5Genesis

5TH GENERATION END-TO-END NETWORK, EXPERIMENTATION, SYSTEM INTEGRATION, AND SHOWCASING

[H2020 - Grant Agreement No. 815178]

Deliverable D2.2

5GENESIS Overall Facility Design and Specifications

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List of Acronyms

Acronym	Meaning
5G PPP	5G Infrastructure Public Private Partnership
5G-IA	The 5G Infrastructure Public Private Partnership
AP	Access point
AR	Augmented Reality
BYOD	Bring Your Own Device
BSS	Business Support System
CA	Carrier Aggregation
CAPEX	Capital Expenditure
CESC	Cloud-Enabled Small Cell
CO	Central Office
CoMP	Coordinated Multi-Point transmission/reception
CPRI	Common Public Radio Interface
C-RAN	Cloud-RAN
CSP	Content Service Provider
CUPS	Control and User Plane Separation
DoS	Denial of Service
DDoS	Distributed Denial of Service
DU	Digital Unit
E2E	End To End
eICIC	Enhanced Inter-Cell Interference Coordination
eMBB	Enhanced Mobile Broadband-5G Generic Service
eMBMS	Evolved Multimedia Broadcast Multicast Services
eNB	eNodeB, evolved NodeB, LTE eq. of base station
EU	European Union
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
EUTRAN	Evolved Universal Terrestrial Access network
FDD	Frequency Division Duplexing
gNB	gNodeB, 5G NR, next generation NR eq. of base station
GPP	General Purpose Processor
HetNet	Heterogeneous Network
H-RAN	Heterogeneous RAN
ICIC	Inter-Cell Interference Coordination
ICMP	Internet Control Message protocol
IDS	Intrusion Detection System
IOT	Internet of Things
KPI	Key Performance Indicator
LPWA	Low Power Wide Area
LTE	Long-Term Evolution
LTE-A	Long-Term Evolution - Advanced
MANO	NFV MANagement and Organisation

Acronym	Meaning
MCS	Mission Critical Services
MEC	Mobile Edge Computing
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
mMTC	Massive Machine Type Communications-5G Generic Service
MONROE	Measuring Mobile Broadband Networks in Europe.
MPTCP	Multipath TCP
NFV	Network Function Virtualisation
NFVI	Network Function Virtualisation Infrastructure
NSMF	Network Slice Management Function
NR	New Radio
OAI	Open Air Interface
OAM	Operations, Administration & Management
OF	OpenFlow
ONAP	Open networking Automation Platform
OPEX	Operational Expenditure
ORI	Open Radio Interface
OSM	Open Source MANO
OSS	Operations Support System
OTT	Over-The-Top
PCell	Primary Cell
PCI	Physical Cell ID
PCRF	Policy and Charging Rules Function
PDCP	Packet Data Convergence Protocol (PDCP)
PoP	Point of Presence
P-GW	Packet Data Node Gateway
PLMN	Public Land Mobile Network
PNF	Physical Network Functions
PPDR	Public Protection and Disaster Relief Systems
RAN	Radio Access Network
RRH	Remote Radio Head
RRM	Radio Resource management
RU	Radio Unit
SDN	Software Defined Network
SDO	Standard Developing Organisation
SDR	Software Defined Radio
STA	Station
TCP	Transmission Control Protocol
UAV	Unmanned Aerial Vehicles
UDP	User datagram Protocol
UE	User Equipment
uRLLC	Ultra-Reliable, Low-Latency Communications
WSMP	Wifi Service Management Platform

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Executive Summary

In the evolution of the telecommunication system towards a fully deployed 5G network, we have reached the phase of verifying the new technologies and validating the 5G network Key Performance Indicators (KPIs) in an end-to-end (E2E) approach. The 5GENESIS project, under the EC ICT work programme, brings together several 5G platforms with the end goal to unveil the potential of a truly full-stack and E2E 5G Facility that meets the targeted KPIs.

Towards this end, 5GENESIS has proposed a functional architectural blueprint relevant to the implementation of an experimental Facility, capable to execute trials and KPI validation activities. On the basis of the work performed as part of the analysis and requirements study presented in Deliverable D2.1, this current deliverable sets out to expand the architectural blueprint to a reference architecture specification that will:

- facilitate a common view across the five Platforms, while preserving the Platforms' specific technological features and administrative independence,
- enable interoperability between the Platforms and re-usability of common components
- support further experimentation projects, in particular those focused on vertical markets, offering one common interface towards the experimenters,
- engage a wide diversity of technologies and chain innovations that span over all domains, achieving full- stack coverage of the 5G landscape,
- unify heterogeneous physical and virtual network elements under a common coordination and openness framework exposed to experimenters or vertical industries,
- enable E2E slicing and experimentation automation,
- align with existing 5G standards and pre-existing H2020 work.

The present document starts with a short review of the main requirements as provided in deliverable D2.1. It then presents a distilled summary of the technologies and standards that the project builds upon, discusses how the 5GENESIS approach is related to these, and documents the envisaged contribution towards the implementation of a 5G experimentation platform. Based on this background and the well-defined architectural design principles introduced, the study delves into the 5G Facility reference architecture to specify in more detail each of the three layers (introduced in D2.1) and their components, as well as interactions among them, concluding to a concrete reference architecture specification. Finally, each Platform presents in a compact manner which reference architecture components will be enhanced in the context of the 5GENESIS project and what are the candidate technologies that might be used as starting points.

The key technical achievements of this deliverable can be summarized as follows:

- Introduction of the reference architecture for the Experimentation Facility, which will be used by all the individual Platforms,
- Description of the components and sequence diagrams for the different architectural layers, as well as for the east/west interface to peer Platforms,
- Documentation of the 5G technologies that will be integrated into the Platforms for further alignment with 5G standards,
- Presentation of the proposed enhancements and starting points in terms of technologies used for the architectural components per Platform.

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1. INTRODUCTION

This deliverable presents the work undertaken as part of task T2.2 of the 5GENESIS project. The main goal for this task is to deliver the reference architecture for the 5GENESIS experimentation Facility, which brings together into a common view a wide variety of supporting 5G technologies at different layers in the Platform.

The key target of the 5GENESIS Facility is to support 5G experimentation and, thus, the overall Facility design is conducted from this angle. The design and development from this perspective will facilitate the validation of 5G capabilities and 5G KPIs for different services coming from various vertical industries. In addition, the project is bringing in concepts such as a common access framework for verticals, alignment with relevant 5G standards, technological advancements in domains such as spectrum management, multi-domain E2E orchestration, the interaction of infrastructure from multiple administrative and experimentation domains.

To this end, Task 2.2 explored several topics, as follows:

- *Pre-existing technological and architectural landscape*: the project looked at existing 5G-related technologies and standards that are related to our reference architecture specification. Together with a summary of the requirements analysis coming from D2.1, this work represents the background onto which we built upon. Section 2 presents our work in this direction.
- *Concepts and design principles underlying the architectural design work:* the project explored the concepts that directed our architecture design and clearly stated a set of design principles that form the basis of our work. Section 3.1 presents this work.
- *Specification of architectural components for each of the three layers of the blueprint architecture:* based on the blueprint architecture described in D2.1, this deliverable introduces the components in each of the three layers – Coordination, Management & Orchestration and Infrastructure. The architecture specification is based on well-established goals, guiding concepts and design principles. The specification of the components is accompanied by sequence diagrams that detail the flow of information in the architecture. Section 3.2 presents the details for the three architectural layers.
- *Specification of east/west interface between peer platforms:* this task explored various ways of delivering a light inter-connection between two Platforms of the Experimentation Facility and presented the resulting conclusion, together with the sequence diagram that details such interaction in Section 3.3.
- *Per-platform planned enhancements for the components in each of the three layers in the architectural blueprint:* this deliverable presents in a compact, easy-to-read format, what enhancements are planned for each component per platform. We also present the existing technologies that are considered as starting points for each of the components per Platform. Section 4 covers these aspects.

This deliverable also contains detailed descriptions of the technological advancements that will be instantiated in the Platforms, referring to the network and management domain.

It delivers a coherent reference architecture to be used throughout the rest of the project. Parts of this reference architecture will be refined in the context of work in WP3 (Implementation), WP4 (Integration, Operation & Maintenance), and WP5 (Tests and Verification), while a comprehensive and refined version of the deliverable – including the architectural findings across the next phases of the project (e.g., common interfaces) – is scheduled to be provided in deliverable D2.4 due Month 24.

Beneficiaries of this deliverable are:

1. The Project Consortium to (i) crystallize a common understanding of the technologies that form the basis of our work, (ii) create a uniform approach to the development of the platform architecture, and (iii) be able to map further work to the right project tasks according to this uniform architecture,

2. The research community and funding EC organizations, (i) to get an understanding of the standards, technologies, and design principles that underline the architectural design of 5GENESIS, (ii) to get a detailed picture of the reference architecture that underlies the 5GENESIS experimentation facility, and (iii) to understand how each platform in the facility implements this architectural blueprint,

3. The general public to get a better understanding of the underlying components and design approach behind the 5GENESIS experimentation Facility.

2. 5GENESIS Overall Facility Design Requirements and Ambition

Moving from the existing network-specific definition and provisioning of services to the 5G envisioned application-driven, flexible, dynamic network services instantiation, the technical capabilities of 5G pave the way for new service paradigms and business opportunities, at the same time introducing additional stakeholders and roles. Great emphasis needs to be put on pilots and experiments to ensure that the technology will be leveraged to the maximum, while at the same time satisfying the stakeholders' expectations to the full extend.

5GENESIS focuses firmly on the urgent drive to facilitate the execution of 5G trials by designing and implementing an Experimentation Facility realised through five, diverse in terms of capabilities and geographically distributed Platforms, in Athens, Málaga, Limassol, Surrey and Berlin. Through the Facility, the project shall exhibit the 5G capabilities and validate 5G PPP Key Performance Indicators (KPIs) and shall fulfil specific innovations applied to the Platforms' implementation.

This section presents the dominant factors that influence and shape the 5GENESIS Facility architecture design, that are mainly: (1) the requirements as identified in task T2.1 and described in detail in deliverable D2.1; (2) an understanding of the architectural landscape, as well as standards and technologies in the 5G domain; (3) the ambition of the 5GENESIS project. These factors are discussed in detail in the following three sub-sections. Subsection 2.3 outlines the 5GENESIS approach and its relation to existing systems.

2.1. Summary of Facility Design Requirements

5GENESIS works towards establishing the 5G Experimentation Facility through five, diverse in terms of capabilities and administratively independent, experimentation Platforms. The guiding principles that shape the Facility specification denote that:

- The 5GENESIS Facility is distributed and is comprised of various geographically dispersed Platforms,
- The Platforms are partially complementary in terms of features, nevertheless aligned to the proposed common reference architecture,
- The Platforms are administratively independent, exposing open interfaces for verticals experimentation and light inter-platform coordination,
- The Platforms accommodate multiple experiments, that can be executed concurrently, coming from various verticals with diverse requirements,
- The Platforms are fully interoperable and can be interconnected in order to form a truly E2E Facility.

To cater for the interoperability and homogeneity mandated by the guiding principles, the high-level blueprint depicted in D2.1 has been proposed as part of Task 2.1 to become the common reference among the member Platforms. The Blueprint defines a 3-layer architecture addressing the Coordination, Management & Orchestration and Infrastructure functional domains.

The experimenter interacts with the Coordination layer to define the service to be deployed and the required network capabilities (the slices). Then the Coordination layer processes the experiment definition and controls the execution by requesting services to the Management and orchestration layer. The Management and Orchestration layer creates the slices, deploys the Network Services (comprised of VNFs and PNFs) and configures the infrastructure elements to allow the final users to connect to the service. The Infrastructure layer provides the requested resources, comprised of software and hardware infrastructural elements.

