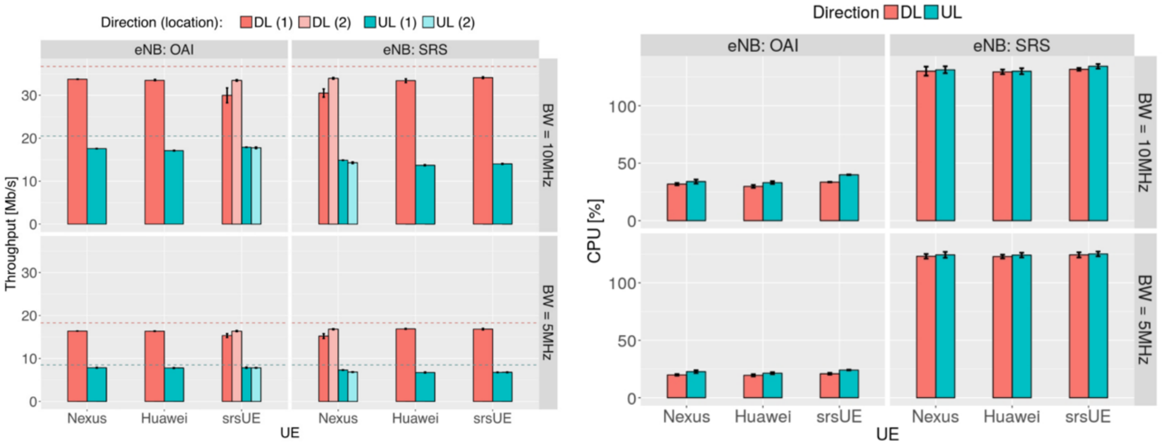


Figure 4-38: Throughput performance obtained with different eNB/UE configurations, UL/DL directions, and 5/10 MHz bandwidths (left); CPU usage at the eNB for different eNB stacks, UEs, bandwidths, and transmission directions (right)

Results are shown in Figure 4-38. While the performance obtained for the throughput are similar, srsLTE requires a much higher load for the processing. Future work will include the investigation on the causes behind this behaviour, as elasticity algorithms deployed upon these platforms may exploit different load scenarios.

4.5.3 Measurement campaigns on the performance of higher layers of the protocol stack

As has been described in [5GM-D2.1], to take advantage of the experiment-driven modelling and optimisation in a cloud enabled network, new challenges arise. A key requirement is the conduction of exhaustive measurement campaigns per VNF and per network slice that will focus on consumption of computational, storage and networking resources and considering cost-effectiveness and the special characteristics and peculiarities due to the use of commodity hardware (the key choice for the cloud-enabled networking). The focus here is on the RAN functionality and more specifically on functionality carried by protocols above the MAC layer at the gNB and UE side. To be more precise, the targeted protocols are the RRC, the PDCP and the RLC for both UP and CP.

The evaluation of such an approach can be based on the actual testbed implementations. Key target is the quantification of the computational and memory resources (CPU/RAM load) that are consumed by the higher layer protocols in the RAN protocol stack as well as to investigate the impact that a function split at the RLC level can provide in terms of delay to a provided service.

5 Architectural Extensibility and Customisation

This chapter details the identified innovation elements and network functionalities towards flexible extensibility and customisation of both network slice functionality and network infrastructure. In a first step, the chapter describes the general framework, where the 5G-MoNArch Network Slice Blueprint concept is used to design network slices incorporating customised network functions. Subsequently, it elaborates on the 5G-MoNArch Network Slice Allocation and Network Slice Congestion Control concepts to demonstrate how a single common infrastructure can efficiently host multiple network slices instances. Finally, the presented concepts are applied to the two 5G-MoNArch testbeds: For the Smart Sea Port scenario, specific network functions for resilience and security extend 'standard' URLLC and mMTC slices to be deployed on a common infrastructure in the city of Hamburg. For the Touristic City scenario, specialised network functions for resource elasticity customise typical eMBB functionality towards the requirements of interactive consumer applications.

5.1 *General means for extensibility and customisation*

In 5G-MoNArch, the Network Slice Blueprint concept is the major means to generate customised network slices that are capable of realising the performance and functional requirements of the addressed service.

GSMA recently started a work to standardise a Generic Slice Template (GST), every Network Slice can be fully described by allocating values (or ranges of values) to each relevant attribute in the GST. GSMA could also standardise some GST for specific vertical use cases.

5G-MoNArch foresees that starting from the GST, an Operator could make some more customisation to build up some more specific basic templates that take into account its own specify network deployment. In this way the Operator could have a catalogue of slice templates to start from when he has to deploy a specific NSI to meet the customer specific requirements for a network slice.

For each vertical (e.g. eMBB, URLLC) the Operator starts from the specific GST for that vertical, customise it according to the peculiarity of his network infrastructure and creates a catalogue. When a customer asks for a communication service the Operator picks the most adequate template from the catalogue and extend and customise it according to the customer specific requirements.

This process, mostly automated, lead to the concrete definition of a NSI in terms of specific configurations that are used by the M&O layer to deploy the NSI. This concrete definition of the specific NSI requested by the customers, with specific extensions and customisation, is the 5G-MoNArch Network Slice Blueprint.

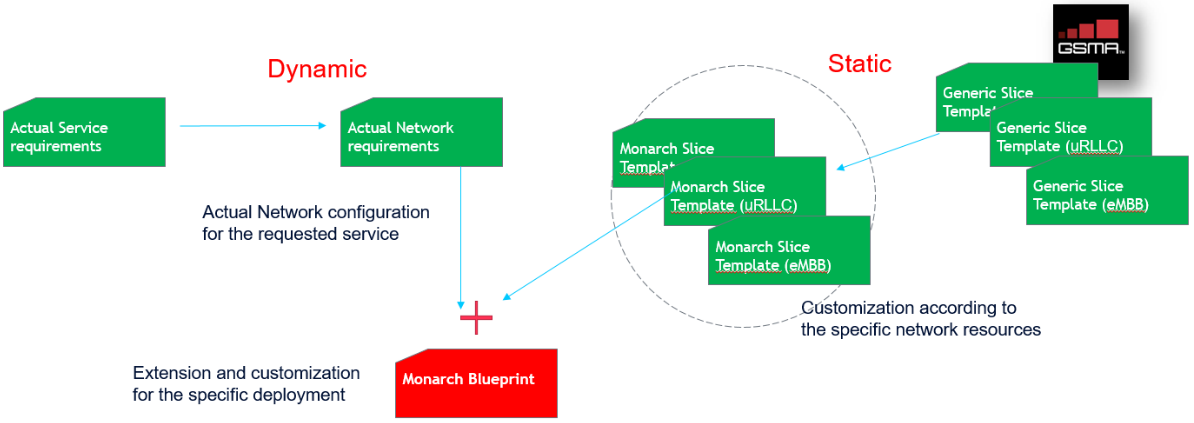

Dynamic
Static
GSMA
Actual Service requirements
Actual Network requirements
Actual Network configuration for the requested service
Monarch Slice Templat
Monarch Slice Template (uRLLC)
Monarch Slice Template (eMBB)
Generic Slice Templa
Generic Slice Template (uRLLC)
Generic Slice Template (eMBB)
Customization according to the specific network resources
Extension and customization for the specific deployment
Monarch Blueprint

Figure 5-1: 5G-MoNArch network slice blueprint for slice extensibility and customisation

5.1.1 5G-MoNArch network slice blueprint concept

The 5G-MoNArch Network Slice Blueprint defines the Network Slice Instance in terms of network functions, their interconnection and configuration according to a specific service request. The chosen approach to define 5G-MoNArch Slice Blueprint is to refer and enhance what is already defined by

SDO. Based on the SotA, a few considerations led to the definition of the 5G-MoNArch Network Slice Blueprint:

- 3GPP Network Management is well defined for release 14 but release 15 slice modelling is not yet complete and there is no clear indication on Slice modelling.
- ETSI MANO, instead, provides a consolidated documentation for the Network Service Descriptor and for the elements that compose the network service

The analysis highlighted several benefits in adopting a MANO based Slice Blueprint. First and foremost, the fact that the resulting blueprint would directly be MANO compatible. Since MANO represents a fixed point in the 5G-MoNArch architecture, this would allow to minimise the number of intermediate functions that would need to translate the 5G-MoNArch Slice Blueprint into a MANO Network Service Descriptor. The MANO model for NS description is based on a set of tables that represent the descriptor for an entity, e.g. MANO defines the Network Service Descriptor and the Virtual Network Function Descriptor. 5G-MoNArch uses the same “Descriptor” based approach for network slicing. 5G-MoNArch network slice blueprint is implemented as a collection of Descriptors (MANO style) that are tables containing all the needed information to deploy an NSI.

Because of the composition of an NSI, 5G-MoNArch Network Slice Blueprint is composed by the following descriptors:

- The NSI: it is described by the 5G-MoNArch Network Slice Descriptor (MNSD)
- The NSSI: it is described by the 5G-MoNArch Network Slice Subnet Descriptor (MNSSD)
- The NF: it is described by the 5G-MoNArch Virtual Network Function Descriptor (MVNFD)
- The connectivity: it is described using the standard define by MANO for connectivity using Virtual Link Descriptor (VLD) and VNF Forwarding Graph Descriptor (VNFGD).

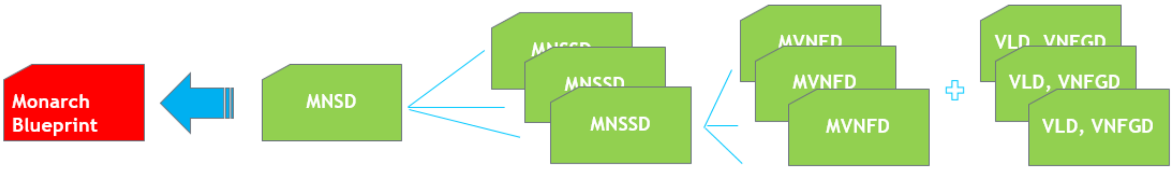


Figure 5-2: 5G-MoNArch network slice blueprint composition with descriptors

From a management point-of-view, a NSI is a collection of NSSI that are defined by the information to setup the virtualised part of the contained NFs, the configuration on the application-level of the NFs (both physical and visualised) and by the information about the connectivity among the NFs. Those are all the information needed to provide a Network Service plus the information about the configuration of the application part of the NFs.

Since the first information needed maps directly to the ETIS NFV MANO Network Service Descriptor, in 5G-MoNArch it was agreed to create the blueprint as an extension of the NSD with application-level information needed to provide the requested service. Figure 5-3 describes the idea behind the extension of the NSD with the inclusion of Application information and configuration in order to obtain a full Blueprint of the Network Slice Subnet.

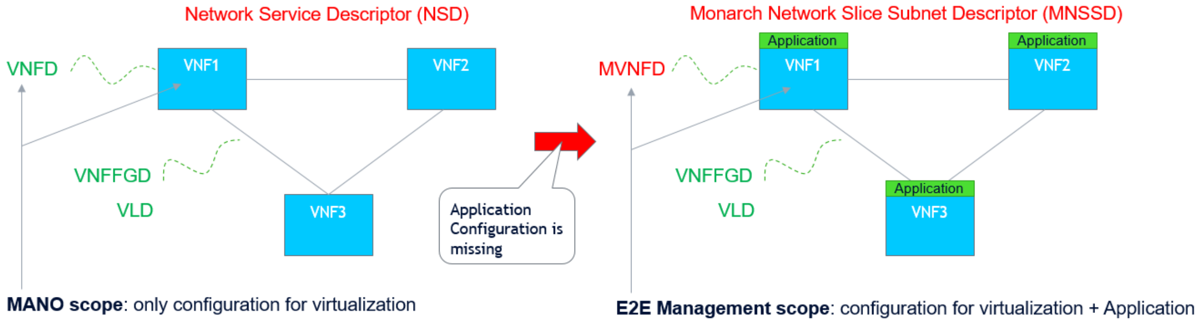

Network Service Descriptor (NSD)
VNFD
VNF1
VNF2
VNFFGD
VLD
VNF3
Application Configuration is missing
MANO scope: only configuration for virtualization
Monarch Network Slice Subnet Descriptor (MNSSD)
MVNFD
Application
VNF1
Application
VNF2
VNFFGD
VLD
Application
VNF3
E2E Management scope: configuration for virtualization + Application

Figure 5-3: Generating a mobile network slice subnet descriptor from a network service descriptor

The connectivity between network slices subnets (NSS), as shown in Figure 5-4, can be described with VNFFGD and VLD. The connectivity among NSSI is implemented through the connectivity among the NFs of one NSSI and the NFSs of another NSSI. Currently ETSI NFV MANO defines also the support for physical links for the VLD.

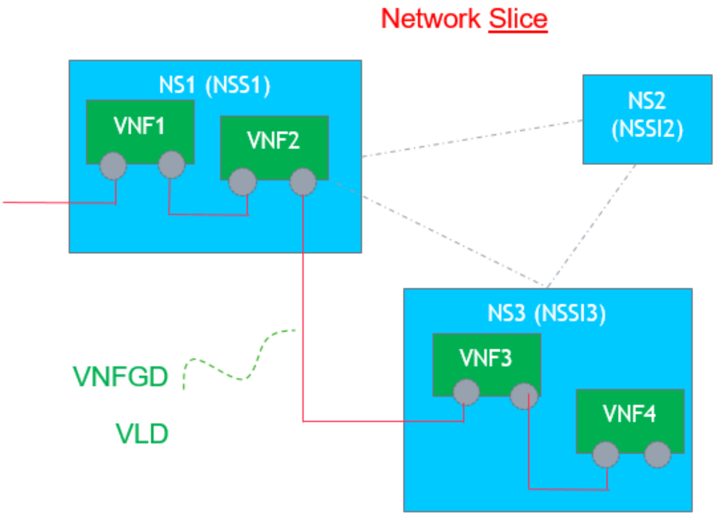


Figure 5-4: Links among network slice subnet instances

5G-MoNArch Network Slice Blueprint represents the collection of NSSIs and their links, so it is a collection of MNSSD and VNFD/VLD, cf. Figure 5-5.