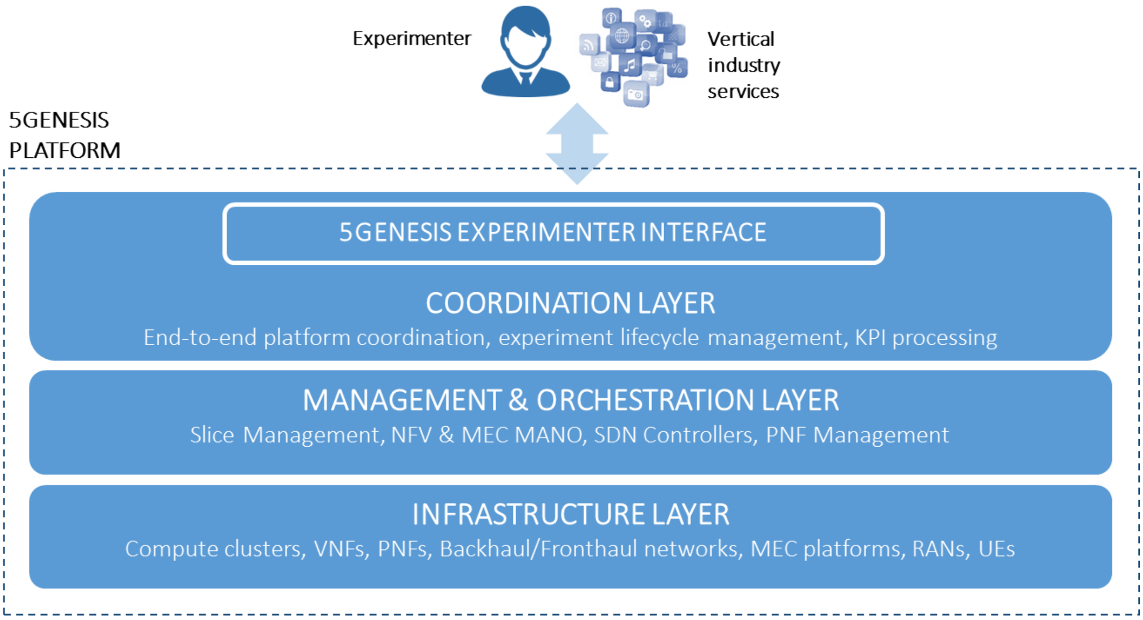

Figure 1: 5GENESIS Experimentation Blueprint

The analysis work for requirement elicitation resulted in a set of Functional and Non-Functional Requirements, either mandatory or optional, which are extensively described in Deliverable D2.1. The functional requirements are organised following the blue print layers as appropriate.

A synopsis of the functional requirement analysis reveals:

- For the **Coordination layer**, eighteen (18) essential requirements have been identified, that cluster around five broad functional domains:
    - *Experimenter Interface*: Related to Open APIs towards experimenters, Facility and Platform Inventory, Experiment Definition, Vertical Experimenter Dashboard and Profiling Experimentation Configurations,
    - *Execution of the Experiments*: Related to Experiment Pre-evaluation, Experiment execution, Experiment life cycle, Inter-experiment Coordination, Southbound Control APIs for Experiment Execution, Experiment Data Storage and Maintenance, Adaptation for Communication with Management,
    - *Measurements and KPIs reporting*: Related to KPIs Validation and Evaluation, Experiment Monitoring, Transparency in Experiments Measurements,
    - *Security*: Requirements related to Experiment Data Isolation and Security Analytics,
    - *Inter-platform Experimentation*.

- For the **Management and Orchestration** layer, seventeen (17) essential requirements have been identified, that cluster primarily around four broad functional domains:
    - *Slice Management:* including service automation: Referring to Slice Management, Slice Isolation, Slice Stitching and Inter-Platform Slice Coordination, Coexistence of Multiple Network Slices and/or Services, Network Slice Support for User Equipment (UE) and Quality of Service Mapping,
    - *Management and Organisation* (MANO): Referring to Resource Catalogue per Service, Adaptation of Service Scale Up and Down, Flexible and Fast Allocation of Network Resources, Distributed NFVI on User or Service Demand, Network Service Composition and NFV Management and Organisation,
    - *Mobile Edge Computing Management:* Extending MANO requirements for MEC management, referring to Resource Catalogue, Adaptation of Services, Flexible Allocation of Resources,
    - *Real-time Network Monitoring.*
- For the **Infrastructure layer**, twenty-two (22) essential requirements have been identified. Most of them can be clustered in the following functional domains:
    - *5G NG Core network*: referring to QoS Management Interface, network function virtualisation infrastructure, SDN Support,
    - *Backhaul network:* addressing High Backhaul Bandwidth, Link Aggregation,
    - *5G NR*: Referring to the use of Regulated Spectrum, 5G Deployments, Support Small Cells and D-RAN as well as Multi-RAT interoperability and/or aggregation,
    - *5G End-User equipment:* (Flexible Configuration of User Equipment),
    - *Multi-access Edge Platform:* Referring to the Experimentation on the Edge Node, Edge Isolation Support and MEC Infrastructure Deployment and Integration,
    - *Virtualised Computing & Management:* Referring to the Infrastructure support via virtual machines or containers, as well as, to the availability of the proper management APIs that are used by the MANO layer components.
- **Cross-layer** requirements, referring to more generic functionalities across the layers, include: KPI Validation (to measure, collect, process, validate and present), Automation, Integration of Satellite Communication, Mobility Support and Management.

On top of the functional requirements of the 5GENESIS Facility, a number of non-functional requirements have been identified, and can be summarised as follows:

- **Standard** ICT systems non-functional requirements, such as scalability, extensibility, maintainability, modularity and interoperability,
- **5GPP Performance KPIs** for Capacity, Ubiquity, Speed, Latency, Reliability, Density, Location Accuracy, Energy Efficiency, Service Creation Time, Network Management CAPEX and OPEX Reduction,

- **Quality of Experience**, in relation to User Perceived Quality, End to End Security Guarantees and Performance of the Network Life Cycle Functions,
- **5GENESIS valued** such as Network Seamless Authentication, Privacy, Authorisation, Service Continuity, and Peak Radio Latency.

2.2. Survey of Existing Architectures and Enabling Technologies

This section surveys existing architectures and enabling technologies that influence our design decisions and affect the architecture definition. The survey is structured per technological domain. The following section, Section 2.3, will discuss how 5GENESIS is based on these technologies and how the different techniques and related standards (Table 1)**Error! Reference source not found.** described in this section influenced our architectural decisions.

Table 1 : Related standards discussed in each subsection

Subsections	SDOs or Fora
5G Service Based Architecture	3GPP
Computing and Networking Virtualisation	ETSI
Network Slicing	3GPP
Multi-Radio Access Technologies	3GPP
Other Technologies for Backhaul	3GPP; IEEE

2.2.1. 5G Service Based Architecture

This subsection analyses the main path towards the 5G Architecture. The aim is to define the implementation options related to possible architecture models.

The mobile core network is responsible for functions such as session management, mobility, authentication and security. The 5G system architecture development is covered in 3GPP's TS 23.501 [1]. Regarding current 3GPP standardization work, Release 15 has recently been finalized and work has started on Release 16. It is worth mentioning that parts of the research conducted in the project has the ambition of targeting other standardization bodies and future 3GPP releases as well.

3GPP TS 23.501 defines the 5G System Architecture as a Service Based Architecture (SBA), i.e. a system architecture in which the system functionality is achieved by a set of Network Functions (NFs) that provide services to other authorized NFs to access their services. The SBA aims to decouple end-user services from the basic network and the platform infrastructure, in order to speed up the network and thus the service delivery.

5G can be introduced either in standalone mode (Option 2 and Option 5) using 5GC or in non-standalone mode, using EPC (Option 3) or 5GC (Options 4 and 7) which are defined in 3GPP [1] [2]:

- Standalone (SA) model uses only one radio access technology. The 5G NR or the evolved LTE radio cells and the core network are operated alone. Three variations of SA are being defined in 3GPP (Figure 2):
  - Option 1 using EPC and LTE eNB access, i.e. as per current LTE networks,
  - Option 2 using 5GC and NR gNB access,
  - Option 5 using 5GC and LTE ng-eNB access.

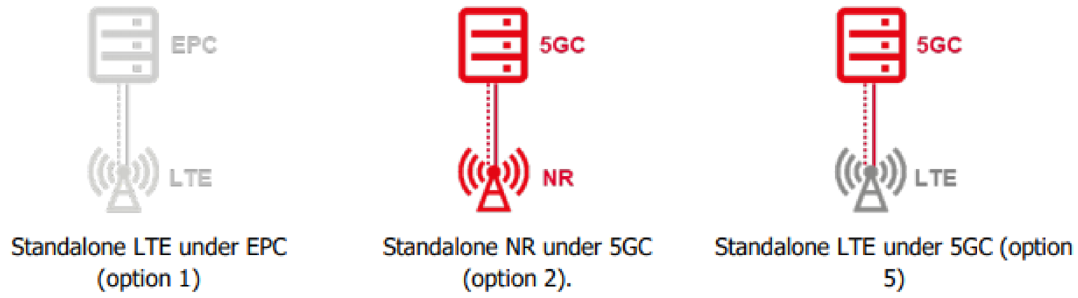

Figure 2: Overview of SA options [2]

- Non-Standalone (NSA) mode combines multiple radio access technologies. The NR radio cells are combined with LTE radio cells using dual connectivity to provide radio access and the core network may be either EPC or 5GC depending on the choice of the operator. Three variations of NSA are defined in 3GPP (Figure 3):
  - Option 3 using EPC and an LTE eNB acting as master and NR en-gNB acting as secondary,
  - Option 4 using 5GC and an NR gNB acting as master and LTE ng-eNB acting as secondary,
  - Option 7 using 5GC and an LTE ng-eNB acting as master and an NR gNB acting as secondary.

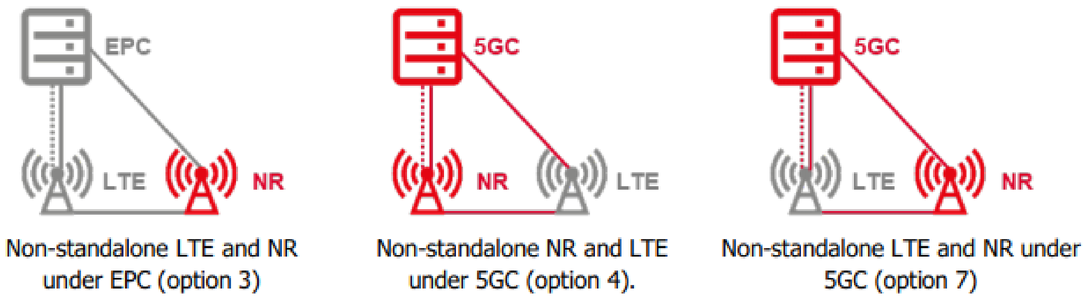

Figure 3: Overview of NSA options [2]

The 5G System architecture shall leverage service-based interactions between Control Plane (CP) and NFs where identified. One of the goals is to minimise the dependencies between the Access Network (AN) and the Core Network (CN). The architecture is defined by a converged CN with a common AN-CN interface that integrates different types of access networks, e.g. 3GPP access and non 3GPP access.

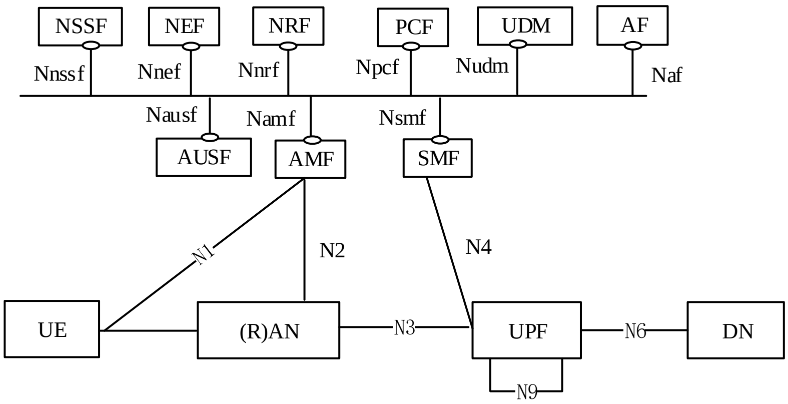

Figure 4 : Next-Generation Service-Based Architecture

(Source: 3GPP TS 23.501 v15.3.0, Figure 4.2.3-1)

The specification defines the core architecture, the functional elements and the interfaces between the elements. The main objective is to deploy 5G in standalone mode, thus deploying 5G core without LTE technology dependencies. Figure 4 above depicts the reference SBA architecture for the standalone mode, which includes the 5G next generation core shown in TS 23.501.

The 5G CN – between the dotted lines in Figure 5 – supports the connectivity of the UE via non-3GPP access network. According to TS 23.501, non-3GPP access networks shall be connected to the 5G CN through N3IWF (non-3GPP InterWorking Function) using the N2 and N3 interfaces.

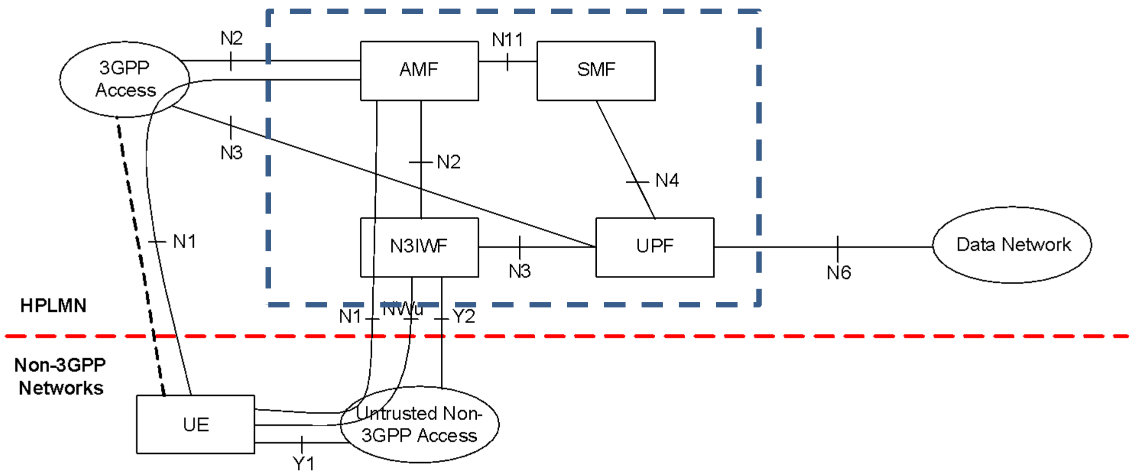

Figure 5: Non-roaming architecture for 5G Core Network with non-3GPP access

(Source: 3GPP TS 23.501, Figure 4.2.8.2.1-1)

In terms of pertinent releases, Release 15 serves as the current baseline and is considered completed in the absence of minor corrections. Release 16 phase 1 is in progress and it is expected to finish in 2020, while Release 17 started in June 2018 and the end date is not yet published[1]. It is noteworthy that Release 15 considers the interaction with non-3GPP networks for the NSA model based on EPC – describing policies for trusted and untrusted access – and the SA interconnection model is expected in the coming releases.

2.2.2. Network Slicing

This section describes the current state of the art on 3GPP specifications related to network slicing. Network slicing support is part of the new SBA specified by 3GPP in TS 23.501 [1]. The terms and conditions in which network slicing is supported in this architecture is detailed in Section 8 of 3GPP TR 23.799. The definition of network slicing provided by the 3GPP and adopted by 5GENESIS, proposes that: "The network slice is a complete logical network (providing Telecommunication Services and Network Capabilities) including Access Network (AN) and Core Network (CN)."

In detail, a 3GPP defined network slice within a PLMN includes the following:

- the Core Network Control Plane and User Plane NFs, as described in 3GPP TR 23.501,

and in the serving PLMN, at least one of the following:

- the NG Radio Access Network described in 3GPP TS 38.300,
- the N3IWF functions (interworking function) to the non-3GPP Access Network.

The management and orchestration of network slices is specified in 3GPP TR 28.801 that also defines the concept of Network Slice Instance (NSI). An NSI includes all functionalities and resources necessary to support a certain set of communication services, thus serving a certain business purpose. An NSI is composed by NFs and the connectivity between them is described by the Network Slide Template (NST).

The TR 28.801 also specifies the related management functions required to implement the slicing instances:

- **Communication Service Management Function (CSMF):** Responsible for translating the communication service related requirement to network slice related requirements,
- **Network Slice Management Function (NSMF):** Responsible for management and orchestration of NSI,
- **Network Slice Subnet Management Function (NSSMF):** Responsible for management and orchestration of NSSI.

The lifecycle of an NSI is shown in Figure 6. The process depicted includes the stages for the preparation phase, then the instantiation (Instantiation, Configuration and Activation) phase, and after that the operation (Run Time) phase. Finally, the NSI is decommissioned when the slice is no longer needed. The instantiation, execution and decommissioning phases should be part of the "Network Slice Management Function".

[1] https://portal.3gpp.org/#55934-releases

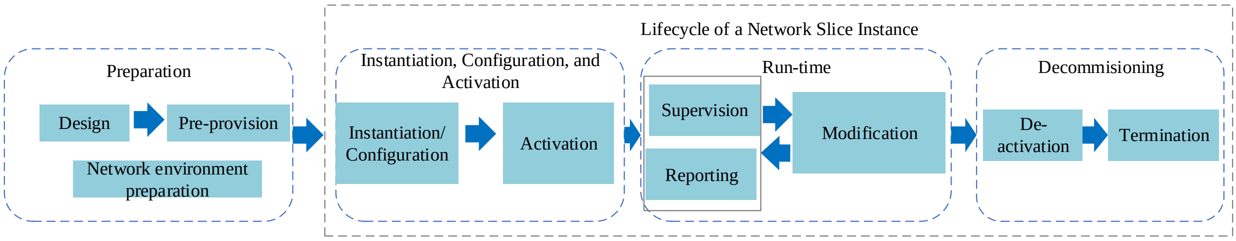

Figure 6: Lifecycle of an NSI

The list of Standard Slice Types (SST) specified by 3GPP in TS 23.501 is shown in Table 2. It is also supported the usage of non-standards STT.

Table 2: Standardised SST values

Slice/Service type	SST value	Characteristics
eMBB	1	Slice suitable for the handling of 5G enhanced Mobile Broadband.
URLLC	2	Slice suitable for the handling of ultra- reliable low latency communications.
MIoT	3	Slice suitable for the handling of massive IoT.

In a recent work item, ETSI NFV analysed the case of Network Slicing as defined by 3GPP and provided a report on the synergies between NFV and 3GPP in order to support slicing in the frame of 5G [3]. The report analysed the information models and concluded to the correlation depicted in Figure 7.

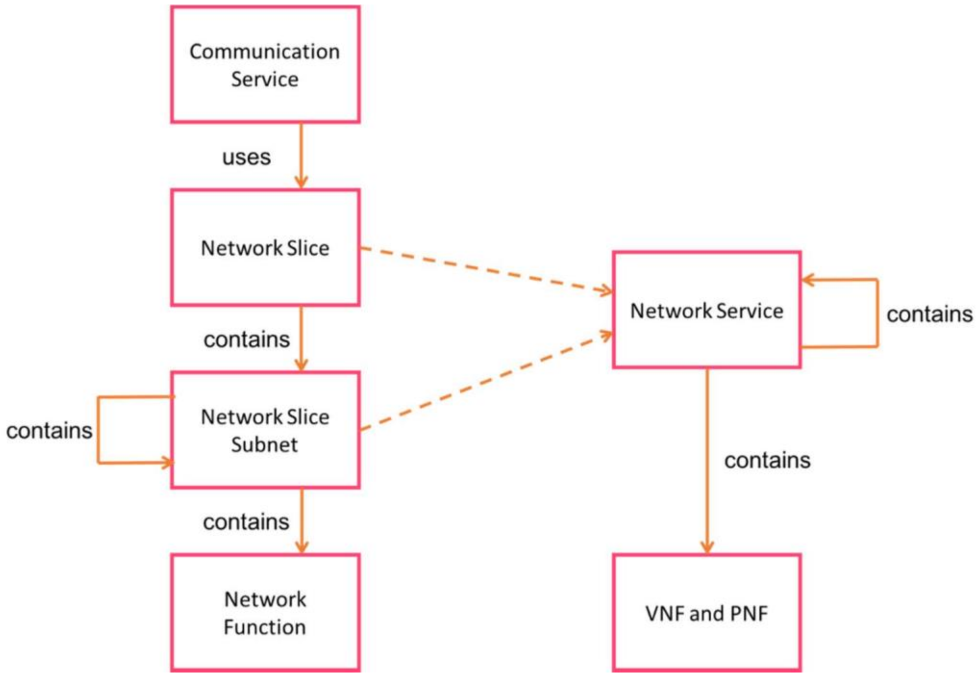

Figure 7: Relating the information models

Under this view, ETSI NFV does not handle the:

- Application-aware NS configuration and management,
- VNF application layer configuration and management,
- Management and deployment of PNFs, or their application layer configuration and management.

At architectural level, the same report presents the following envisioning of Network Slice Management within the NFV framework (Figure 8). To properly interface with NFV-MANO, the NSMF and/or NSSMF, the type of NS or set of NSs, VNFs and PNFs that can support the resource requirements for a Network Slice Instance (NSI) or Network Slice Subnet Instance (NSSI) needs to be determined, as well as whether new instances of these NSs, VNFs and the connectivity to the PNFs need to be created or existing instances can be reused. From a resource management viewpoint, a NSI can be mapped to an instance of a simple or composite NS or to a concatenation of such NS instances. The different NSIs can use instances of the same type of NS (i.e. they are instantiated from the same NSD) with the same or different deployment flavours. Alternatively, different NSIs can use instances of different types of NSs.

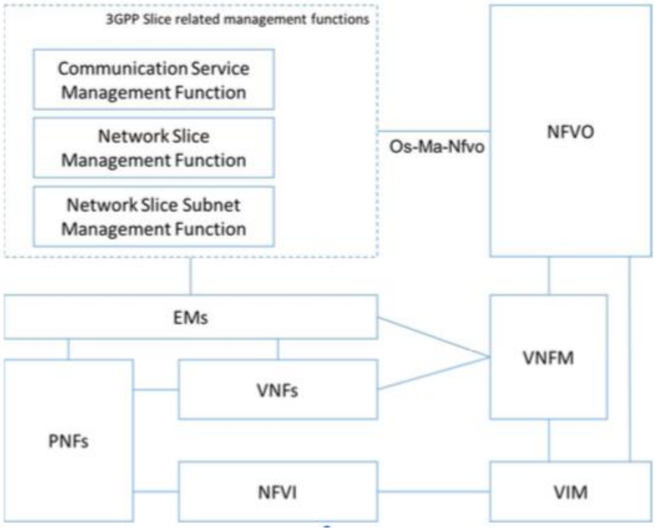

Figure 8: Network Slice management in NFV framework

2.2.3. Computing and Networking Virtualisation

2.2.3.1. Network Function Virtualisation (NFV)

NFV technology was initiated in 2012 by the European Telecommunications Standards Institute (ETSI) NFV Industry Specification Group (NFV ISG), to allow customers to transfer the networking functions from vendor-specific and proprietary hardware appliances to software hosted on commercial off-the-shelf (COTS) platforms [4]. The main idea is to provide the network services in virtual machines (VMs) working in Cloud infrastructures, where each VM can perform different network operations (e.g., firewall, intrusion detection, deep packet inspection, load balancing) [5]. The main benefits of deploying network services as virtual functions are: (1) flexibility in the allocation of network functions in general-purpose hardware; (2) rapid implementation and deployment of new network services; (3) support of multiple versions of service and multi-tenancy scenarios; (4) reduction in capital expenditure (CAPEX) by managing energy usage efficiently; (5) automation of the operational processes, thus improving efficiency and reducing operational expenditure (OPEX) costs.