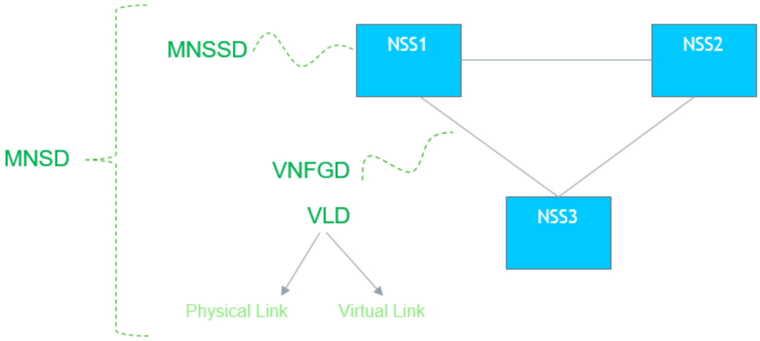


Figure 5-5: 5G-MoNArch network slice blueprint

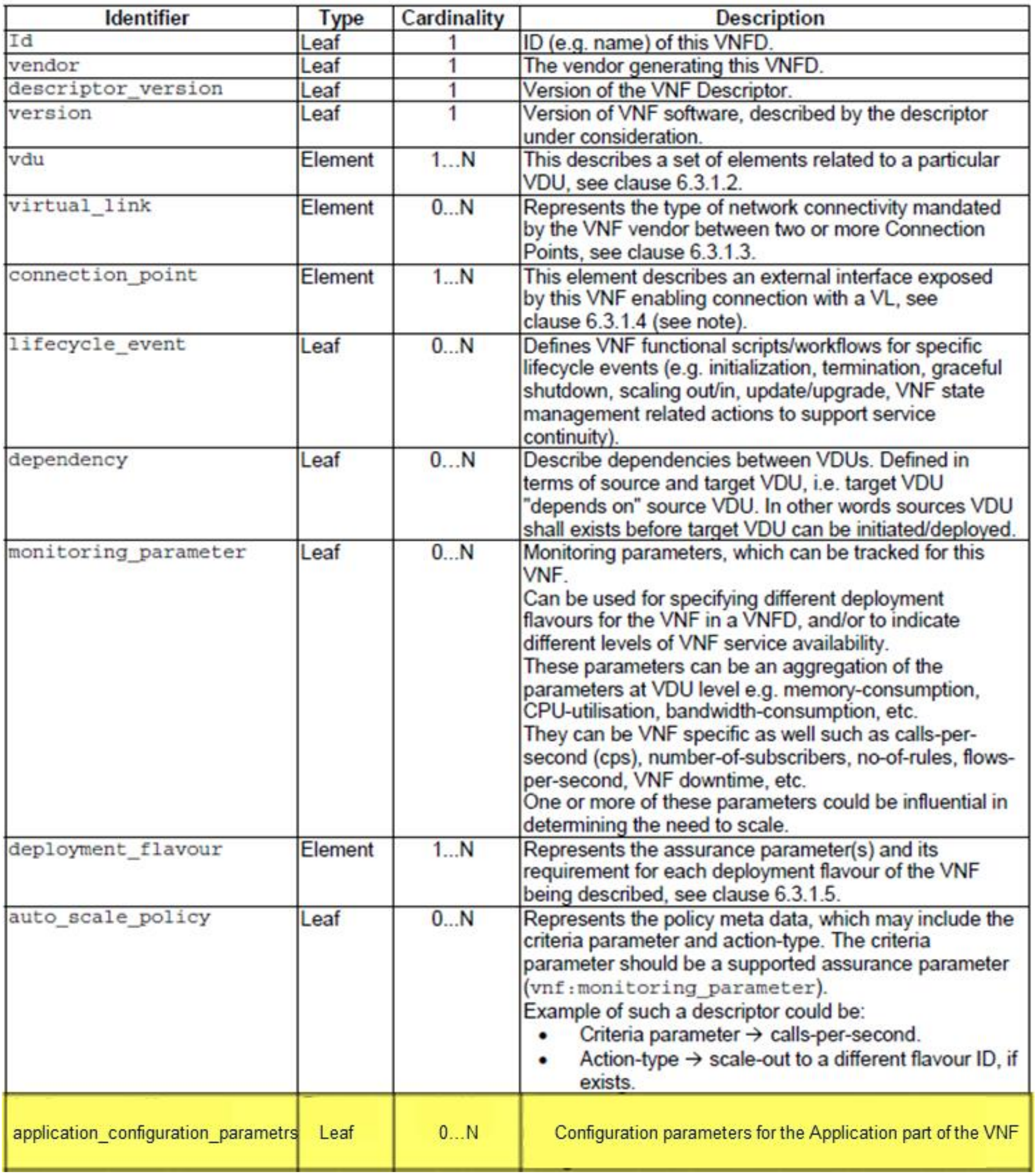
5.1.2 5G-MoNArch network slice blueprint implementation

This section presents the implementation proposed for 5G-MoNArch Blueprint as a collection of enhanced ETSI NFV MANO NS descriptors as described in Section 5.1.1. The reference structure used for the definition of each descriptor and its components is the ETSI NFV MANO framework. The schema in Table 5-1 depicts the 5G-MoNArch VNF Descriptor. The introduced novelties over the ETSI NFV MANO VNFD are highlighted.

MVNFD is the enhancement of ETSI NFV MANO VNFD with the addition of application level configuration data. 5G-MoNArch introduces a new raw *application_configuration_parameters* in order to accommodate such information. The configuration parameter for the application part of the VNF will be compliant with the 3GPP configuration parameters defined in the Network Resource Model (NRM) for each 3GPP NF [3GPP TS 28.541], [3GPP TS 28.543]; optionally some vendor specific configuration parameter could also be introduced. A complete definition of the *application_configuration_parameters* is for further study. Since a new MVNFD structure has been defined, also the 5G-MoNArch Network

Slice Subnet Descriptor (MNSSD) needs to be defined following the same approach as per the VNFD, the ETSI NFV MANO Network Service Descriptor was analysed and used as a reference.

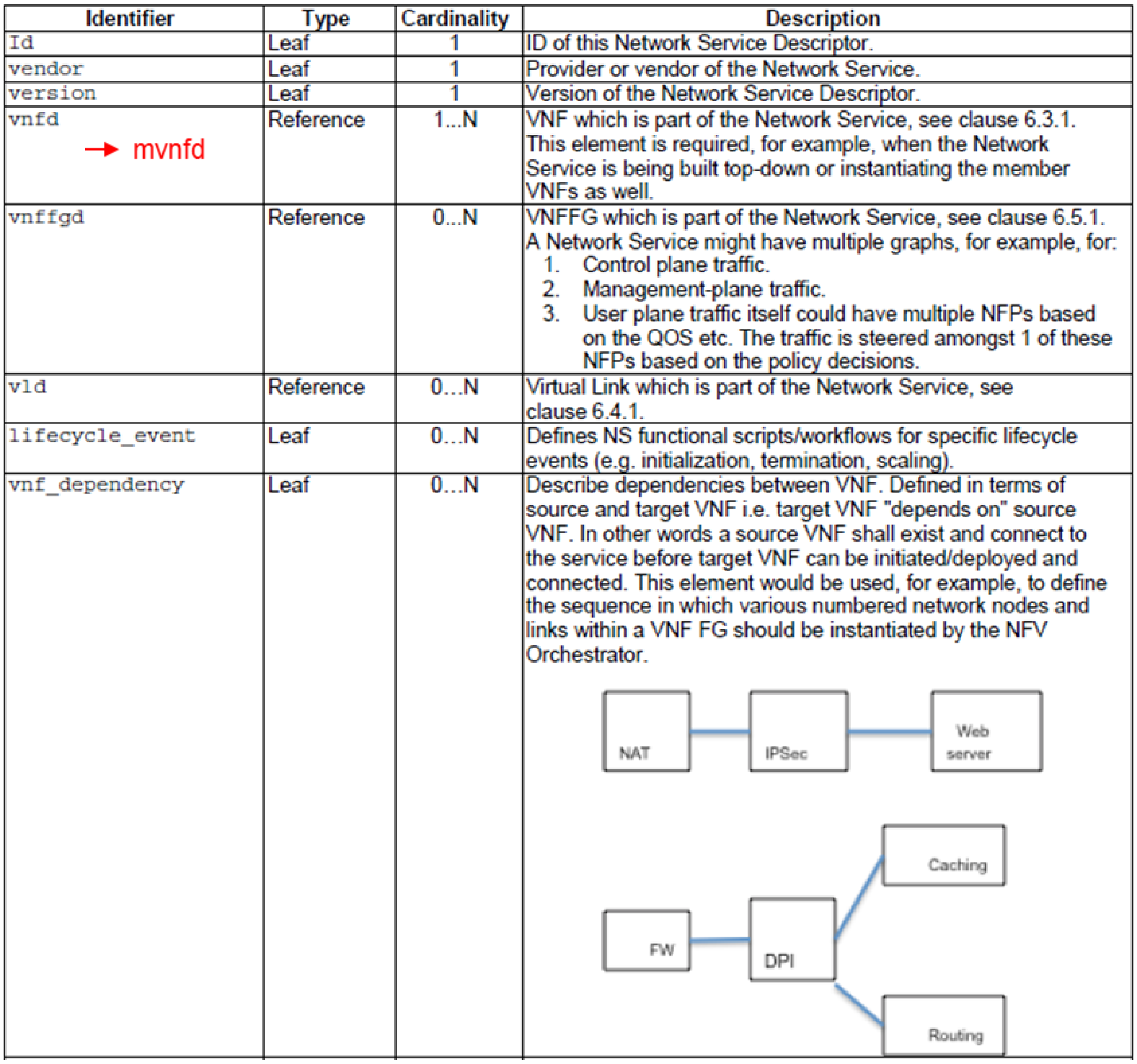
Table 5-1: 5G-MoNArch VNF descriptor



Identifier	Type	Cardinality	Description
`Id`	Leaf	1	ID (e.g. name) of this VNFD.
`vendor`	Leaf	1	The vendor generating this VNFD.
`descriptor_version`	Leaf	1	Version of the VNF Descriptor.
`version`	Leaf	1	Version of VNF software, described by the descriptor under consideration.
`vdu`	Element	1...N	This describes a set of elements related to a particular VDU, see clause 6.3.1.2.
`virtual_link`	Element	0...N	Represents the type of network connectivity mandated by the VNF vendor between two or more Connection Points, see clause 6.3.1.3.
`connection_point`	Element	1...N	This element describes an external interface exposed by this VNF enabling connection with a VL, see clause 6.3.1.4 (see note).
`lifecycle_event`	Leaf	0...N	Defines VNF functional scripts/workflows for specific lifecycle events (e.g. initialization, termination, graceful shutdown, scaling out/in, update/upgrade, VNF state management related actions to support service continuity).
`dependency`	Leaf	0...N	Describe dependencies between VDUs. Defined in terms of source and target VDU, i.e. target VDU "depends on" source VDU. In other words sources VDU shall exists before target VDU can be initiated/deployed.
`monitoring_parameter`	Leaf	0...N	Monitoring parameters, which can be tracked for this VNF. Can be used for specifying different deployment flavours for the VNF in a VNFD, and/or to indicate different levels of VNF service availability. These parameters can be an aggregation of the parameters at VDU level e.g. memory-consumption, CPU-utilisation, bandwidth-consumption, etc. They can be VNF specific as well such as calls-per-second (cps), number-of-subscribers, no-of-rules, flows-per-second, VNF downtime, etc. One or more of these parameters could be influential in determining the need to scale.
`deployment_flavour`	Element	1...N	Represents the assurance parameter(s) and its requirement for each deployment flavour of the VNF being described, see clause 6.3.1.5.
`auto_scale_policy`	Leaf	0...N	Represents the policy meta data, which may include the criteria parameter and action-type. The criteria parameter should be a supported assurance parameter (`vnf:monitoring_parameter`). Example of such a descriptor could be: • Criteria parameter → calls-per-second. • Action-type → scale-out to a different flavour ID, if exists.
application_configuration_parametrs	Leaf	0...N	Configuration parameters for the Application part of the VNF

In this case, since all the information need to set up a network service are already present, the only parameter that needs to be changed to setup an NSSI is the reference to the VNFD, which, in the case of the model used here, will point to the MVNFD, cf. Table 5-2.