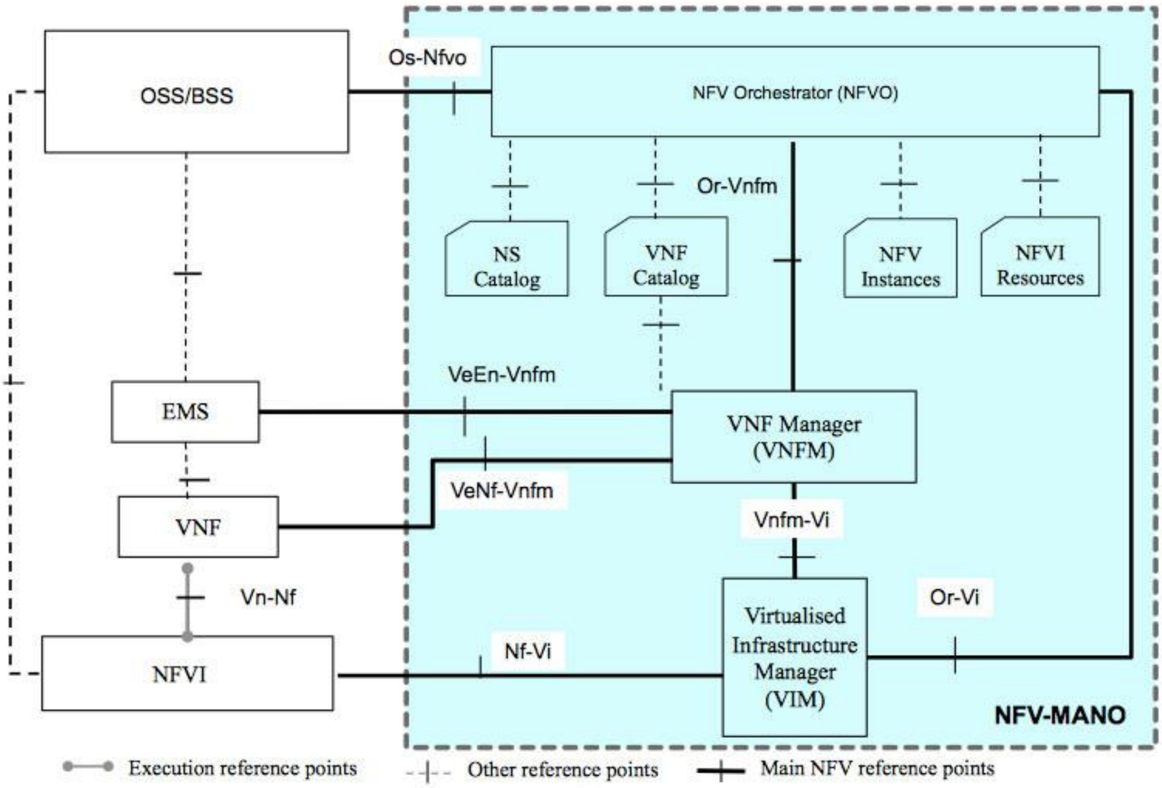

Figure 9: NFV MANO Architecture

The NFV Architecture depicted in Figure 9 is comprised of four main functional elements [6]:

- **The Virtual network function (VNF)** layer virtualises a certain NF, that operates independently of others. A particular VNF can run on one or more VMs and it can be divided into several sub-functions called VNF Components (VNFCs). VNFCs monitoring is performed using Elemental Management Systems (EMSs). Automation of the operational processes is feasible and results in improvement of the efficiency and reduction of the OPEX costs.
- **The NFV infrastructure (NFVI)** is comprised of all the hardware and software required to deploy, operate, and monitor the VNFs. Particularly, NFVI includes a virtualisation layer necessary for abstracting the hardware resources (processing, storage, and network connectivity) to ensure independence of the VNF software from the physical resources. The virtualisation layer is usually composed of virtual server (e.g. Xen [7], Linux-KVM [8], Dell-VMware [9], etc.) and network (e.g., VXLANs [10], NVGRE [11], OpenFlow, etc.) hypervisors. The NFVI Point of Presence (NFVI-PoP) defines a location for network function deployments as one or many VNFs.
- **NFV management and orchestration (MANO)** is comprised of three components:

  - *The virtualised infrastructure manager (VIM)*, which manages and controls the interaction of VNFs with physical resources under its supervision (e.g. resource allocation, deallocation, and inventory),
  - *The VNF Manager (VNFM)*, which is responsible for managing the VNF life-cycle (e.g., link initialisation, suspension, and termination),
  - *The NFV Orchestrator (NFVO)*, which is responsible for realising network services on NFVI. Also, NFVO performs monitoring operations of the NFVI to collect information regarding operations and performance management.
- **Operations support systems and business support systems (OSS/BSS)** element comprises the legacy management systems and assists MANO in the execution of network policies. The two systems (OSS and BSS) can be operated together by telecommunications service providers or operators, either automatically or manually to support a range of telecommunication services.

Additional details on choices for orchestrators are presented in Annex 6.1.

2.2.3.2. Multi-access Edge Computing (MEC)

In late 2014, ETSI launched the Industry Specification Group Mobile Edge Computing (ISG MEC)[2] to develop a standardized, open environment for efficient and seamless integration of applications from vendors, service providers, and third-parties across multi-vendor computing platforms at the edge of mobile networks. The objective of this group is to create a standardized and open environment to integrate applications and services from different providers into multi-vendor Multi-access Edge Computing platforms.

Starting with use case driven requirements, ISG has defined the reference architecture and a set of APIs for the key MEC interfaces. These include specifications relating to the essential functionality of:

- The application enablement platform (API framework),
- Specific service-related APIs,
- Management and orchestration-related APIs.

Between the end of 2016 and the beginning of 2017, ISG MEC expanded the scope of its activities to include additional access technologies besides cellular, hence the renaming itself into *Multi-Access* Edge Computing but keeping the same consolidated MEC acronym.

MEC has been designed to offer cloud-computing capabilities at the edge of the network, that can be used by operators and third parties, such as content providers or application developers. MEC provides an ultra-low latency and high bandwidth platform for all kinds of applications and services, which can be quickly and flexibly deployed. This way, multiple use cases (e.g. IoT, video analytics and location services) are enabled, leading to a new ecosystem based on the edge of the network and its capabilities.

MEC provides a comprehensive set of requirements to guide vendors developing the solution, with a scope that includes the orchestration and applications/services lifecycle management

[2] The ETSI MEC public page is available at http://www.etsi.org/technologies-clusters/technologies/multi-access-edge-computing

within the Edge nodes. It excludes any customer/developer facing process and the physical and virtual infrastructure.

ETSI-MEC focuses on 3 main topics:

1. Definition of a Reference Architecture, including an Orchestration layer for the Edge,
2. Services/applications Lifecycle Management (application start-up and register, find application, subscribe to application, etc.),
3. Definition of 4 Service APIs (Radio Network Information Service, Location Service, UE Identity Service and Bandwidth Management Service) and the general principles for Mobile Edge Service APIs.

MEC initiative has defined a framework for Edge Computing, that is implemented with a reference architecture [12], which includes the system entities that build the complete solution and the reference points between them. The architecture in Figure 10 highlights the system- and host- level components, whereas the network level is not visible as there are no MEC-specified reference points to access those entities. Solid lines represent reference points that are in scope of the MEC specifications, whereas dotted lines are deemed out of scope, either left to proprietary implementation or in scope of other SDOs.

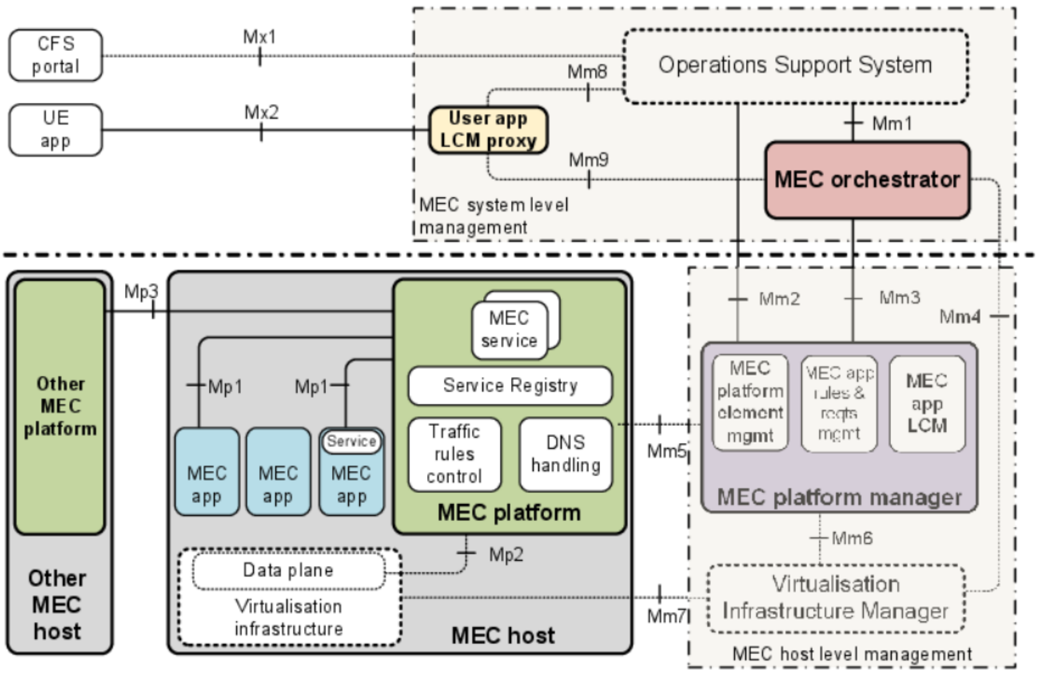

Figure 10: ETSI MEC reference architecture

The **MEC host** is a logical element that embraces the MEC platform and the virtualization infrastructure which provides compute, storage and network resources to the MEC applications. The virtualization infrastructure includes a data plane element that enforces the forwarding rules received by the MEC platform when routing the traffic among the applications, the services and the networks.

MEC applications run as virtual machines on top of the virtualization infrastructure provided by the MEC host. The applications interact with the MEC platform over the Mp1 reference point to handle the MEC services available in that MEC host. In fact, applications may consume MEC services, but also provide them to the MEC platform, which can further provide those to other applications. At the time of instantiating a MEC application in the system, the system level management validates the service and resource requirements that may be indicated by the MEC application, e.g., its constraints on maximum allowed latency. The selection of the target MEC host(s), as well as the decision to relocate applications, is performed based on these requirements.

The **MEC platform** encompasses a collection of baseline functionalities that are required to run applications on the MEC host and enable MEC applications to discover, advertise, provide and consume the MEC services. Such essential functionalities include traffic steering, provisioning of persistent storage, and time references. In addition, the MEC platform supports configuring the local DNS proxy/server, in order to direct the user traffic to the MEC applications. Different MEC platforms may communicate to each other through the Mp3 reference point.

The **MEC platform manager**, still at the host level, consists of the MEC platform element management, the MEC application lifecycle management (LCM) and MEC application policy management functions. The application LCM is responsible for instantiating, terminating and relocating a MEC application, as well as providing indications to the MEC orchestrator on some application related events. The policy management includes authorizations, traffic rules, DNS configurations and resolving issues when a set of policies are in conflict.

The **Virtualization Infrastructure Manager (VIM)** is responsible with managing the virtualized resources for the MEC applications, like allocating and releasing virtualized compute, storage and network resources, therefore it has the Mm7 reference point towards the Virtualization Infrastructure for this purpose.

The **MEC orchestrator** plays a pivotal role as it has the supervision over the resources and capabilities of the entire MEC system. In many ways it is similar to the ETSI Network Functions Virtualization Orchestrator (NFVO) and has similar responsibilities, like coordination and control of instantiation, healing, resolving resource conflicts, etc. Uniquely to MEC, however, the MEC Orchestrator is also responsible of managing the MEC applications and the related procedures by supporting onboarding of the applications, checking their integrity and authenticity, validating the policies associated with them and maintaining a catalogue of the available applications. It is up to the orchestrator to ensure that application requirements (e.g. latency, user throughput, etc.) are fulfilled, with the selection of the appropriate target MEC host, and, if required, also to trigger the application relocation.

From the MEC system point of view, the operator's **OSS** is the highest-level management system to assist in getting the MEC applications running in the desired location of the network. OSS receives requests to instantiate and terminate the mobile edge applications from the Customer Facing Service portal (CFS) and from the clients in the user equipment and works with the orchestrator to fulfil these.

The **CFS** acts as an entry point for the 3rd parties and is envisioned to be similar to other such portals in cloud platforms. The **User application lifecycle management proxy (User app LCM proxy)** is a function that MEC application clients can use to request services related to onboarding, instantiation and termination of the applications. For example, it can be used to request application relocation from an external cloud into the MEC system. The User app LCM proxy can be only accessed from the mobile network - including from the UE - using the Mx2 interface.