Table 5-2: 5G-MoNArch Network Slice Subnet Descriptor (MNSSD)

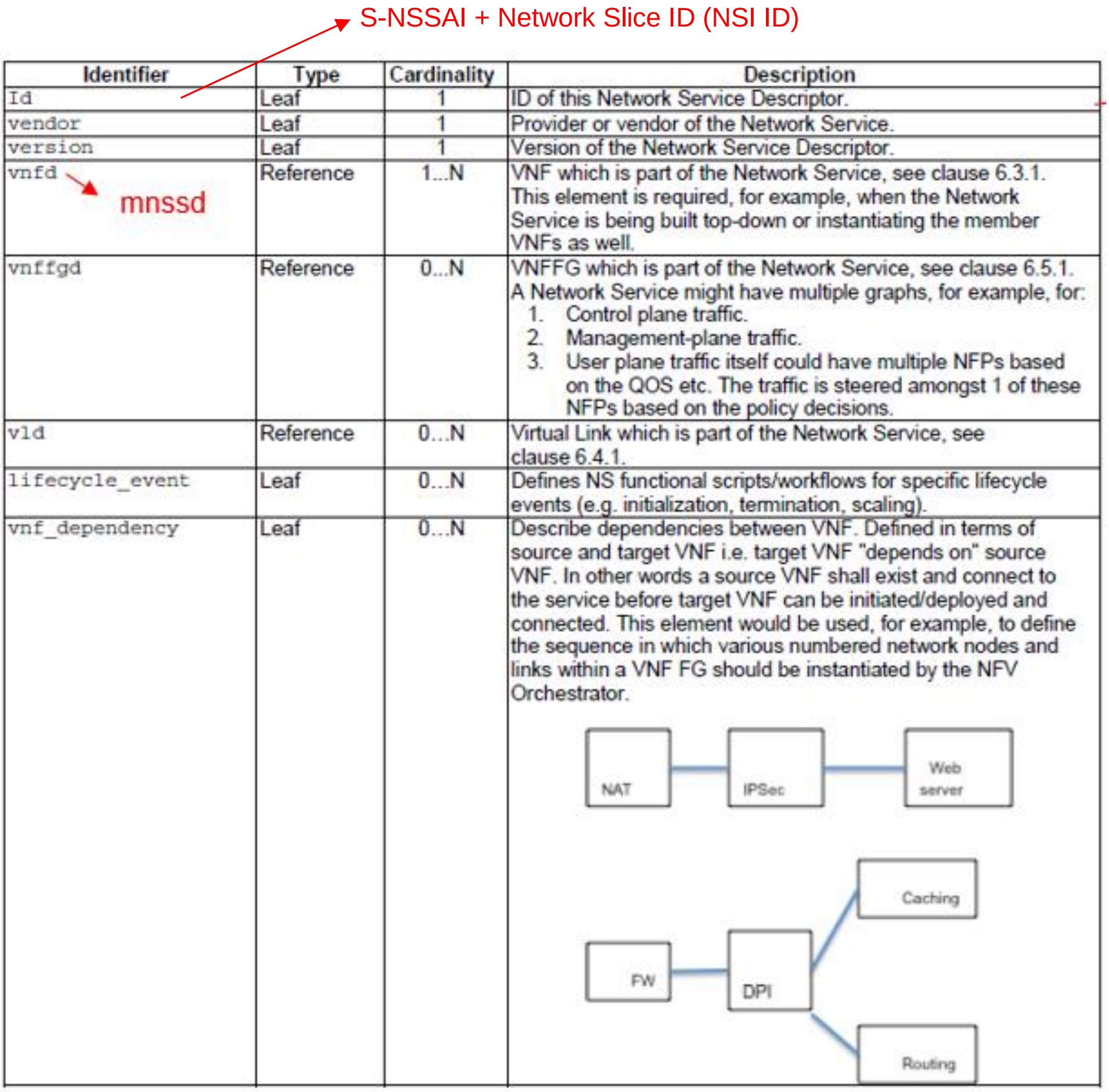


Identifier	Type	Cardinality	Description
Id	Leaf	1	ID of this Network Service Descriptor.
vendor	Leaf	1	Provider or vendor of the Network Service.
version	Leaf	1	Version of the Network Service Descriptor.
vnfd → mvnfd	Reference	1...N	VNF which is part of the Network Service, see clause 6.3.1. This element is required, for example, when the Network Service is being built top-down or instantiating the member VNFs as well.
vnffgd	Reference	0...N	VNFFG which is part of the Network Service, see clause 6.5.1. A Network Service might have multiple graphs, for example, for: 1. Control plane traffic. 2. Management-plane traffic. 3. User plane traffic itself could have multiple NFPs based on the QOS etc. The traffic is steered amongst 1 of these NFPs based on the policy decisions.
vld	Reference	0...N	Virtual Link which is part of the Network Service, see clause 6.4.1.
lifecycle_event	Leaf	0...N	Defines NS functional scripts/workflows for specific lifecycle events (e.g. initialization, termination, scaling).
vnf_dependency	Leaf	0...N	Describe dependencies between VNF. Defined in terms of source and target VNF i.e. target VNF "depends on" source VNF. In other words a source VNF shall exist and connect to the service before target VNF can be initiated/deployed and connected. This element would be used, for example, to define the sequence in which various numbered network nodes and links within a VNF FG should be instantiated by the NFV Orchestrator.

The same approach is used to define 5G-MoNArch Network Slice Blueprint (MNSB), see Table 5-3, that is a collection of MNSSD and links among them. Summing things up, MNSD will result in a schema which, again, will be derived from MANO's network service descriptor. Nevertheless, also at this level, a few elements need to be introduced:

- ID will be replaced by the S-NSSAI plus the NSI ID, defined by 3GPP in [3GPP TS 23.501].
- 5G-MoNArch Network Slice Blueprint will replace the reference to the VNFD with a reference to the (M)NNSD.

Table 5-3: 5G-MoNArch network slice blueprint



S-NSSAI + Network Slice ID (NSI ID)

Identifier	Type	Cardinality	Description
Id	Leaf	1	ID of this Network Service Descriptor.
vendor	Leaf	1	Provider or vendor of the Network Service.
version	Leaf	1	Version of the Network Service Descriptor.
vnfd mnssd	Reference	1...N	VNF which is part of the Network Service, see clause 6.3.1. This element is required, for example, when the Network Service is being built top-down or instantiating the member VNFs as well.
vnffgd	Reference	0...N	VNFFG which is part of the Network Service, see clause 6.5.1. A Network Service might have multiple graphs, for example, for: 1. Control plane traffic. 2. Management-plane traffic. 3. User plane traffic itself could have multiple NFPs based on the QOS etc. The traffic is steered amongst 1 of these NFPs based on the policy decisions.
vld	Reference	0...N	Virtual Link which is part of the Network Service, see clause 6.4.1.
lifecycle_event	Leaf	0...N	Defines NS functional scripts/workflows for specific lifecycle events (e.g. initialization, termination, scaling).
vnf_dependency	Leaf	0...N	Describe dependencies between VNF. Defined in terms of source and target VNF i.e. target VNF "depends on" source VNF. In other words a source VNF shall exist and connect to the service before target VNF can be initiated/deployed and connected. This element would be used, for example, to define the sequence in which various numbered network nodes and links within a VNF FG should be instantiated by the NFV Orchestrator.

5.2 *Deploying multi-slice networks*

This section is the first attempt to model the overall network slice lifecycle management process, captured in Figure 5-6. This process is composed of two phases, namely the network slicing pre-operation phase and the network slicing operation phase. In the former phase, the NSMF produces the network slice blueprint based on the network requirements of the slice and with the support of predefined templates related to standardised slices. Upon this decision the NSMF should proceed with slice resource pre-selection taking into account the available resources, needed computational power, network topology, currently operating NSIs along with their demands, etc.

In the network slicing operation phase, the NSMF should proceed, using this as input, with the actual slice deployment. In this phase, the actual functions' configuration is setup in each domain. Such configuration includes functions' parameterisation and placement according to the available resources. The operation phase also includes the slice performance monitoring sub-phase. That is, the NSI/NSSI performance monitoring modules (cf. Figure 3-13) continuously control whether the slice is able to meet the SLA requirements and, if not, to inform the corresponding functions; eventually, an alarm can be triggered. If the changes relate to updates in the functions' configuration and proper placement then the slice configuration functionality should be triggered. Similar procedures can be implemented when the slice requirements are updated at the user side, i.e., at the CSMF. Section 5.2.1 provides the most relevant use case on slice allocation focusing on NSI and NSSI sharing. Section 5.2.2 provides a detailed example of this procedure, related to the network slice allocation, focusing on the involved M&O layer functions.

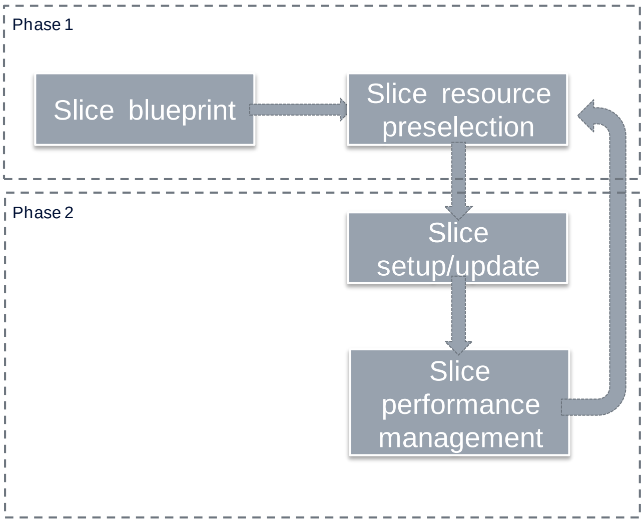


Figure 5-6: Network slice lifecycle management process in 5G-MoNArch

5.2.1 Cross-slice orchestration with shared NF

Figure 5-7, from [3GPP TS 28.530], represents the two main scenarios related to resource sharing in network slicing:

- More communication services share the same NSI
- More NSI share some NSSIs

According to those two scenarios 5G-MoNArch M&O layer has to support the following use cases:

- The allocation of a NSI to serve a new communication service. The allocation process is intended to create a new NSI or reuse an existing NSI.
- The creation of a new NSI reusing existing NSSIs sharing them among NSIs
- Updating the communication service requirements in the case of sharing the NSI o3 the NSSIs

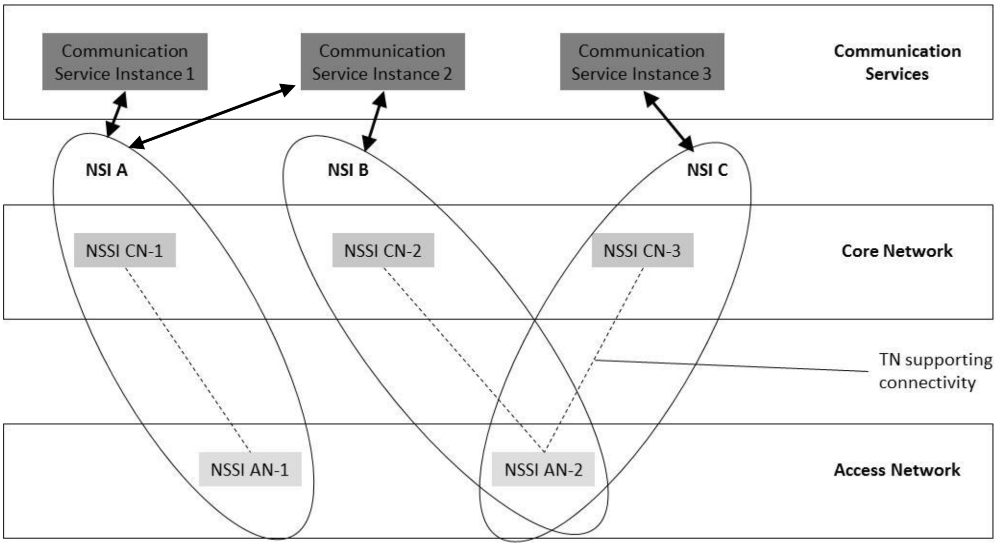

Communication Service Instance 1
Communication Service Instance 2
Communication Service Instance 3
Communication Services
NSI A
NSI B
NSI C
NSSI CN-1
NSSI CN-2
NSSI CN-3
Core Network
TN supporting connectivity
NSSI AN-1
NSSI AN-2
Access Network

Figure 5-7: Slice subnetwork sharing across two or more network slices

According to the functional split of 5G-MoNArch M&O layer, as in chapter 3.3.3, some management functions are specifically defined for the cross-slice orchestration, especially when shared NFs are involved. In the Cross-Slice M&O block are present the following management functions: Cross Slice Requirement verification and Cross Subnet Requirement Verification. These management function support the use cases proposed in this chapter. The network slice and subnetwork slice sharing scenarios proposed by 3GPP have been evaluated and analysed with the conclusion that the following user stories has to be supported by 5G-MoNArch M&O layer trough the new management function introduced in the Cross-Slice M&O function.

Network slice allocation using an existing NSI

The M&O layer has to provide a network slice instance that fits the requested network requirements. The allocation process foresees to use an existing network slice instance (NSI) to optimise the network resource usage or to create a new NSI.

The M&O layer verifies if other existing NSIs support the requested communication service. An identified existing NSI has to be compatible with the network requirements, the network management policies let it to be shared and it still supports the new overall performance, capacity and lifecycle management requirements for all the communication services it has to provide. If no existing NSI can be used the M&O layer has to create a new one, if possible.

Detailed description

The 5G Operator receives the request to provide a new communication service. The 5G Operator uses the M&O layer to provide an NSI to satisfy the request. The M&O layer performs the following steps:

- Verify if there is an NSI that is compatible with the network requirements.
- If no compatible NSI exists, create a new NSI and associate the requested communication service to it.
- If any compatible NSI exists, verify if the network management policies (e.g. related to sharing) allow using it.
- If the policies don’t allow using any of the identified NSIs, create a new NSI and associate the requested communication service to it.
- If the M&O layer finds an existing NSI that can be used, verify if the identified NSI supports the overall performance, capacity and lifecycle management requirements for the communication services it has to serve.
- If yes, use it to satisfy the current communication service request.
- If none of the identified NSIs support the overall performance, capacity and lifecycle management requirements for the communication services, verify the network management policies to decide to reconfigure one of the identified NSIs or to create a new NSI.
- In case the network management policies don’t allow to reconfigure any of the identified NSIs, create a new NSI and associate the requested communication service to it.
- In case the network management policies allow reconfiguring one of the identified NSIs, proceed defining the new requirements for the NSI according to the overall performance, capacity requirements and lifecycle management for all the communication services.
- Verify if the new overall requirement for the NSI are still compatible with the network management policies.
- If the verification is positive, associate the requested communication service to it otherwise create a new NSI.
- In the case of creating a new NSI, verify if the original updated network requirements are compatible with the network management policies and the resource availability.
- If yes, the new NSI can be created otherwise the provisioning request is denied.

Network slice creation using existing NSSIs

The M&O layer has to create a new network slice instance (NSI) that meets the requested network requirements. The M&O layer tries to use existing network slice subnets instances (NSSIs), sharing them, to optimise the network resource usage.

The M&O layer has to provide the constituent network slice subnets that will be used for the network slice. The allocation process verifies, for each requested network slice subnet, if there are sharable NSSIs available that support the requirements, otherwise I have to create a new one.

Detailed description

The M&O layer has already identified that the requested communication service cannot rely on an existing NSI, so it is proceeding to create a new NSI.

As part of a new NSI creation process, The M&O layer decomposes the network slice requirements into network slice subnet requirements.

The M&O layer allocates the network slice subnets using existing NSSIs or creating new ones, if possible. The M&O layer verifies if there are already deployed NSSIs that can be shared in terms of network management policies and that are compatible in terms of requirements.

To provide each requested NSSI, the M&O layer performs the following steps:

- Verify if there is an NSSI that is compatible with the network subnet requirements.
- If there is no compatible NSSI, create a new NSSI.
- If there is a compatible NSSIs, verify if the network management policies (e.g. related to sharing) let me use it.
- If the network management policies don’t allow me to use any of the identified NSSIs, create a new NSSI.
- If any compatible NSSI exists, verify if it supports the overall performance, capacity and lifecycle management requirements for all the NSIs it has to serve.
- If yes, use it to satisfy the current request for network slice subnet allocation.
- If none of the identified NSSIs supports the overall performance, capacity and lifecycle management requirements requested by all the NSIs, verify the network management policies (e.g. related to an NSSI maximum capacity) to decide if to reconfigure one of the identified NSSIs or to create a new NSSI.
- In case the network management policies allow to reconfigure one of the identified NSSIs, proceed defining the new requirements for the NSSI according to the overall performance, lifecycle management and capacity requirements for all the NSIs it has to serve.
- Verify if these new overall requirements for the NSSI are still compatible with the network management policies.
- If the verification is positive, reconfigure the NSSI, otherwise create a new NSSI.
- In the case of creating a new NSSI, verify if the original updated network requirements are compatible with the network management policies and the resource availability.
- If yes, the new NSSI can be created otherwise the NSI allocation request is denied and, consequently, the NSI creation request is denied.

Requirements update when the NSI is shared among services

The M&O layer has to modify a network slice instance (NSI) according to a request of network requirements update.

The M&O layer verifies if the current NSI already supports the new requirements and if it still supports the new overall performance, capacity and lifecycle management requirements for all the communication services it has to provide. If needed and if it is possible accordingly to the network management policies (e.g. related to an NSI maximum capacity), The M&O layer reconfigures the NSI, otherwise the operator creates a new network slice instance to support the communication service.

Detailed description

The M&O layer receives the request to update the network requirements of a communication service provided by an NSI.

The M&O layer performs the following steps:

- Verify if the current NSI is still compatible with the new network requirements
- If yes, verify if the new overall performance, capacity and lifecycle requirements for all the communication services are still compatible with the NSI.
- If yes, use it to satisfy the current communication service request.

- If no (no compatibility with the network requirements or with the overall performance, capacity and lifecycle requirements), evaluate, according to the network management policies and to the requirements of the other services, if updating the current NSI or if allocating a new one.
- To update the current NSI, define the new requirements according to the overall performance, capacity and lifecycle requirements for all the communication services.
- Verify if these new overall requirements are compatible with network management policies.
- If yes, reconfigure the NSI.
- Otherwise, proceed allocating a new NSI to support the updated communication service.
- If the M&O layer has provided a new NSI to fulfil the new requirements, evaluate the network requirement and the performance, capacity and lifecycle requirements for the remaining communication services that are still using the old NSI (if any) to decide if that NSI has to be reconfigured.

Requirements update when some NSSI is shared among NSIs

The M&O layer has to modify an existing NSI according to a request of network requirements update. Alternatively, if there is another NSI which could support the new network requirements, the M&O layer may decide to use the alternative NSI.

The M&O layer verifies if the current NSI already supports the new requirements. If the NSI doesn't fit the new requirements, The M&O layer evaluates if reconfiguring the current NSI or using some other existing NSI that fits the new requirement.

Detailed description

The M&O layer receives the request to update the requirements of an NSI. This NSI is not shared with other communication services but some NSSIs are shared with other NSIs.

The M&O layer performs the following steps:

Verify if the current NSI is still compatible with the new network requirements and if the shared NSSIs are compatible with the overall performance, capacity and lifecycle requirements for all the NSIs they are supporting.

If the current NSI and shared NSSIs are still compatible, continue using them.

If not, verify, according to the new requirements and to the network management policies (e.g. related to sharing or NSI capacity), if reconfiguring the current NSI or using some existing NSI already compatible with the new requirements to provide the update communication service.

If the M&O layer decides to use an existing NSI, the chosen NSI has to be:

- Sharable according to the network management policies.
- Compatible with the new requirements.
- Compatible with the overall performance, capacity and lifecycle requirements for all the communication it has to serve.
- If the M&O layer decides to reconfigure the current NSI it has to update the subnets requirement and to verify if it is possible to update the current NSSIs and/or create new NSSIs.
- For each requested subnet, the M&O layer has to verify if the current NSSI is still compatible with the new network requirements
- If yes, and if the NSSI is shared, verify if it is compatible with the new overall performance, capacity and lifecycle requirements for all the NSIs it has to serve.
- If yes, use it to satisfy the current update request.
- If no (no compatibility with the network requirements or with the overall performance, capacity and lifecycle requirements), evaluate, according to the network management policies and to the requirements of the other NSIs using it, to update the current NSSI or to provide a new one.
- To update the current NSSI, define the new requirements according to the overall performance, ì capacity and lifecycle requirements for all the NSSIs that are using it.
- Verify if these new overall requirements are compatible with network management policies.
- If yes, reconfigure the NSSI.

- Otherwise, proceed allocating a new NSSI to support the updated communication service.
- If the M&O layer has provided a new NSSI to fulfil the new requirements, evaluate the network requirement and the performance, capacity and lifecycle requirements for the remaining services that are using the old NSSI (if any) to decide if the NSSI has to be reconfigured.
- If the M&O layer decides to use an existing NSI, the old NSI has to be dissociated from the communication service.

5.2.2 5G-MoNArch network slice allocation

With reference to the M&O functional split described in Section 3.3.3, this section describes a high-level call flows for slice allocation, in order to give an example on the interaction among the management function. The call flow shows how the management system proceeds allocating a Network Slice Instance (NSI) to support a communication service seeking for an existing NSI to share or creating a new NSI. This call flow is simplified to give a first overview of the interaction among the management functions.

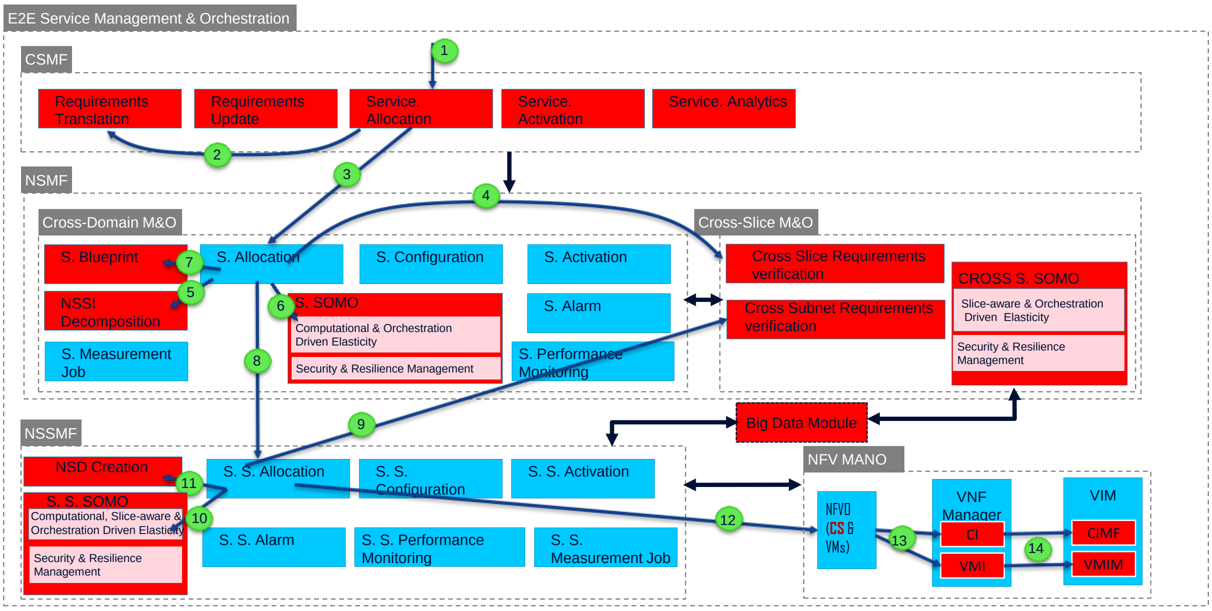


Figure 5-8: Network slice allocation flow

(1) The Communication Service Allocation function receives the request for the allocation of a new communication service with the related service requirements.

(2) The Communication Service Allocation function triggers the Requirements Translation function to translate the service requirements into network requirements.

(3) The Communication Service Allocation function triggers the Slice Allocation function inside the Cross-Domain M&O of the Network Slice Management Function requesting the allocation of an NSI

(4) The Slice Allocation function triggers the Cross Slice Requirement Verification function to verify if an existing slice that fits the purpose. If an existing NSI is available it is used maybe after optimising it for the sharing triggering the Cross.S.SOMO.

(5) If none existing slice is available, the Slice Allocation function triggers the NSS Decomposition function to define the network slice constituents in terms of network slice subnets.

(6) To optimise the network slice, the Slice Allocation function triggers the S.SOMO

(7) The Slice Allocation function triggers the Slice Blueprint function to completely define the slice in terms of its constituents (e.g. NFs, connectivity and topology) and their configuration.

(8) To deliver the network slice a set of network slice subnets has to be allocated, this means recusing existing NSSIs that fits the requirements or creating new NSSIs. To do this the Slice Allocation function triggers the Slice Subnet Allocation function inside the NSSMF. 5G-MoNArch management system foresees the possibility to have more NSSMFs, maybe for

different domains, so the Slice Allocation function triggers all the NSSMF responsible for the subnet allocation that are requested for this network slice. The following steps are repeated for each requested slice subnet.

(9) The Slice Subnet Allocation function triggers the Cross Subnet Slice Requirement Verification function to verify if an existing slice subnet fits the purpose. If an existing NSSI is available it is used maybe after updating it.

(10) If none existing slice subnet is available, the Slice Subnet Allocation function has to create a new one, to optimise it triggers the S.S.SOMO

(11) If none existing slice subnet is available, the Slice Subnet Allocation function has to create a new Network Service to provide the slice subnet, to do this the Slice Subnet Allocation triggers the NSD Creation function. This function produces a Network Service Descriptor that will be the input for the request toward MANO for the network service creation

(12) The Slice Subnet Allocation function triggers MANO, with the appropriate NSD, to create the network service to support the network slice subnet. In the NSD are the requirement for the connectivity inside the network service and for the connection among the other subnets.

5.2.3 5G-MoNArch network slice congestion control

This section describes a high-level flow for slice congestion control. The flow shows how the management system reacts to the increasing resource requirements of a given slice. In this case, the need for additional network resources is related to perceived performance reduction at the slice level, due, for instance, to an increased slice load. This description gives an example of the interactions among the management functions, related to possible implementation of the cross-slice congestion algorithm detailed in Section 4.4.1.

In Figure 5-9, a first flow is represented. In this case, the S. Alarm module in the NSMF, informs the S. SOMO that a given slice performance is decreasing. Accordingly, the S. SOMO verifies whether there is a need for additional network resources according to the slice requirements defined at the S. Blueprint. The S.SOMO monitors the network resource availability and allocates additional resources to the slice accordingly. After this step, it exchanges related information at the S.S SOMO modules related to each slice domains. Finally, the S.S. SOMO verifies whether the new resource allocation is compatible with the resource availability at the domain level, if necessary it update the resource allocation decision, and accordingly demands its implementation at the MANO level.

A slightly different flow is described in Figure 5-10. In this case, the S. SOMO cannot allocate additional resources to the slice according to the feedback received by the S. Measurement Job, as the system may be overloaded. Accordingly, the S. SOMO requests the Cross S. SOMO to initiate a cross slice congestion procedure. Therefore, the latter 1) identifies the slices with looser requirements for which the amount of allocated resources can be reduced and 2) updates their resource allocation. After this step, it exchanges related information at the S.S SOMO modules for each of the domains of the involved slices. Finally, the S.S. SOMO verifies and potentially adjusts the new resource allocation plan and demands its realisation at the MANO level.