In addition to the functional elements, the Reference Architecture defines three types of reference points, which enable interaction between the different system entities and support the Life Cycle management [13]:

- Mobile edge platform functionality (**Mp**) reference points,
- Management reference points (**Mm**),
- Reference points connecting to external entities (**Mx**).

2.2.3.3. Software Defined Networking (SDN)

The basic architecture of SDN uses modularity-based abstractions, similar to formal software engineering methods. A key abstraction of the SDN paradigm is the separation of the network control and forwarding planes. Conceptually, in SDN networks, resources are treated as a dynamic collection of arbitrarily connected forwarding devices with minimal intelligence. A typical SDN architecture divides processes such as configuration, resource allocation, traffic prioritisation, and traffic forwarding in the underlying hardware, using a 3-tier structure consisting of application, control, and data planes as highlighted below and depicted in Figure 11.

- **Tier 1 - Data (forwarding) plane**: The Data plane is the set of network physical components (switches, routers, virtual networking equipment, firewalls, middle box appliances, etc.), almost the same as in conventional networks. It aims at efficiently forwarding the network traffic based on a certain set of rules as instructed by Tier 2 - Control plane. That way, SDN technology makes the hardware (physical) infrastructure of the network rather flexible, by removing intelligence and isolated configuration per network element, and moving these functionalities to the control plane.
- **Tier 2 - Control plane**: The Control plane contains the logic to decide on how traffic can be routed through the network from one node to another based on end user application requirements. Such control logic is incorporated into external software application elements called SDN controllers. An SDN controller handles all Tier-1 forwarding devices by translating individual application requirements and business objectives (e.g. traffic prioritising, access control, bandwidth management, QoS) into relevant programmable rules and announcing them to the data plane. By introducing programmability through these rules, flow tables can be manipulated in individual elements in real time, based on network performance and service requirements.
- **Tier 3 - Application plane**: The Application plane is the layer to include all applications and services of the network. Conceptually, the application plane is situated above the control plane to enable applications communicating with data plane through requesting network functions from control plane, while performing network related tasks. The Application plane uses APIs to capture the individual application parameters (delay, throughput, latency, etc.), based on which the SDN controller configures the individual network elements in the data plane for efficient traffic forwarding [14] [15].

The SDN controllers represent the focal point in the SDN system to oversee and manage the flow of traffic among southbound switches/routers (network-wise) by using APIs according to each application requirements. In order for an SDN controller to perform such tasks, it requires information regarding the state of the underlying network provided by collections of pluggable modules, which perform different information gathering procedures about the data link layer devices, providing full inventory of the network below, as well as devices capabilities. In addition, when the SDN controller has full view of the network, it adds extensions and bundles to improve the controller capabilities and provide customised forwarding rules created using algorithms that analysed information and statistics gathered from the network.

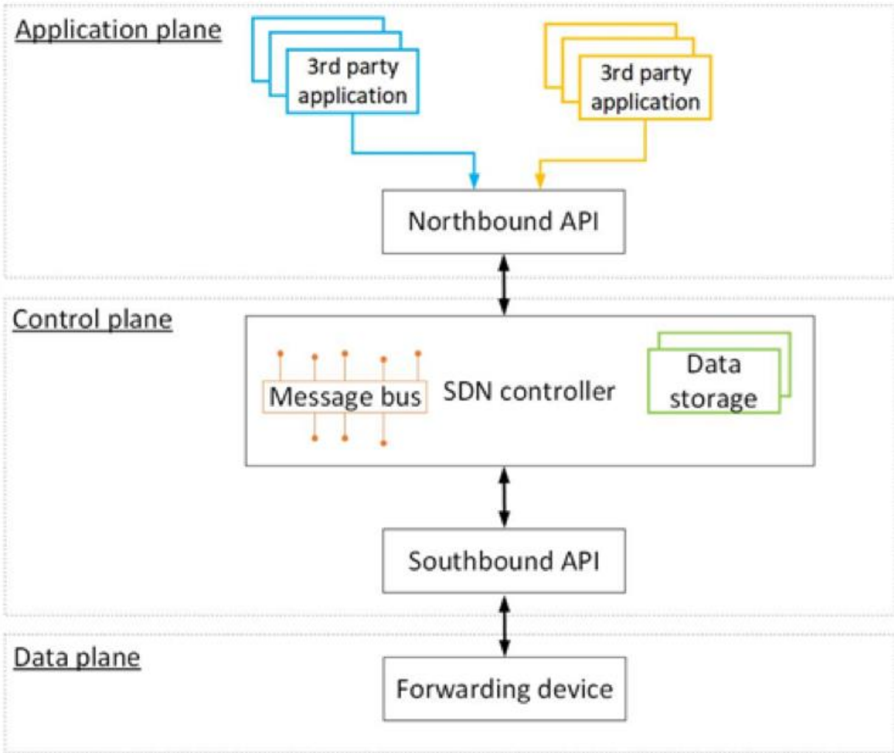

Figure 11: Three-tier structure of a typical SDN controller

There are two different approaches to reach the logical centralization of the SDN Control Layer - Single and Distributed controller [16]:

- **Single Controller:** In single controller implementation, only one instance of an SDN controller exists in the network. All the switches are connected and controlled by that single machine in a centralized manner. Many early SDN adopters are using this solution.
- **Distributed Controller:** The distributed controller addresses the two principal issues that appear in the single controller approach: (a) Scalability, when the SDN controller has to handle multiple forwarding path requests from switches, and (b) Robustness, when, in case of a controller failure, switches are not be able to forward new packets and eventually the entire network collapses. In the distributed controller approach, the SDN control plane consists of multiple SDN Controllers, which can share the load in the network equally. Furthermore, one controller can take over another controller when it crashes, thus fixing both issues that exist in the single SDN controller.

2.2.4. Multi-Radio Access Technologies (RAT)

2.2.4.1. 5G New Radio

5G New Radio (NR) is the name of the new air interface introduced by 3GPP Release 15 and is the successor to LTE, LTE-Advanced and LTE-Advanced Pro. The first version of 5G-NR has been released in Summer 2018 and an updated version is supposed to be ready in Summer 2019 under 3GPP Release 16, coinciding with first products appearing on the market.

5G-NR is fundamentally different from LTE in many aspects. First of all, it has been designed from ground up for a very wide frequency range, including mm-Wave. Secondly, it supports a diverse set of uses cases: **enhanced mobile broadband** (eMBB), ultra-reliable **low latency communications** (URLLC) and **massive machine type communications** (mMTC).

To support all these new features, 5G-NR introduces many innovations, such as flexible numerology (i.e., different bandwidth parts can have different subcarrier spacing and slot durations), new channel codes (LDPC and polar), flexible TDD structure, and support for beam management for deployments in mm-Wave bands. 5G-NR promises throughputs definitely higher than 1Gpbs per user and latencies down to 1ms (at the PHY layer).

The specifications allow two modes of operation: standalone (SA) and non-standalone (NSA). First deployments will most likely use the latter, meaning that 5G-NR will only work with the support of a 4G network that acts as an anchor providing all the signalling information. This mode also works with legacy 4G core networks.

2.2.4.2. WiFi

The 5G Facility will emphasise on innovative radio spectrum use and sharing, including licensed, unlicensed, and licensed-shared access, advanced backhauling and coexistence of multiple RAT technologies. One of the challenges is to demonstrate effective massive IoT and multimedia communications in a multi-RAT and multi-spectrum licensing scheme environment, by employing RRM solutions. More specifically, a 5G NR network and several RATs, including LTE-A and WiFi will be deployed in order to validate 5G KPIs.

Hence, WiFi has become an integral part of their strategy to address the capacity limitations of future networks. That's why the efforts into interconnecting mobile and WLAN networks have been accelerated. For the NSA model, 3GPP's TS 23.402 and TS 33.402 specifications fully cover the needed interfaces to complete the interconnection between 3GPP and non-3GPP networks. For the SA model, we have to wait until Release 16 is finalised to understand how to seamlessly interconnect WiFi with 5G networks.

2.2.5. Other Technologies for Backhaul

2.2.5.1. Satellite

Satellite backhaul is an ideal choice for MNOs to expand their service in rural areas where the existing infrastructure is limited or non-existent. The cost of installing terrestrial backhaul infrastructure in such rural areas is very high and does not leave any margin for profit. In the case of developing countries, the Average Revenue Per User (ARPU) is very low to justify the expansion of the network, whereas in developed countries the population density is low. The use of satellite for backhaul reduces the infrastructure cost, while at the same time providing access to new users.

Satellite backhauling is also beneficial for serving remote areas that are geographically challenging. In this case, fixed links are usually non-existent and terrestrial wireless links might need several hops to enable backhauling, thereby increasing the cost and making the link more prone to outages. Satellite links require only a line-of-sight of the satellite with the terminal and they overcome this problem relaying the traffic to the core network.

Even though satellite backhaul connectivity is more suited for rural and remote areas, it can also be very useful in urban areas in cases where a very quick solution is required. In such scenarios, a satellite terminal and backhaul link can be installed within a day. Additionally, when the terrestrial backhaul links are congested due to high traffic demand or outage, satellite links can serve as bandwidth extension or as backup solution for service continuity.

In the context of 5G, coverage expansion will not be limited to terrestrial unserved and underserved areas, but will also extend offshore, thereby satisfying the 5GInfrastructure Association (5GIA) requirement for ubiquitous access. Offshore coverage extension can only be achieved via satellite backhauling. Furthermore, and of equal importance, are geostationary Ka-band High Throughput Satellites (HTS), capable of delivering high-speed broadband services to offshore users, which is another requirement in a complete 5G network.

The 5G use case “5G Connectivity Using Satellites” is one of the 74 use cases identified in 3GPP TR 22.891 (Reference Section §5.72) which was produced within the SA1 working group [17]. Furthermore, the following use cases can either be served only by satellites, or the satellite provides a more efficient solution:

- Areas where it is not possible to deploy terrestrial towers: For example, maritime services, coverage on lakes, islands, mountains or other recreational areas that can only be covered by satellites;
- Disaster relief: During natural disasters or other unforeseen events that entirely disable the terrestrial network, satellites are the only option;
- Emergency response: Besides wide scale natural disasters, there are specific emergency situations in areas where there is no terrestrial coverage. For example, a public safety Use Case of an accident in a power plant;
- Secondary or backup connection (limited in capability) in the event of the primary connection failure or for connected cars;
- Connectivity in rural areas that are hard to cover using terrestrial networks;
- Connectivity for remotely deployed sensors, e.g. farms, substations, gas pipelines, digital signage, remote road alerts;
- Low bit-rate broadcast services: Satellites can broadcast wide area emergency messages at a more efficient rate than terrestrial networks.

2.2.5.2. Terrestrial Backhaul

The expected traffic growth in 5G imposes stringent requirements to the transport network [18]. Transport networks are nowadays adopting the paradigm of converged fronthaul and backhaul (BH) infrastructures, integrating advanced wireless access and novel optical network solutions [7]. These solutions comprise mmWave and Sub-6 wireless technologies, or the use of a hybrid optical network platform combining both passive and active optical technologies [19].

Given that not always it is possible to deploy fiber connections and also considering that the increased number of small cells makes not feasible their direct connection to the core network, wireless backhauling of small cells to the macro-cell is considered a cost-efficient solution. A seamless integration of mmWave BH with Sub-6 Non- Line-of-Sight (NLoS) technology is generally recognised as the technology providing the ideal combination of capacity and coverage by operators deploying wireless BH, particularly in complex urban deployments [20].

Such a capacity increase in the BH is expected to be achieved using small cells at mmWave frequencies, being other possibility the use of massive multiple-input-multiple-output (m-MIMO) systems at Sub-6 frequencies. The former is adequate for Line-of-Sight (LoS) links, particularly for fixed antenna deployments, being less suitable for NLoS links, suffering from high attenuation. The latter can multiplex many links, achieving relatively low data rates per link. It is ongoing, however, the research on mmWave addressing the NLoS problem [21] [22] at mmWave frequencies, which would provide both capacity and coverage [23].