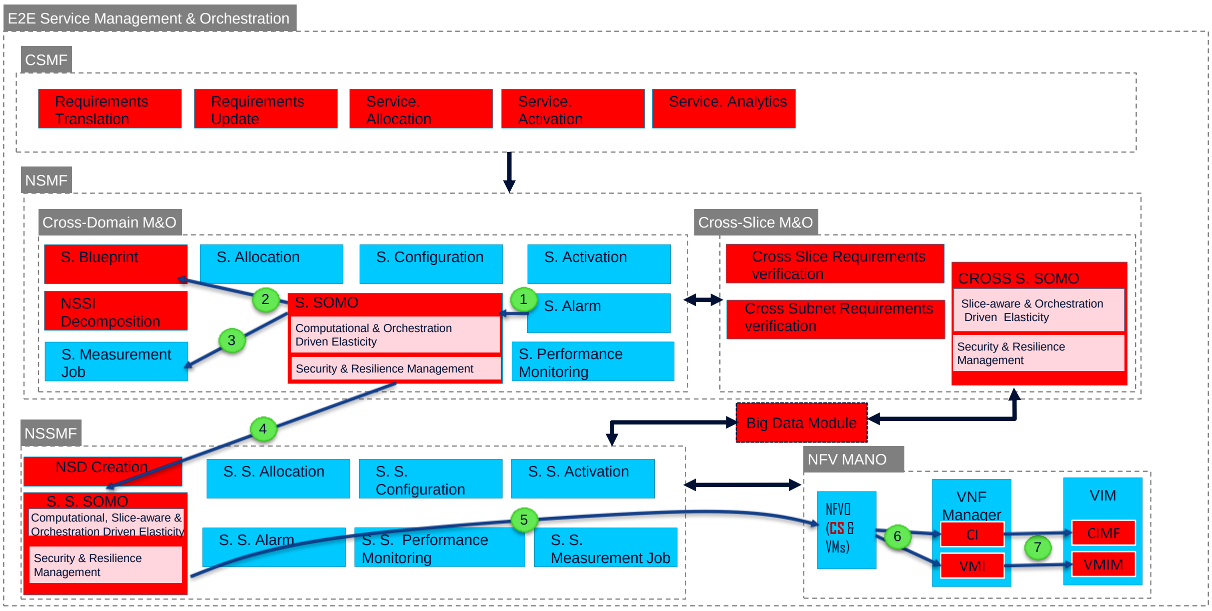


Figure 5-9: Network slice congestion control flow

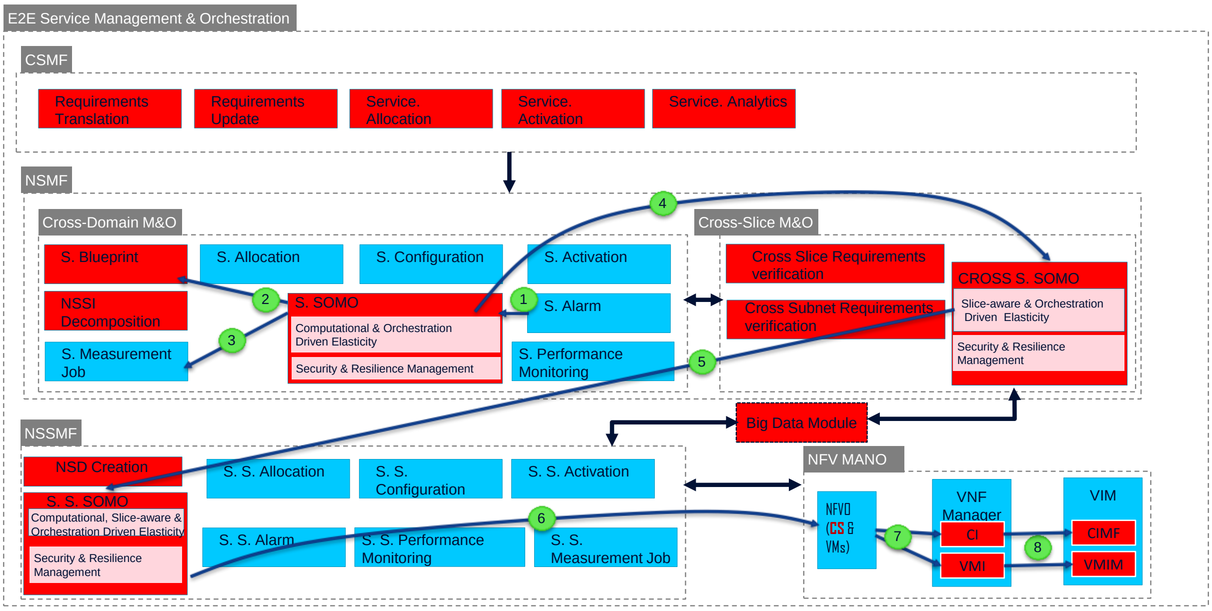


Figure 5-10: Cross-slice congestion control flow

5.3 *Integration of functional innovations for 5G-MoNArch use cases*

5.3.1 Resilience and security

5.3.1.1 Basic concepts and required architecture components

A network slice intended to support URLLC services needs to fulfil high resilience, reliability and security requirements. Such specialised service requirements coming from the customer need to be carefully translated into the resource-facing service description, e.g. by including in the slice template the network functions and their corresponding configurations that can support the specified requirements. Furthermore, the slice template need to contain the instructions for actual deployment, management, orchestration and control of specialised NFs that will be executed by different functions of 5G-MoNArch architecture, e.g. instructions on LCM of specialised VNFs that will be executed by VNFM.

The following paragraphs discuss the main specialised NFs needed for enabling high reliability, resilience and security along with their placement in 5G-MoNArch architecture as depicted in Figure 5-11.:

- RAN reliability sub-plane comprises the functions for multi-connectivity (data duplications) and network coding for improved RAN resilience. It appears as the pool of resilience-enabling network functions which can be on demand, dynamically instantiated and configured based on the actual network context, resilience requirements as well as agreed SLAs with the slice tenant. Such sub-plane resides in the Network layer, which provides the required UP and CP functionality. A corresponding control application ('Reliability Control') in the Control layer needs to be instantiated as well, cf. Figure 5-11.
- Functions for improving the telco cloud resilience include FM functions specialised for resolving the network issues in 5G virtualised networks by jointly handling the faults coming from virtualised and physical infrastructure and taking into account slice requirements. Therefore, the 5G network FM needs to leverage on the information available at E2E Service M&O, 3GPP Network Management, as well as NFV MANO entities cf. Figure 5-13. The 5G network FM can be seen as a part of the 3GPP Network Management module including considerable extensions compared to the legacy FM in order to incorporate slicing and virtualisation awareness. Furthermore, due to many interrelations between security and resilience considerations as well as common tools for detection of security and network issues, the Cross-slice M&O function responsible for inter-slice management will incorporate Cross-slice Security and Resilience Management function ('X-slice S&R Mgmt', cf. Figure 5-11) specialised for addressing jointly the security and resilience considerations. Cross-domain M&O function is taking care of the coordination/negotiation between different management domains (e.g., RAN, CN) within a single slice and it can incorporate the functionality for joint dealing with security and resilience issues, i.e. Cross-domain Security & Resilience Management ('X-domain S&R Mgmt', cf. Figure 5-11). Additionally, the "5G island" is the robust solution which relies on the edge cloud for "standalone" network operation, i.e., without permanent connectivity to the central cloud. This concept aims at estimating the need to migrate certain NFs from central cloud in order to have it available at the edge cloud once the connectivity towards the central cloud is lost. Finally, a crucial building block for improving the telco cloud resilience is the load-aware 'Scalable and Resilient Control Framework', cf. Figure 5-11.
- As security is one of the fundamental requirements of ultra-reliable services, a set of specialised NFs for improving the level of security needs to be deployed in order to achieve the required level of service reliability. Security Trust Zones (STZs) define a logical area of infrastructure and services where a certain level of security and trust is guaranteed. Security level corresponds to the quality of being protected against threats, whereas trust assures that certain expectations will be met throughout a defined period of time. The main properties of STZ are detection, prevention and reaction which describe the capabilities of the STZ to achieve the promised security and trust levels. Different STZs with specific security level and means of achieving required security level can be deployed all over the network. Within different STZs, the network functions responsible for Security Threat detection, protection or reaction, as well as the Threat Intelligence Exchange (ThIntEx) NFs (collectively referred to as STZ VNFs) can be deployed based on the actual security level that needs to be implemented. Furthermore, the function that coordinates the activity of Security Trust Zones (STZm – Security Trust Zone Manager) deployed across network slices needs to be present. STZm component is located at the Controller layer (cf. Figure 5-11) in order to reach for different network slices and coordinate threat intelligence exchange by means of the corresponding ThIntEx NF, e.g. to share the information about security incidents detected in different network slices. This element is in charge of improving the reaction against threats and avoiding propagation of threats across-slices. Furthermore, a security monitoring manager (SMm) will be deployed at the Control layer in order to receive the data provided by the different detection, prevention and reaction components deployed through the STZs of the same network slice. Finally, the Cyber Security

Dashboard, located in the Service layer, provides tenants with visualisation and awareness of the security status of the deployed network slices at any point in time.

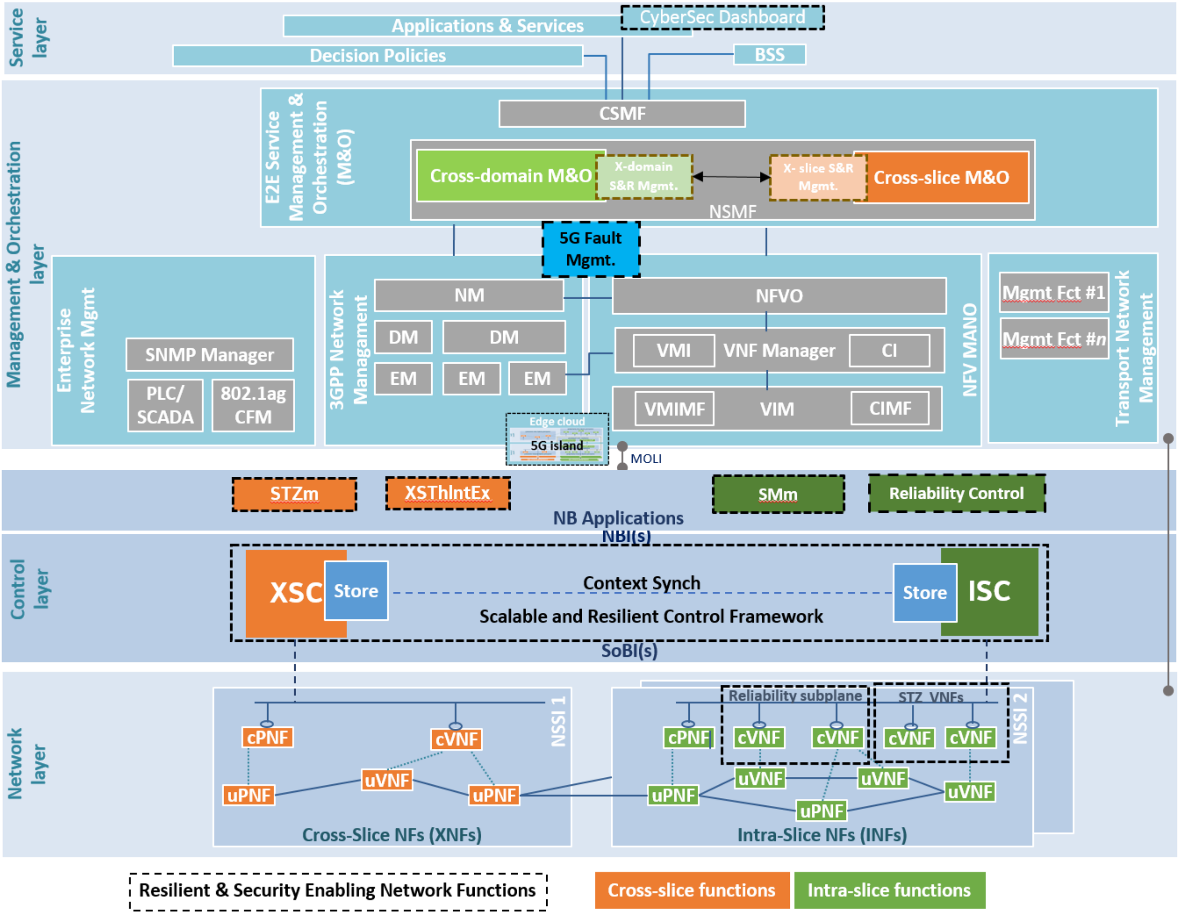


Figure 5-11: Customised 5G-MoNArch architecture instance enriched with the necessary elements to enable resilience and security functional innovations [5GM-D3.1]

The next step in the context of enabling resilience, reliability, and security aims at providing more detailed studies on actual mapping between required levels of resilience, reliability and security and the exact functional description, parameterisation, deployment as well as LCM instructions. Furthermore, the mechanisms and involvement of entities from 5G-MoNArch architecture for dynamic activation and deactivation of specialised functions as well as dynamic change of their parameterisation will be studied. Finally, providing additional details on approaches for coordination of security and resilience, across different network slices and domains, comprises a further target of the upcoming work.

The following section describes the target functional architecture to be utilised for the Hamburg *Smart Seaport* use case. It explains how selected security and resilience functions are integrated into the seaport network.