Radio links at mmWave bands require high-gain directional antennas and dense small cell deployments to overcome a high near-field path loss and poor diffraction. As a positive feature, high-gain antennas offer interference isolation, providing an opportunity to incorporate self-backhauling, i.e. the very same radios are used both for mobile access and for BH [24]. V-Band (60 GHz) and E-band (70/80 GHz), are commonly used for small cell deployment. The 60 GHz band is mainly considered for small cell deployment in dense urban areas, given the limited range of about 250 m; whereas E-band links might serve larger distances (up to about 2.5 km), usually needed in less populated areas. This difference in range of nodes working at these frequencies originates from oxygen attenuation/absorption, with higher impact to 60 GHz links.

To further increase the data rate of wireless FH/BH links, techniques like LoS-MIMO can be deployed [25], which requires optimal antenna spacing of the transmit antennae and the receive antennae for a given distance. Since this is wavelength dependent, mmWave systems are most suitable for LoS-MIMO transmission. With tolerable separation of the antennae of about 40 cm, orthogonal channels and independent MIMO streams can be achieved over a distance of about 100 m. LoS-MIMO can be further enhanced using hybrid beamforming. This way an even larger number of MIMO streams can be achieved, facilitating ultra-high data rate transport connections for small cells in dense urban areas.

2.2.6. Spectrum management

Spectrum management is a question of national sovereignty. The Administrations in each country define which part of the spectrum is usable for government applications (e.g. military services) and which part of spectrum is usable by non-governmental (e.g. commercial services) applications.

The management of non-governmental spectrum is under the responsibility of the National Regulatory Authorities (NRA). It is the NRA that decides to which radio service it will allocate a given band within a country, authorizes specific networks and/or devices to use a specific part of that band, and defines the conditions under which such networks and devices might use the spectrum.

In principle, to avoid interference resulting from different uses of spectrum in countries close to each-other, the NRA decisions should be aligned with the Radio Regulations (RR) updated by ITU every 4-5 years during a World Radiocommunication Conference (WRC). The Radio Regulations allocate, i.e. reserve, specific bands for specific services. In each band, the majority of countries will follow ITU allocations, although there might be situations where a country is not able to allocate a band to the services indicated by ITU. In such cases, these exceptions are also indicated in the footnotes of the Radio Regulations.

Typically, the NRA authorizes the use of non-governmental spectrum under two different licensing regimes:

- A licensed regime whereby the NRA issues individual rights of use to specific networks and/or devices, so they may use part of the band in an exclusively basis spectrum. The leasing of the spectrum rights was allowed, under certain circumstances.
- A licensed–exempt regime, whereby the NRA automatically issues "general authorizations" to networks and/or devices that ensure they are conformant to radio standards accepted by the NRA in that band.

The spectrum panorama started to change in the last two decades, with several spectrum techniques being pushed by the NRAs in several parts of the world. The most relevant spectrum sharing schemes introduced in the last two decades are described in the Annex 6.3.

For the spectrum sharing feature, vertical spectrum sharing methods have lately emerged in the context of mobile communications. Unlike horizontal sharing solutions where several networks are allowed to access the spectrum with the same priority (e.g. WiFi, Multfire), vertical sharing allows the several networks to access the spectrum with different priorities (e.g. TV white spaces (TVWS), Licensed Shared Access (LSA), Citizens Broadband Radio Service (CBRS)). When the networks use several bands, each band may adopt different type of sharing (e.g. LTE-Unlicensed, Licensed Assisted Access (LAA), LTE-WLAN aggregation (LWA)).

2.3. Facility Approach

Section 2 has surveyed related architectures that influence the overall 5GENESIS architecture design. Although at this high-level view this is not readily apparent, the intention of the consortium as the implementation of 5GENESIS experimental Facility is progressing, is to follow closely the related standards and reuse as much as possible available implementations, while enhancing and expanding functionalities.

Initially, the section has reviewed the 5G SBA architecture, in order to identify the approach, the network functions and the concepts around the new specifications. Under this view, the 3GPP standards such as Release 15 and 16 will be the main path that the project will follow. Moreover, the previous sections have provided an overview of the network slice concept, surveying approaches from different SDOs on how it can be supported. At the moment, network slicing remains a hot issue in the literature as it goes beyond 3GPP and affects other technological domains as well. The initial approach proposed by ETSI will be considered as a first implementation target. However, it is expected that further down the line the implementation will be more complex while including management of resources that are beyond NFV MANO jurisdiction.

The architecture survey has included an overview of three major technologies that offer management and orchestration of virtualised infrastructures and offer programmability and softwarisation, namely NFV, SDN and MEC. All of the above are parts of the enlarged 5G architecture. The study focused mostly on the main architectural components in order to be able to include them in the 5GENESIS architecture design realised in this task.

Finally, an overview of other Radio Access Technologies has been presented, which is also part of the unified, service-based 5G architecture for supporting of Non-3GPP networking technologies. Particular components have been identified, however are not yet visible in the resulting architecture at the moment. The reason is that the actual functions are part of the 5G New Core which is considered as a deployable, configurable set of network functions to be instantiated in the virtualised environment.

All the background technological advances discussed in this section form the basis for the innovation introduced by 5GENESIS and pave the way towards designing a 5G experimentation Facility that will offer the needed features for verticals in the framework of ICT-19 projects. The next section capitalises on the established knowledge on the aforementioned domains, along with specific key principles and requirements in order to design the 5GENESIS Experimental Facility architecture.

3. 5GENESIS Overall Facility Design Specification

5GENESIS has as its main goal the creation of an Experimentation Facility, that spans over five geographically distributed Platforms (in Athens, Malaga, Limassol, Berlin, and Surrey), supporting a diverse set of features. Towards this main goal, we have defined a reference architecture that creates a uniform functional guideline underlying the five Platforms. In this context, the designed reference architecture, (1) facilitates a common view across the five Platforms, while preserving the Platforms' specific technological features and administrative independence; (2) enables interoperability between the Platforms; (3) offers one common interface towards the experimenters and (4) allows for the creation and re-usability of common components across the Platforms (e.g., in the Coordination and Management & Orchestration layers).

The well-established design principles that form the basis of the 5GENESIS architectural design are presented in Section 3.1. These principles, together with the vision and requirements summarised in Section 2, are reflected in the described reference architecture. Section 3.2 presents the reference architecture, starting with a general view across the three layers – Coordination, Management & Orchestration, Infrastructure – and continues with analysing in detail the functionality of the components in each of these three layers. Sequence diagrams that detail the flow of actions between the different components in each layer are presented, as well as the east-west interconnection between two different platforms.

3.1. Reference Architecture Design Principles

This section presents the main concepts and the design principles governing the reference architecture design.

3.1.1. General concepts

Each of the five platforms participating in the 5GENESIS Facility has its own physical topology, architecture and specific technical features. Nevertheless, in the endeavour to create the 5GENESIS Experimentation Facility and make it available for future experiments, the project's proposition envisages the harmonisation of the different Platforms under a common reference architecture, whose higher layer elements are to be replicated across the five platforms.

The resulting reference architecture is ***conceptually aligned with the 3GPP 5G vision*** as expressed in 3GPP TS 23.501 v15.3.0 [1], allowing for experimentation of 5G services. The resulting architecture offers flexible support for different types of requirements, in a service-aware infrastructure with elastic, software-driven and programmable capabilities.

The 5G architecture of 3GPP is defined as service-based together with the interaction between network functions. Architecture elements are defined as network functions that offer their services via interfaces of a common framework to any network functions that are permitted to make use of these provided services. This architecture model, which further adopts principles like modularity, reusability and self-containment of network functions, is chosen to enable deployments taking advantage of the latest virtualization and software technologies [1].

Aligned with the 3GPP 5G vision, the 5GENESIS reference architecture design follows the service architecture and other defined principles to support a co-developed 5GENESIS experimentation Facility, and to allow the architecture to evolve towards a full 5G system. Service functional components are specified, and high-level interfaces between components and layers are well-defined in architecture design. Cross-Platform interfaces are also defined to offer light interconnections between the Platforms.

The 3GPP architecture also specifies the high-level functionality and features of the 5G System for both 3GPP and Non-3GPP access and for the interoperability with the EPC [1], such as supporting for edge computing, network slicing, support for specific service, etc.

Aligned with the 3GPP architecture functionality, the 5GENESIS reference architecture design specifies key 5G functional components in its layer architecture including slicing, edge computing, etc. which will allow 5GENESIS experiments on distinct key features of the 5G system. The 5GENESIS architecture design provides a functional feature mapping in tabular format, as well as planned enhancements, per component per architectural layer for each Platform.

Moreover, this common reference architecture has been designed based on the following concepts:

1. ***preserve and ensure Platform administrative independency, yet support interoperability and interworking** with the other (5GENESIS) platforms when required,*
2. ***allow each Platform to re-use existing components*** and seamlessly incorporate them into the Experimentation Facility,
3. ***present one common and open API towards the Experimenter/Vertical***, thus creating common and open methods for the Experimenter to interface with the Experimentation facility,
4. ***facilitate the re-use of common components*** in the Coordination and Management & Orchestration layers,
5. ***enable inter-connection between two different platforms*** to allow for an experiment (or part of) to be performed in a different platform than the one where the Experimenter submitted the experiment,
6. ***consolidate all elements and functionalities that have been identified as essential in 5G networks*** (at least for Release 15 specifications), including: 5G NR RAN, 5G NG Core, network and resource slicing with service automation, mmWave radio, NFV, SDN, MEC, User Plane/Control Plane separation (CUPS), spectrum management, Cloud-RAN, multi-RAT interoperability and aggregation.

3.1.2. Design Principles

Our architectural blueprint refers to the high-level structures of the system. Architectures can be categorized by their communication style, deployment model, physical layout, etc. based on their areas of focus. To support the co-developed 5GENESIS Experimentation Facility, and to allow the architecture to evolve, the 5GENESIS facility architecture was designed in line with the following set of design principles:

(1) Layered Architecture

A layered architecture model focuses on distributing the roles and responsibilities around a broader technical function. Components within the 5GENESIS architecture are organized into horizontal layers, each layer performing a specific role within the architecture.

- Layer separation: No logic related to one layer's concern should be placed in another layer. Components of one layer can be designed and developed separately from other layers. This allows different 5GENESIS facility layers (e.g., infrastructure) to decouple concerns for independent scale and technology evolution.
- Layer isolation: Components of one layer communicate with associated neighbour layers using well-defined interfaces. Changes made in one layer are isolated to the components within that layer, possibly affecting an associated layer only. For example, the top layer 5GENESIS Facility experimenters communicate through the experimenter interface of the Coordination layer only and will not be affected by infrastructural changes.

(2) Modular Architecture

The modular architecture principle allows the replacement or addition of any component / module without affecting the rest of the system. A modular architecture is needed for the 5GENESIS Facility to (i) make it possible to scale so as to support future use cases without affecting current experimentations, (ii) solve, upgrade and maintain related problems during long periods of experimentation, (iii) improve the usability, and (iv) deliver more experimentation features more frequently. The following three guiding principles are identified for the 5GENESIS Facility:

- Strong encapsulation: hiding implementation details inside components to achieve low coupling between different components. In this way, 5GENESIS Facility partners can work in isolation on decoupled parts of the Facility.
- Well-defined interfaces: well-defined and stable APIs between components will be available. 5GENESIS Facility components can be replaced by any implementation that conforms to the interface specification to allow long term evolution and updating. The interfaces between the components are outside the scope of this document and are planned to be further investigated in the context of WP3; however, the underlying principle applies to our Experimentation Facility reference architecture.
- Explicit dependencies: the relationships between different modules are clearly expressed and verified. As a result, it is ensured that distinct components developed by different partners will work together in the final integrated 5GENESIS Experimentation Facility.

(3) Service Oriented Architecture

The service-oriented architecture (SOA) architectural model focuses on how different business functions of a system work with each other. They are created, exposed and consumed as a set of services. This architectural model is used for the 5GENESIS Facility to (i) allow it to scale to meet the requirements of large scale 5G experiments, (ii) improve the flexibility and reusability, and (iii) enable experiments in another platform. The main guiding principles are:

- **Service statelessness:** Design services by separating them from their state data whenever possible. Shifting away the service state management overhead to make services easier to horizontally scale up for large scale 5G experiments, such as for massive IoT experiments.
- **Standardized service contract:** Adhere to a standard communications agreement and protocol. This allows the 5GENESIS Facility to support interconnection between components from different partners, and also to support coordination with another Platform, regardless of the individual Platform-underlying technology stacks and implementations.
- **Service composability:** Services are components that can be combined to solve complex problems. Reusability is realized by effectively and repeatedly composing services from other services. It increases the 5GENESIS Facility components' reusability and allows extensions for future experiment requirements by recomposing services for various problems.
- **Service discoverability:** Services are supplemented with description meta-data, allowing for effective discovery and interpretation by machines or humans. Platform experimental capabilities should be described and discovered in the service registry or inventory list.

(4) Deployment-agnostic

Deployment agnostic principles minimise the support and maintenance effort needed by the infrastructure and environment of the experiment. Experiments focus on their own code and application logic only. The 5GENESIS Facility will adopt cloud native, container, etc. deployment-agnostic technologies, for efficient and flexible infrastructure usage and demanding future 5G services (while not being 100% deployment-agnostic).

- **Deployment-agnostic**: deployment is enabled in many heterogeneous environments. The 5GENESIS architecture is not specific to one type of network devices, environment, etc., but runs on any combination of execution environments and underlying network infrastructures.

3.2. 5GENESIS Reference Architecture Model

Following up from the requirement analysis, summarised in Section 2.1, the current technological and architectural landscape described in Section 2.2, and aligning with the underlying concepts and principles described in Section 3.1., the project proposes the expansion of the basic three-layer blueprint architecture, described in deliverable D2.1, to a reference architecture that shall support 5G experimentation through the Experimentation Facility.

Figure 12 depicts the components inside each of the three layers – Coordination, Management & Orchestration, and Infrastructure – while also showing connections between the major blocks in the architecture:

- ***Platform Coordination layer*** – The Platform Coordinator layer is responsible for the overall coordination of the platform, achieving overall supervision and E2E configuration for service deployment and management/monitoring. At this layer the interfaces towards the experimenter are exposed, the Experiment Lifecycle is managed, as well as security aspects, and analytics to fulfil the goals of KPI monitoring & validation are implemented. Moreover, this layer is responsible for exposing east/west interfaces to another Coordinator in other 5GENESIS platforms, facilitating interworking.

- *Management and Orchestration layer* – This layer includes functionality related to virtualisation, management of network slices, management of virtualised resources, as well as traditional Network Management System functionality for controlling the Physical Network Functions (PNFs) and other network elements. This layer interfaces with both the Coordination layer (northbound) and the Infrastructure layer (southbound), enabling the mapping of the experiments onto the physical network and ensuring the associated management that comes with this mapping.
- *Infrastructure layer* – This layer involves the E2E components which handle the user traffic, including the 5G Core Network & NFVI, the transport network (e.g. x-haul), the MEC platform and the multi-RAT radio elements, as well as the end-user equipment. The composition of functionalities supported in this layer is considered as platform-specific. This is the layer where many of the 5G-specific enhancements are introduced at the network and user equipment level, as discussed in detail in Section 3.2.3.

Detailed presentation of each of layers is available in subsequent Sections (3.2.1-3.2.3), while Section 3.4 discusses the cross-platform east/west interface.

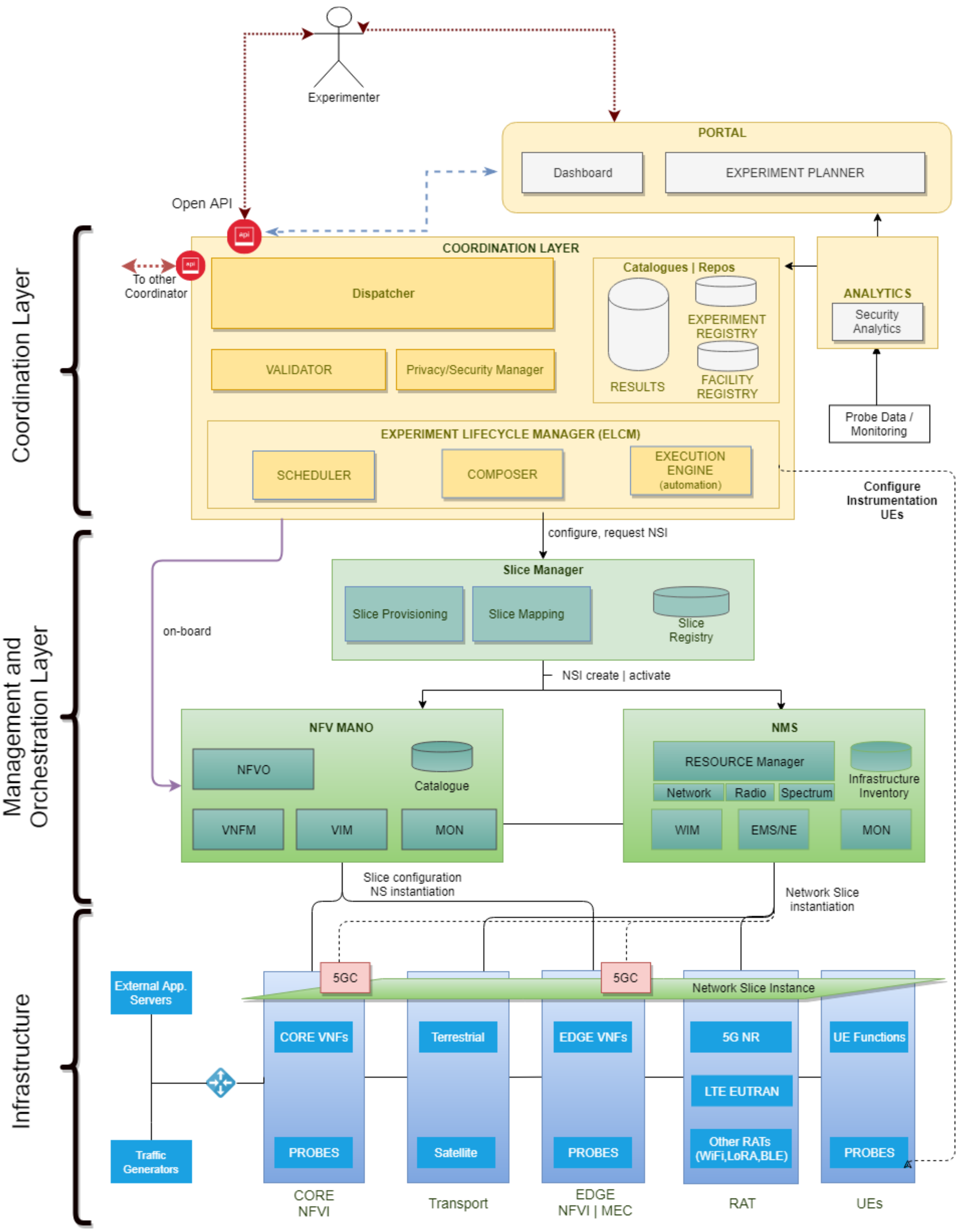

Figure 12: 5GENESIS reference architecture

3.2.1. Platform Coordination layer

The Platform Coordination layer of the 5GENESIS reference architecture is the layer through which the experimenter interfaces with the Facility. At this layer, the east/west interfaces with peer platforms exist, as well as functionality related to experiment specifications, lifecycle management, security aspects.

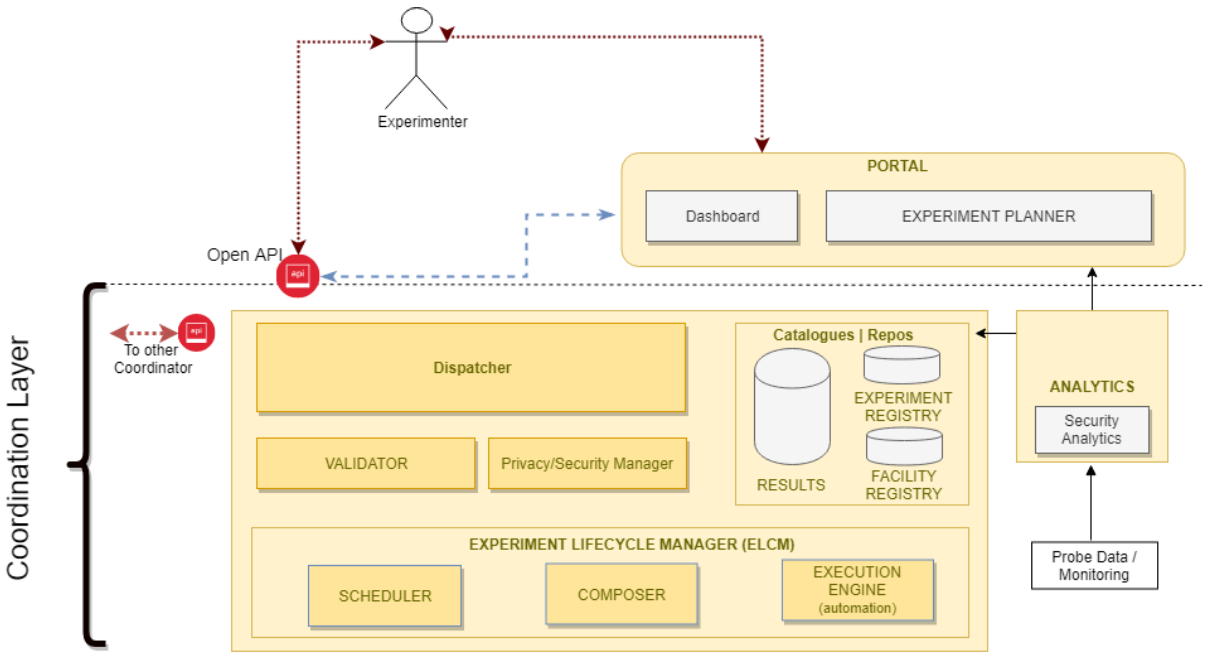

Figure 13: Coordination layer

The architecture of the platform coordination layer is shown in Figure 13. It includes the components described in the following subsections.

3.2.1.1. Portal

The Portal primarily provides the Web UI that exploits the Open API exposed by the Coordinator and secondly allows the experimenter to execute a number of preparatory actions related to the experiment and monitoring of their status as well as visualise the outcome of certain experiments, following the approach adopted in [26]. In detail, the Portal allows (1) on-boarding of service package (i.e. network service, slice and VNF descriptors, VNF images, configuration scripts); (2) on-boarding of testing descriptor (i.e. test scenario definition, scripts); (3) planning of testing cases (i.e. plan execution time, resource reservation, configuration) and (4) access and visualisation of the results of the experiments. The information and data model that the project will adopt for the descriptors included in the service package, shall be in-line with the currently accepted and defined ETSI NFV format (i.e. OSM compatible [27]). Moreover, the project will specify and implement a Network Slice descriptor scheme in order to support the Network Slice creation on top of each platform physical infrastructure. Eventually, the project may extent the descriptor scheme in order to cover specific requirements of the platform that are beyond current MANO jurisdiction.

The Portal includes two main components: i) the Dashboard that essentially provides the UI and methods for presentation and visualisation of the results and ii) the Experiment Planner that acts as means for enabling intuitive experiment configuration and planning operations to the experimenter.

The Portal will use the 5GENESIS Open API to communicate with the coordination block component.

3.2.1.2. 5GENESIS Open API

The 5GENESIS Open API is the interface offered by the Coordination layer for the definition and execution of the experiments. The 5GENESIS Open APIs are designed to be used as an extension point of the features offered by the 5GENESIS platform towards verticals in ICT-19 projects.

The anticipated procedures to be exposed through 5GENESIS Open API are the following:

1. Store and delete descriptors,
2. Consult descriptors available in the database,
3. Validate descriptors,
4. Define experiments,
5. Monitor status of the facility and the experiment,
6. Schedule the execution of a testing experiments,
7. Retrieve measurements and testing reports,
8. Notifications,
9. Access control and authorisation.

The 5GENESIS Open API is used by the Web UI and can be also used directly by advanced users of the platform.