5.3.1.2 Network architecture for the Smart Seaport use case

For the *Smart Seaport* use case deployed in the Hamburg testbed of 5G-MoNArch, a customised architecture instance of the general overall architecture as described in Section 3.1 is utilised. For this instance, a subset of the 5G-MoNArch enabling common network functionality as well as selected functions of the use-case-specific functions as developed in WP3 (cf. Section 5.3.1.1) are utilised. The latter include cross-domain and cross slice security and resilience management, 5G Fault Management functions as well as multi-connectivity-enabled RAN for increased reliability (RAN reliability sub-plane.)

The *Smart Seaport* target architecture instance is depicted in Figure 5-12. It shows the network functions in each layer, Network layer, M&O layer, and Service layer. Currently, the optional 5G-MoNArch control layer is not foreseen to be part of the *Smart Seaport* testbed. The network functions are distributed across four locations in Hamburg and Nuremberg. In Hamburg, there are the Deutsche Telekom (DT) Data Centre, the Hamburg Port Authority Data Centre (and private networks), and the TV Tower hosting the base station. In Nuremberg, one of the central office Data Centres (‘central cloud’) of DT is hosted. The four locations are depicted in yellow in Figure 5-12.

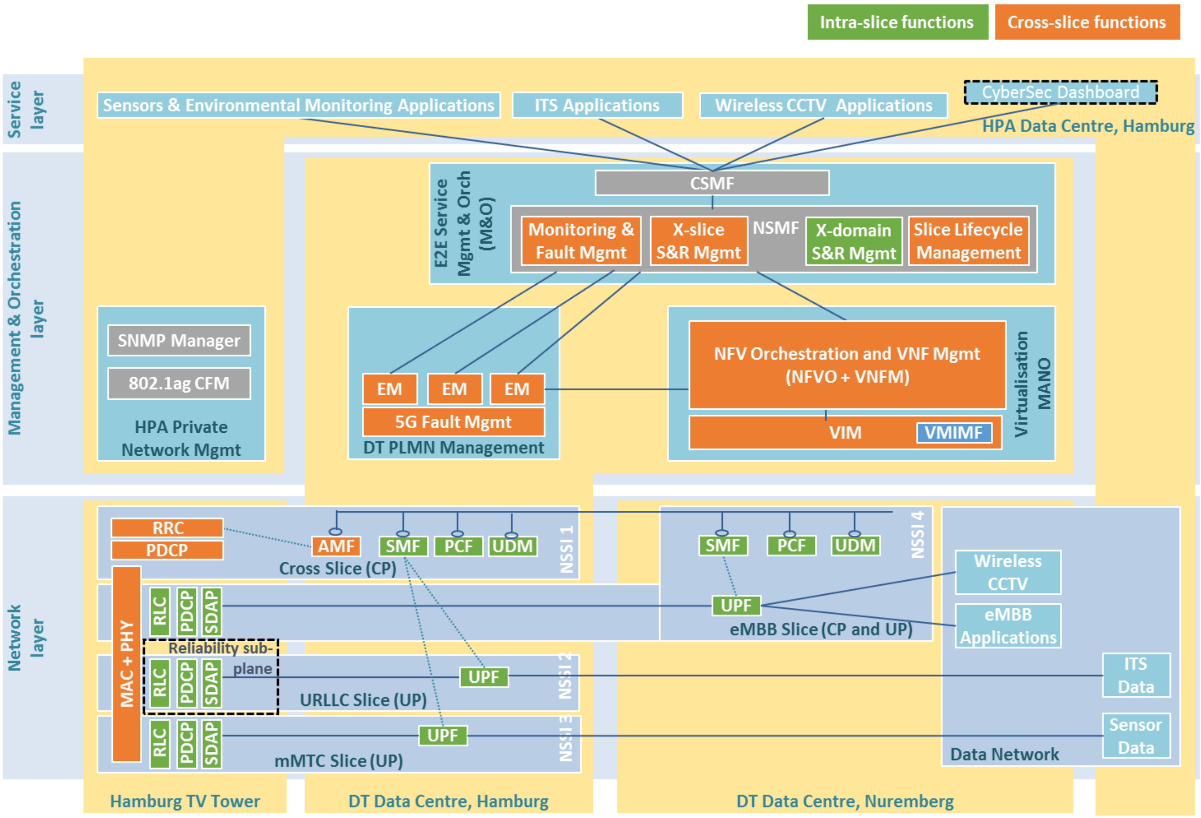


Figure 5-12: Targeted functional architecture for the Smart Seaport use case

In the Network layer, the testbed implements three network slices, enhanced Mobile Broadband (eMBB) communication, Ultra-Reliable Low-Latency Communication (URLLC), and massive Machine-Type Communication (mMTC) delivering the Augmented Reality (AR), Intelligent Transport Systems (ITS), and Environmental Sensing use cases, respectively. They have the following deployment characteristics:

eMBB network slice: The eMBB network slice is utilised to carry the AR traffic (e.g., augmented maintenance for HPA service staff) as well as providing eMBB services like Internet access or video streaming to cruise ship tourists. In the Radio Access Network (RAN), the slice uses the common PHY and MAC layers of the testbed radio infrastructure. SDAP, PDCP, and RLC layers are slice-specific due to customisations reflecting service requirements. Further, RRC is common for all deployed slices. In the control plane (CP), the AMF is shared with other network slices, while PCF, UDM, and SMF are dedicated to the eMBB slice. Core network user plane (UP) function(s) are dedicated and therefore service-specific. Besides AMF, all core network functions of the eMBB slice (from CP and UP) run in DT’s central cloud data centre in Nuremberg, one of DT’s central office sites. Further, the AR applications (and other eMBB-like applications) in the Data Network that process the incoming user data are also hosted in Nuremberg.

URLLC network slice: The URLLC network slice is utilised for ITS applications in the seaport area, in particular for traffic light control. Similar to the eMBB slice, the URLLC slice uses the common RRC and lower radio layers (MAC and PHY) and service-specific upper radio layers (RLC, PDCP, SDAP) in the RAN. One such service-specific customisation comprises the WP3 reliability sub-plane for multi-connectivity, thus increasing reliability in the radio network. In the core network, AMF is shared with all three deployed slices, while SMF, PCF, and UDM are shared among the slices deployed in the local edge cloud (DT Data Centre, Hamburg), i.e., URLLC slice and mMTC slice. An alternative deployment option would comprise separate PCFs for each of the two slices. Further details of PCF selection can be found in clause 6.3.7.1 of [3GPP TS 23.501]. The core network UP uses a dedicated and customised UPF instance. Due to latency requirements for traffic light control, all network functionality in CP and UP is deployed locally. Therefore, also the ITS Data applications in the Data Network are operated in the local HPA Data Centre in Hamburg.

mMTC network slice: The mMTC slice is used to carry traffic from environment sensors deployed in the Hamburg seaport, particularly from the barges patrolling through the seaport. The slice has the same setup as the URLLC slice in terms of deployment of network (CP and UP, RAN and core network) and application functions. Nevertheless, upper layer radio functions (RLC, PDCP, SDAP) and core network UPF are realised as dedicated instances with customised behaviour.

The Management & Orchestration layer comprises DT's functionalities for managing public land mobile networks (PLMN), particularly Element Management (EM) functions and novel advanced 5G Fault Management functions as developed in WP3. For the virtualisation management and orchestration (MANO), the Hamburg seaport testbed utilises a VM-based virtualisation approach. The deployment uses a streamlined ETSI NFV MANO architecture, i.e., VIM and an NFV lifecycle management component integrating NFV Orchestrator and VNF Manager. Nevertheless, in general, container-based solutions could be incorporated. For e2e M&O, NSMF and CSMF incorporate according monitoring as well as fault and slice lifecycle management functions. From WP3, cross-domain and cross-slice security and resilience management functions are incorporated into NSMF. A lightweight CSMF implementation provides mediation capabilities between NSMF and the Service layer. Beyond these M&O layer functions operated by DT in their Hamburg Data Centre, the deployment comprises the management functions for HPA's private networks, namely SNMP Managers and 802.1ag Connectivity Fault Management running in HPA Data Centre in Hamburg. The latter functions manage the largely wireline network infrastructure of HPA which is also used to connect the UPs of the local network slices with the HPA Data Centre. More specifically, as depicted in Figure 5-5, the *ITS* and *Environmental Monitoring/Sensor Data applications* run in the HPA Data Centre in Hamburg where the UP data coming from the URLLC and mMTC slice, respectively, are forwarded to. Form the mobile network perspective, these application fucntions belong to the Data Network outside the operator domain. Only in case of the eMBB slice, the application (*AR Data*) is hosted in the DT Data Centre in Nuremberg. Finally, each of the three applciations also has a management and control component residing in the service layer, executed in the local HPA Data Centre. They interact with the CSMF to provide the specific service requirements used to customise the slice instances and to receive latest performance and configuration details about the network slice hosting the respective service.

5.3.2 Resource elasticity

5.3.2.1 Basic concepts and required architecture component

As discussed in Section 4.3.5, resource assignment in the network should avoid overprovisioning and assign resources just where and when they are needed. This flexibility is referred to as resource elasticity, which includes the ability (i) to scale resources according to the demand, and (ii) to gracefully scale the network operation when insufficient resources are available.

Elasticity has been traditionally implemented in the context of communication resources, where the network gracefully downgrades the quality for all users if its communication resources (e.g., spectrum, radio link capacity) are insufficient. In the framework of a softwarised network, a new paradigm for resource elasticity that comprises processing power, memory, and storage resources is needed. While cloud frameworks typically aim at guaranteeing that the computational resources required by a function are always there, in the orchestration environment considered here this may not be possible, since (i) the timescales involved in RAN functions are much tighter than those considered in cloud solutions, which cannot prevent outages at such short timescales, and (ii) cloud resources are typically limited at the edge, preventing cloud solutions to exploit multiplexing gains. Adding more elasticity to the resource consumption of NFs requires an understanding of the nature of the different resources and performance trade-offs, leading to different dimensions of elasticity which are described next.

This section provides a set of ideas on how to provision resource elasticity, in particular the technical challenges in the virtualised architecture of 5G systems that resource elasticity is meant to address, as well as design hints on the type of solutions or mechanisms that could address those challenges. Table 5-4 provides a summary of the content of this section.

Table 5-4: Innovation areas, challenges, and potential solutions towards an elastic architecture

Innovation Areas	**Challenges**	**Potential Solutions**
Computational elasticity	Graceful scaling of computational resources based on load	Elastic NF design and scaling mechanisms
Orchestration-driven elasticity	NF interdependencies	Elastic cloud-aware protocol stack
Slice-aware Elasticity	E2E cross-slice optimisation	Elastic resource provisioning mechanisms exploiting multiplexing across slices

A first challenge in virtualised networks is the need to perform graceful scaling of the computational resources required to execute the VNFs according to the load. In that respect, the computational elasticity innovation refers to the ability to scale NFs and their complexity based on the available resources. In case of resource outage, NFs would adjust their operation to reduce their consumption of computational resource while minimising the impact on network performance.

The second challenge can be illustrated with the current LTE design of the protocol stack, where the NFs co-located in the same node are inter-dependent, i.e., interact and depend on each other. One example of logical dependencies within the stack is the recursive interaction between MCS, Segmentation, Scheduling, and RRC. In addition to logical dependencies, traditional protocol stacks also impose stringent temporal dependencies, e.g., the HARQ requires a receiver to send feedback informing of the decoding result of a packet within 4 milliseconds after the packet reception. Indeed, traditional protocol stacks have been designed under the assumption that certain functions reside in the same (fixed) location and, while they work close to optimality as long as such NFs are co-located in the same node, they do not account for the possibility of placing these NFs in different nodes. To deal with this challenge, a new protocol stack, adapted to the cloud environment, needs to be designed. This new protocol stack relaxes and potentially removes the logical and temporal dependencies between NFs, with the goal of providing a higher flexibility in their placement. This elimination of interdependencies among VNFs allows the orchestrator to increase its flexibility when deciding where to place each VNF, hence the name orchestration-driven elasticity.

A third challenge of the envisioned 5G architecture appears at the intersection of virtualisation and network slicing, i.e., the need for E2E cross-slice optimisation such that multiple network slices deployed on a common infrastructure can be jointly orchestrated and controlled in an efficient way while guaranteeing slice isolation. To address this challenge, it is important to devise functions that optimise the network and resource consumption by exploiting statistical multiplexing gains. Indeed, due to load fluctuations that characterise each slice, the same set of physical resources can be used to simultaneously serve multiple slices, which yields large resource utilisation efficiency and high gains in network deployment investments, as long as resource orchestration is optimally realised.

5G-MoNArch foresees that all the above elasticity-related functionalities could be greatly enhanced with an AI and Big Data Analytics Engine. This activity is in line with the goal of the ETSI ENI (Experiential Network Intelligence) [ETSI ENI17]. Focused on optimising the operator experience, this engine would be equipped with big data analytics and AI capabilities that could enable a much more informed elastic management and orchestration of the network, often allowing proactive resource allocation decisions based on the history rather than utilising reactive approaches due to changes in load.

Elasticity mainly addresses two domains: network M&O and network control. The former shall incorporate the elements needed to (i) flexibly assign resources to different slices and (ii) find the best location of a VNF belonging to a certain network slice within the infrastructure. The latter, instead, shall provide an inner loop control of network functions, to enforce elasticity at faster time scales, such as the ones needed in the RAN.

The integration of the elasticity and the big data modules inside the 5G-MonArch M&O layer is depicted in Figure 5-13, while an overall view is provided in Figure 5-14.

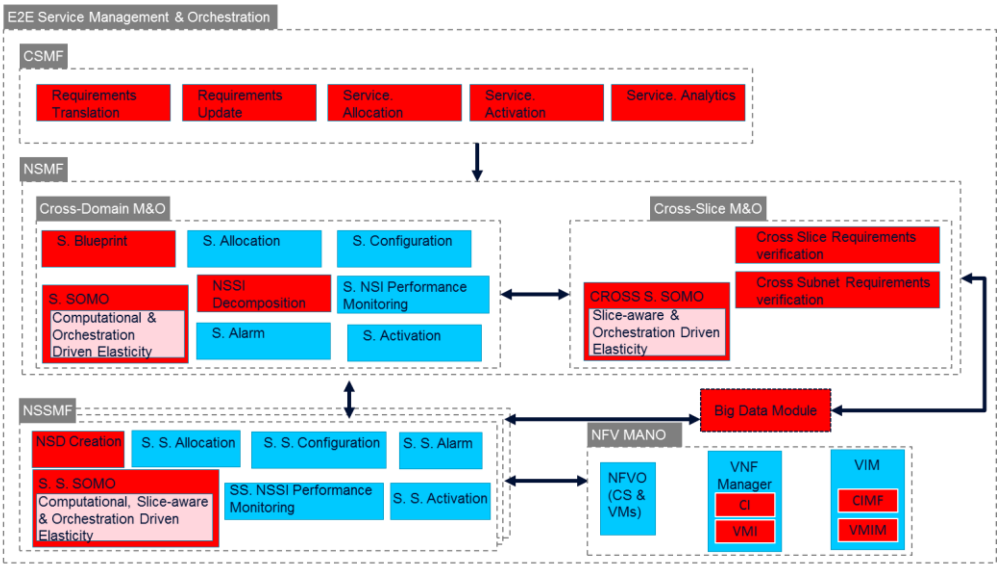


Figure 5-13: Elasticity and Big Data modules within the 5G-MonArch M&O layer

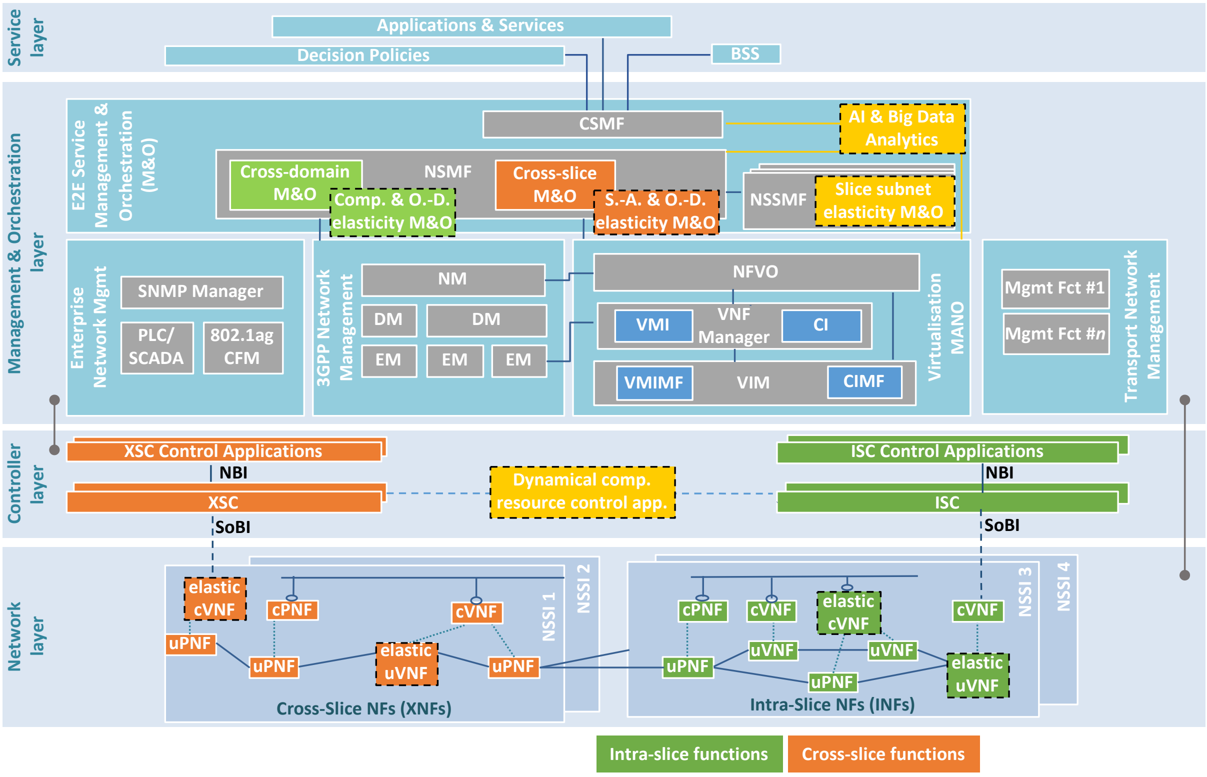


Figure 5-14: Elasticity modules in the overall 5G-MoNArch architecture

The interactions between the M&O layer and the controller layer are described in Figure 5-15. The details on the depicted interfaces are provided in D4.1 [5GM-D4.1]. The following paragraphs provide some more detail on each of the identified innovation areas.

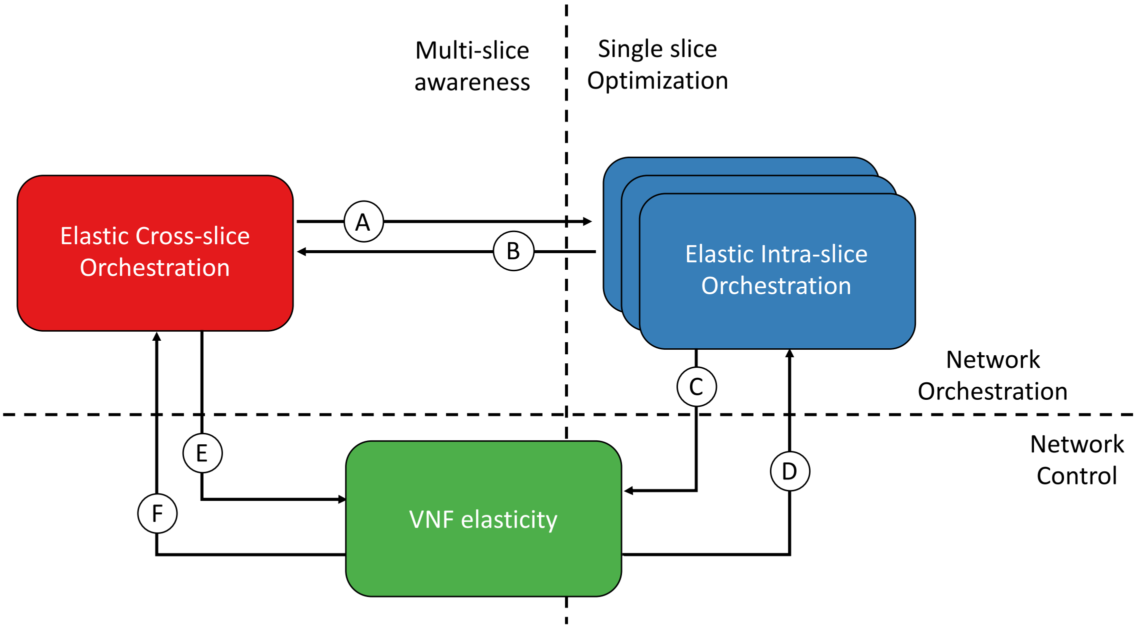

Multi-slice awareness
Single slice Optimization
Elastic Cross-slice Orchestration
Elastic Intra-slice Orchestration
A
B
C
D
E
F
Network Orchestration
Network Control
VNF elasticity

Figure 5-15: High-level interactions across elastic modules in the M&O and Controller layers

Computational elasticity

The goal of exploiting computational elasticity is to improve the utilisation efficiency of computational resources by adapting the NF behaviour to the available resources without impacting performance significantly. Furthermore, this dimension of elasticity addresses the notion of computational outage, which implies that NFs may not have sufficient resources to perform their tasks within a given time. In order to overcome computational outages, one potential solution is to design NFs that can gracefully adjust the amount of computational resources consumed while keeping the highest possible level of performance. RAN functions in particular have been typically designed to be robust only against shortages on communication resources; hence, the target should be directed at making RAN functions also robust to computational shortages by adapting their operation to the available computational resources. An example could be a function that chooses to execute a less resource-demanding decoding algorithm in case of resource outages, admitting a certain performance loss.

In addition, the scaling mechanisms, i.e., the modification of the amount of computational resources allocated to such computationally elastic NFs may help in exploiting the elasticity of the system if they are properly designed. There are two significant ways to scale a NF: (i) horizontal scaling, where the system is scaled up or down by adding or removing new identical nodes (or virtual instances) to execute a NF, and (ii) vertical scaling, where the system is scaled out or in by increasing or decreasing the allocated resources to the existing node (or virtual environment) [Wil12]. As an example, in the RAN domain, supporting higher system throughput by adding additional access points is referred as horizontal scaling, whereas an increase in operating bandwidth is referred as vertical scaling.

Orchestration-driven elasticity

This innovation focuses on the ability to re-allocate NFs within the heterogeneous cloud resources located both at the central and edge clouds, taking into account service requirements, the current network state, and implementing preventive measures to avoid bottlenecks. The algorithms that implement orchestration-driven elasticity need to cope with the local shortage of computational resources by moving some of the NFs to other cloud servers which are momentarily lightly loaded. This is particularly relevant for the edge cloud, where computational resources are typically more limited than in the central cloud. Similarly, NFs with tight latency requirements should be moved towards the edge by offloading other elastic NFs without such tight timescale constraints to the central cloud servers.

To efficiently implement such functionalities, special attention needs to be paid to (i) the trade-off between central and edge clouds and the impact of choosing one location for a given function, and (ii) the coexistence of Mobile Edge Computing (MEC) and RAN functions in the edge cloud. This may imply scaling the edge cloud based on the available resources, clustering and joining resources from different locations, shifting the operating point of the network depending on the requirements, and/or adding or removing edge nodes [OSB16].

Slice-aware Elasticity

Finally, this dimension of elasticity addresses the ability to serve multiple slices over the same physical resources while optimising the allocation of computational resources to each slice based on its requirements and demands, a challenge earlier referred to as E2E cross-slice optimisation. Offering slice-aware elastic resource management facilitates the reduction of Capital Expenditure (CAPEX) and OPEX by exploiting statistical multiplexing gains. Indeed, due to load fluctuations that characterise each slice, the same set of physical resources can be used to simultaneously serve multiple slices, as Figure 5-16 illustrates.

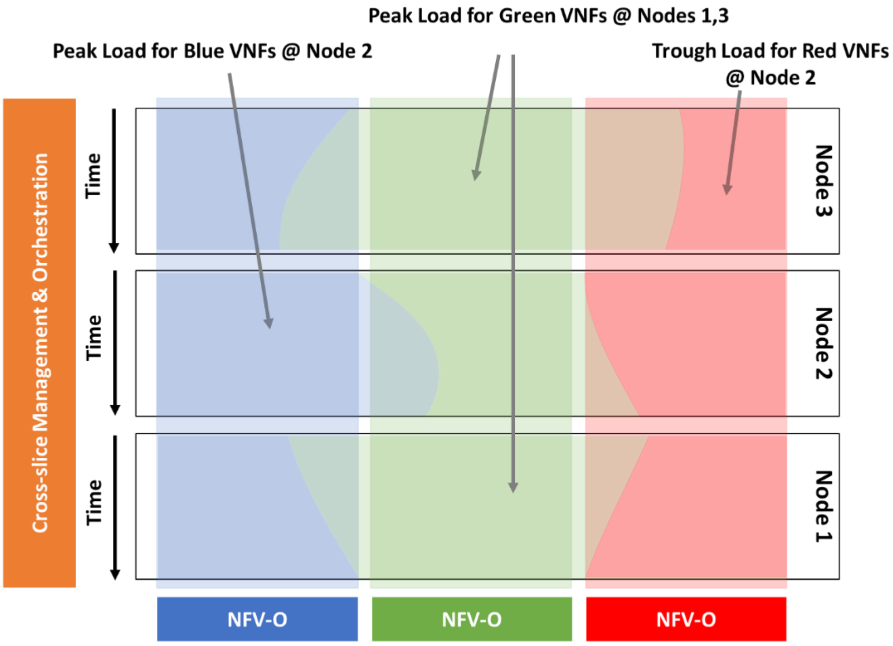

Peak Load for Green VNFs @ Nodes 1,3
Peak Load for Blue VNFs @ Node 2
Trough Load for Red VNFs @ Node 2
Cross-slice Management & Orchestration
Time
Time
Time
Node 3
Node 2
Node 1
NFV-O
NFV-O
NFV-O

Figure 5-16: Illustration of slice-aware elasticity

Adaptive mechanisms that exploit multiplexing across different slices (when resource isolation is not needed) must be designed, aiming at satisfying the slice resource demands while reducing the amount of resources required. Hence, the solutions must necessarily dynamically share computational and communications resources among slices whenever needed. An elastic admission control system would be also required, as elastic slices need not have the same amount of available resources as e.g., a highly resilient slice where all resource demands must be fully satisfied at each point in time. Furthermore, in this context a monitoring module should be deployed to retrieve the information required to take optimal sharing decisions, considering trust relationships issues for slices managed by different tenants.

5.3.2.2 Network architecture for the Touristic City use case

As for the *Smart Seaport* use case deployed in the Hamburg testbed of 5G-MoNArch, a customised architecture instance of the general overall architecture as described in Section 3.1 is deployed for the *Touristic City* use case. Also, for this scenario, a subset of the 5G-MoNArch architecture is deployed, with some specific modules developed in WP4 (cf. Section 5.3.1.1), among them the Cross-Slice elasticity module, the big data analytics module, and the slice subnet elasticity module.

The *Touristic City* target architecture instance is depicted in Figure 5-17 below that shows the network functions in each layer, Network layer, M&O layer, and Service layer. Currently, the optional 5G-MoNArch control layer is not part of the *Touristic City* testbed, but possibly some of the core network functionality may be implemented in such way. Due to the smaller extent, the network functions of this testbed are deployed in three main location: the antenna site (where the radio PNF are executed), the edge cloud, and a central cloud (that has a higher latency to the UE). They are depicted in yellow in Figure 5-17. In practice, the edge and the central cloud are two dedicated cloud infrastructure domains, connected via fibre to the antenna site. The central cloud emulates a farther processing site, with an increased latency but a lower operational cost. Both sites are deployed in the premises of the demo, but are owned by the operator.

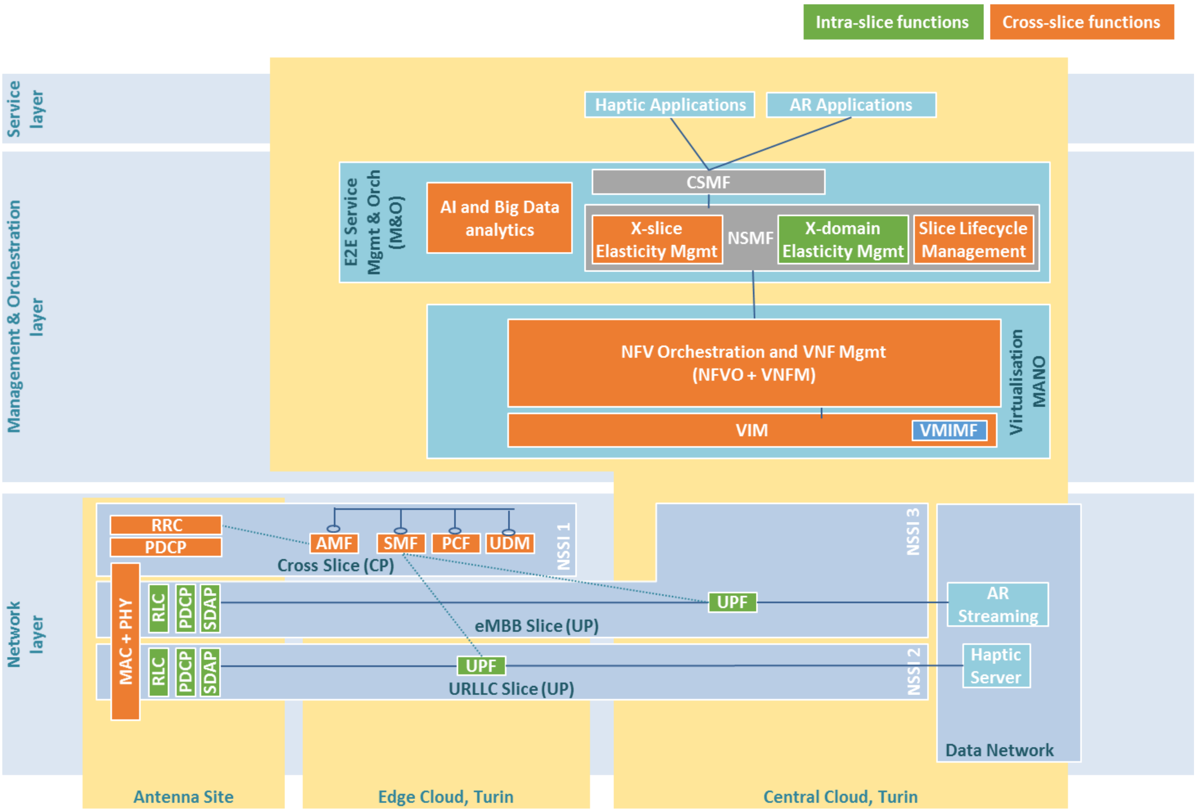


Figure 5-17: Targeted functional architecture for the Touristic city use case

In the Network layer, the testbed implements two network slices: an enhanced Mobile Broadband (eMBB) communication and an Ultra-Reliable Low-Latency Communication (URLLC), one. They are used to provide two different services: the high-res video streaming for the Augmented Reality applications and the haptic server that connects the avatars for their interactions. They have the following deployment characteristics:

- eMBB network slice: The eMBB network slice deliver the high resolution 360 video to the mobile user. In the Radio Access Network (RAN), the slice uses the common PHY and MAC layers of the testbed radio infrastructure, while the higher layers are slice-specific due to customisations reflecting specific service requirements. The RRC instead, is common to both slices. The CP functionality is shared across slices, while the UP function (UPF) is dedicated to each slice. In terms of deployment, the core functions are deployed in the central cloud, as well as the UPF. Also, the application server run in the central cloud,
- URLLC network slice: The URLLC network slice is utilised for delivering the low latency haptic interactions among the avatars (one fixed and one mobile). The radio deployment is equivalent to the eMBB network slice. Also, the core function setup is similar in terms of sharing and deployment. However, the UPF may be moved from one cloud to the other according to the specific load of the network, according to the inputs coming from the elasticity modules deployed in the NFV-O.

The management of the network comprises an implementation of the 3GPP elements CSMF, NSMF and NSSMF that, in turn, include specific elasticity modules such as the network slice admission control. The testbed includes both PNFs and VNFs that are managed by a VM-based virtualisation approach and the related MANO modules. The MANO stack is a simplified one, that relies on a VIM and an ad-hoc implementation of the VNFM and NFV-O. Nevertheless, container-based virtualisation may be included, particularly for the radio functions. The loop is closed by monitoring modules that report the current load to the management modules that use this information (e.g., network load, cpu load) to trigger both cross-slice and intra slice elasticity algorithms.

6 Conclusions and Outlook

This deliverable has refined the baseline architecture of 5G-MoNArch (from [5GM-D2.1]) towards the "Initial Overall Architecture". Particularly, the design of the 5G-MoNArch overall functional architecture has followed the baseline requirements and related KPIs for 5G-MoNArch [5GM-D6.1] and identified gaps from [5GM-D2.1]. Building on the target KPIs and the gaps identified, the main contribution here is to design an architecture that (i) takes the current SotA on 5G architectures, from previous projects as well as standardisation efforts, (ii) addresses the gaps identified within those architectures, and (iii) provides a complete architecture design, comprising SotA and novel modules as well as the descriptions of interfaces between them.

The proposed architecture consists of four different layers identified as Service layer, Management & Orchestration (M&O) layer, Controller layer, and Network layer. A key contribution of this deliverable is the definition of the role of each layer, the relationship between layers, and the identification of the required internal modules within each of the layers. In the proposed architecture, multiple management domains for E2E network slice deployment and operation have been explored from both 3GPP and ETSI NFV perspectives. In particular, the proposed initial architecture extends the reference architectures proposed by 3GPP and ETSI NFV by building on these architectures while addressing several gaps identified within the corresponding baseline models.

In order to meet E2E network slice requirements and operation, several intra-slice and cross-slice (i.e., inter-slice) innovation elements have been identified that can impact the operation of the CN or RAN NFs. In terms of inter-slice management and control, the following modules have been developed: (i) slice-aware RRM with both intra and inter-RAN configuration modes, (ii) utilisation of network and UE data analytics in slice selection and radio resource optimisation, and (iii) slice-aware functional operation and admission control. These functions require novel algorithms and solutions that are critical in order to realise and efficiently operate network slices' resources. The fundamental guidelines for these solutions have been defined in this deliverable.

The architecture design has also addressed the interaction between intra-slice and cross-slice control functions and different implementation options for the control functions' realisation at RAN-level. In this context, the interactions needed for several functionalities between intra- and inter slice control functions at CN and RAN levels have been identified, namely (i) mobility management, (ii) radio access technology selection or (iii) context sharing. The conceptual interaction between these functions will be leveraged in further refinements of the architecture to specify the required interfaces for these interactions.

The Controller layer is an optional architectural layer of 5G-MoNArch RAN consisting of intra-slice and cross-slice controllers, for re-programmability and functional re-configuration of decomposed RAN functions. The use of these layers will depend on the need for providing this level of programmability and flexibility for specific network functions.

Beyond the overall architecture design, another key contribution of this report is the intermediate design of some of the key modules within the architecture to address various identified gaps. To this end, three enabling innovations (and the associated network functionalities) have been developed, namely flexible cloudification of the mobile network protocol stack, adaptive network slicing via inter-slice control and management, and experiment- and implementation-driven modelling and optimisation. Novel approaches for the design of these modules have been presented here, including a preliminary evaluation for many of the procedures.

The ultimate goal of the proposed architecture is to allow for the instantiation of slices that can satisfy specific requirements. Therefore, the proposed architecture accommodates potential NFs and solutions to achieve slice resiliency, security, and elasticity. These functions can be thus instantiated by the 5G-MoNArch architecture when deploying slices that need to provide the corresponding services.

Remaining work towards the final deliverable D2.3 includes the final design of the overall architecture, in particular the "internals" of the innovative modules identified within the architecture and the respective interfaces. In conjunction with WPs 3 and 4, the final novel functions and algorithms for resource-elastic operation as well as for customised security and resilience will be integrated into the overall architecture of the addressed use cases and testbeds. This will also comprise the work on the concrete network slice blueprints that are required when employing the 5G-MoNArch slice design and slice lifecycle management operations. These will provide the conceptual foundation for the concrete implementation work in WP 5 as well as the evaluation and validation of WP 6.

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Appendix A Summary of 5G System Gaps Identified by 5G-MoNArch

In the first deliverable from WP2 of 5G-MoNArch (D2.1) [5GM-D2.1], a baseline architecture has been delineated. This baseline architecture is based on the consolidated view coming from the work of the relevant fora, consortia, SDOs (such as 3GPP and ETSI), 5G-PPP Phase 1 projects along with 5G-PPP working groups (WGs). Following that delineation, a 5G system gap analysis was performed, identifying the additional modules/mechanisms that are required in addition to the baseline architecture to meet the 5G objectives. Furthermore, an overview of 5G-MoNArch innovations along with their mapping onto the identified gaps has been provided. A summary of the gap analysis is outlined as follows.

(1) **Inter-dependencies between NFs co-located in the same node**: Traditional protocol stacks have been designed under the assumption that certain NFs reside in the same node, i.e., fixed location and NF placement; while they work close to optimality as long as such NFs are co-located in the same node, they do not account for the possibility of placing these NFs in different nodes. The logical and temporal dependencies between NFs should be relaxed and (as much as possible) removed to provide a higher flexibility in their placement.

(2) **Orchestration-driven elasticity not supported**: It is necessary for the architecture to flexibly shift NFs to nodes that better fit the specific requirements of each covered service; when doing so, it is necessary to take elasticity considerations into account.

(3) **Fixed functional operation of small cells**: In the current networks, the functional operation of small cells does not change relative to service requirements or the location of the small cell, which can be, e.g., unplanned and dynamic. That is, the functional operation and the associated operation mode of the small cells based on the pre-determined functional operation remain fixed. This can also incur higher operational expenditure (OPEX), when the network is planned for the highest or peak service requirements. However, slice-awareness and 5G tight KPIs can necessitate on-demand flexible small cell operation.

(4) **Need for support for computational offloading**: Current architectures do not fully support delegating costly NFs beyond the network edge towards RAN (e.g., for cases like group mobility in D2D context). Addressing this gap can result in saving on energy consumption, signalling overhead or to offload resource demanding tasks when needed.

(5) **Need for support for telco-grade performance (e.g., low latency, high performance, and scalability)**: Most of management and orchestration technologies are inherited from IT world. Adopting such technologies in the telco domain without key performance degradation is a great challenge as the added functionalities in the control and M&O layer, as well as the more modular NFs, should still offer the same telco grade performance, without degradation.

(6) **E2E cross-slice optimisation not fully supported**: Architecture should allow for the simultaneous operation of multiple network slices with tailored core / access functions and functional placements to meet their target KPIs.

(7) **Lack of experiment-based E2E resource management for VNFs**: Current 5G systems are missing E2E resource management of VNFs that takes advantage of E2E software implementations on commodity hardware in a dynamic manner. Indeed, most of the proposals so far rely on simplifying assumptions that yield simple but possibly unrealistic models. To design algorithms that perform well in reality it is necessary to rely on more elaborate, experiment-based, models.

(8) **Lack of a refined 5G security architecture design**: There are various critical gaps in the literature and architectural deployments related to orchestration & management, accountability, compliance & liability, as well as performance and resilience.

(9) **Lack of a self-adaptive and slice-aware model for security**: E2E network slicing demands a revaluation and research on various aspects of traditional security (e.g., privacy, integrity, zoning, monitoring, and risk mitigation).

(10) **Need for enhanced and inherent support for RAN reliability**: RAN reliability should be a built-in solution/element of the architecture, through the application of mechanisms such as multi-connectivity and network coding.

(11) **Indirect and rudimentary support of telco cloud resilience mainly through management and control mechanisms**: The architecture should address resilience in a

structured way taking into account different aspects (e.g., individual network elements (NEs)/NFs, telco cloud components, fault management, and failsafe mechanisms).

(12) **Need for (radio) resource sharing strategy for network slices**: While basic mechanisms for multi-slice resource management have been studied in 5G-PPP Phase 1 projects, elastic mechanisms need to be devised that improve the utilisation efficiency of the computational and radio resources by taking advantage of statistical multiplexing gains across different network slices.