3.2.1.3. Dispatcher

The **Dispatcher** is responsible for managing all the requests received through the 5GENESIS Open API. A normal workflow of the Dispatcher when using the Portal as the entry point to the experimentation platform is the following:

Once the experiment has been configured and the user starts its execution, the Portal will send a notification to the Dispatcher telling that there is a request to execute an experiment. When the Dispatcher receives the notification of running an experiment, it will retrieve the information of the testing case defined previously through the Portal and store it in the **Experiment Registry.** This information will be used to generate the **5GENESIS experiment descriptor file** associated to the experiment, which will include information about VNFs, PNFs and experiment execution. The format of this file will be common to all the platforms, that is, all the platforms should be able to process this file. This experiment description file will be also checked to detect inconsistencies between the parameters configured through the Portal and the features supported by the platform.

Optionally, the experimenter can access the platform directly through the 5GENESIS Open API. In This case, the experimenter has to provide the experiment descriptor to the Dispatcher.

3.2.1.4. Validator

The **Validator** is responsible for validating the uploaded descriptors. The Validator will be invoked in two different phases.

In the first phase, when the experimenter provides descriptors to add components to the catalogue, this component will be a compliant parser that will check if the descriptors are valid 5GENESIS descriptors. It is expected that the Validator will check all the descriptors against the original descriptor scheme in order to structurally and syntactically validate them.

In the second phase, the Validator will be activated by the Dispatcher for every experiment request in order to check the validity of specific configurations and parameters to run the experiment. Apart from a pure check of the range of the parameters, the project will explore more powerful methods to predict whether the propose configuration for the experiment will run properly in the platform. One approach will be the use of model-based testing [28].

3.2.1.5. Privacy and Security Manager

The **Privacy and Security Manager** provides the functionality for adding/removing users and assigning profiles and roles. A secondary role is to define access rules and specifying data privacy issues across the experimenters.

3.2.1.6. Experiment Lifecycle Manager

The **Experiment Lifecycle Manager** is in charge of the execution of the experiment. The **Scheduler** is the sub-component responsible for admitting new experiments and queuing them planning their execution according to the resource or Platform availability and also possible prioritisation. When a certain experiment is considered to be executed, the experiment descriptor will be translated into the specific configuration of the Platform (**Compositor**). Finally, the **Executor** component will communicate with the Slice Manager in the Management & Orchestration Layer, which is in charge of configuring and provisioning the resources and the E2E slice. The **Automation** component is optional, as it depends heavily on the level of automation and non-human interactions available in each platform. This component will allow for the execution of the experiment without human intervention and will influence the application servers deployed at the infrastructure layer and with the user equipment through the Management and Orchestration layer.

3.2.1.7. Analytics

The **Analytics** module collects and analyses the data from the probes available in the Management & Orchestration and Infrastructure layers. This module provides analytics related on KPIs and on traffic anomalies and security issues.

a) KPI computation

The raw measurements collected by the probes deployed in the platform will be post-processed to compute the KPIs related on the use case under test.

b) Advanced big data processing and security analytics

Advanced network insights, either per-service or aggregated, as well as detect and report traffic anomalies, which may correspond to either malfunctions or security incidents. For this purpose, the platform will collect traffic information (e.g. flow data, logs, events) from the measurement probes across the network, normalise and aggregate them in a common storage infrastructure, and employ Machine Learning (ML) techniques for incident detection and classification. In specific, the pipeline of this component will consist of the following stages:

- *Data ingestion, cleaning, normalisation and storage:* at first, the data are collected using various approaches (push / pull), non-relevant data will be discarded, while the relevant data are homogenised to a common format, saved as structured output in a scalable database. Commonly used technologies from the Big Data domain can be used to accommodate collection and storage of vast amounts of information.
- *Analytics:* this is the core operation of the platform. A Big Data processing framework will be employed in order to execute ML algorithms on the stored data, either in batch or streaming modes. The aim will be to detect and classify anomalies, so the analytics pipeline might be comprised of a chain of anomaly detection algorithms, followed by incident classification ones.

3.2.1.8. Coordination layer workflow

Figure 14 depicts the sequence diagram that models the interactions between the different components in the Platform Coordination layer when an experimenter accesses the Portal, defines an experiment based on a predefined type of slice offered by the Platform, and executes it.

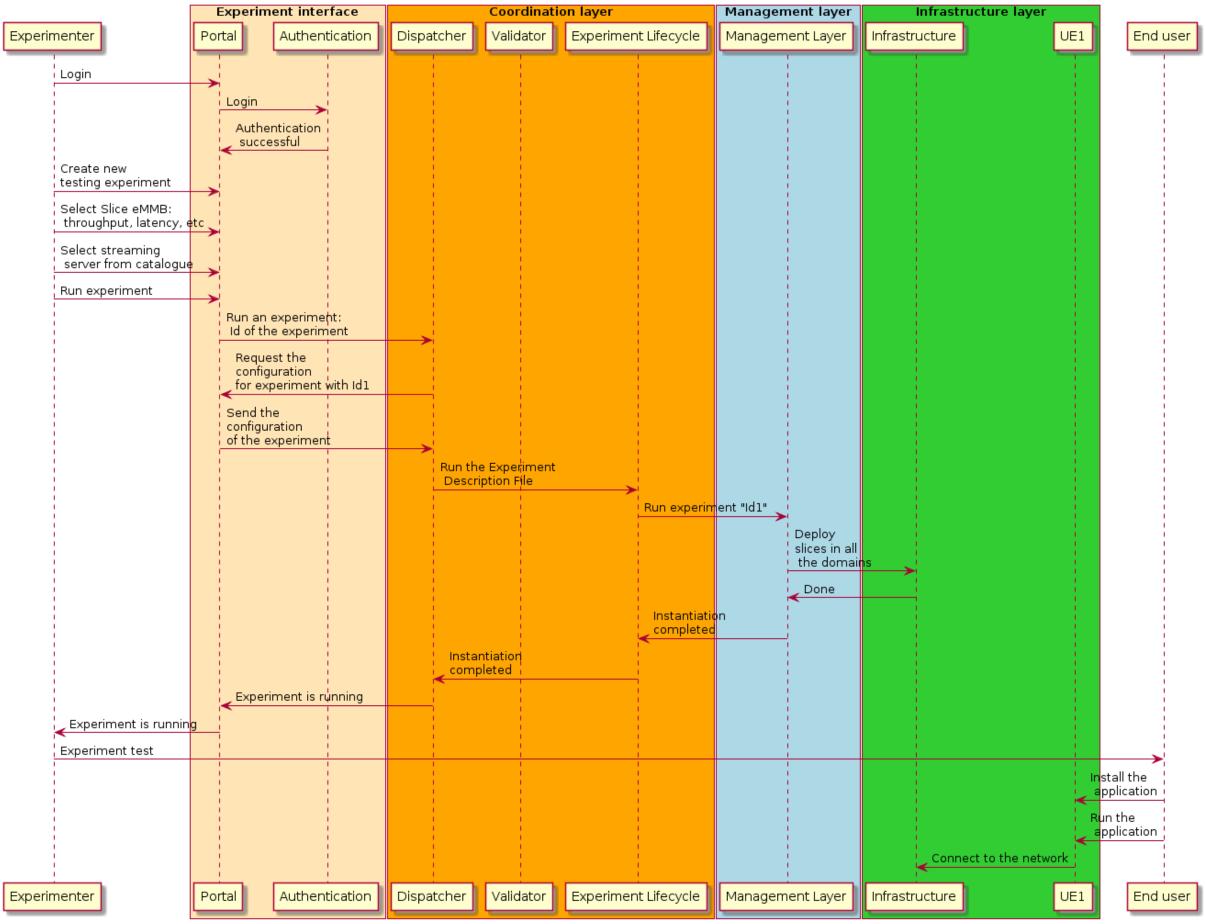

Figure 14: Sequence diagram when using a predefined slice

A different sequence diagram is shown in Figure 15. In this second diagram, the user uploads a VNF descriptor that will be validated before storing it in the catalogue. After that, the experimenter configures a new testing experiment selecting, from the catalogue, the VNFs and radio configurations that will be part of the slice.

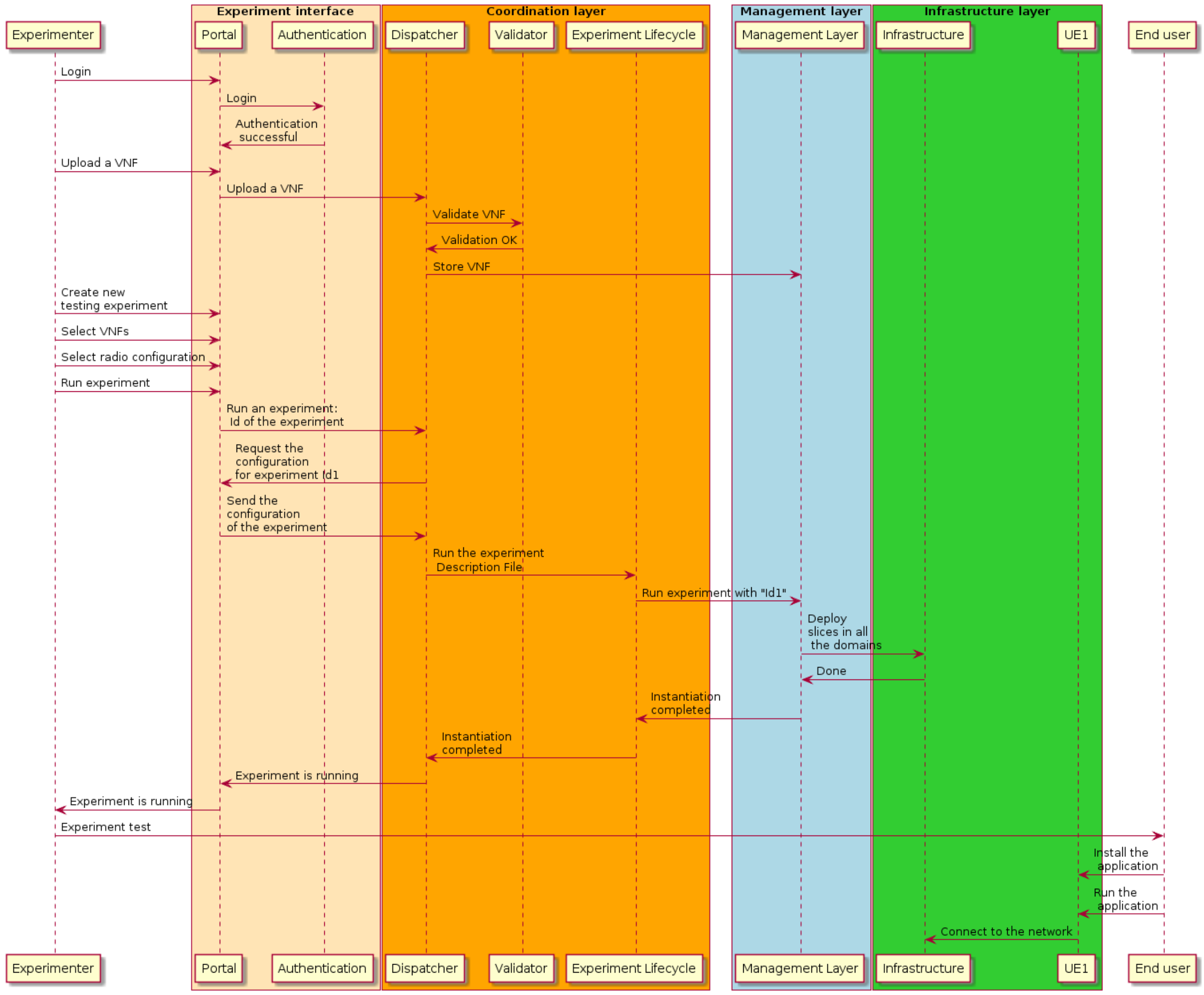

Figure 15 Sequence diagram when the experimenter defines a slice

3.2.2. Management and Orchestration layer

The Management and Orchestration layer of 5GENESIS architecture (see Figure 16) consists of three major components, namely:

1. Slice Manager – responsible for the management of the network slices,
2. NFV MANO – responsible for the orchestration of Network Services and lifecycle management of VNFs,
3. Network Management System (NMS) – responsible for the management of non-NFV resources such as transport network (e.g. back/front-haul, WAN) and Mobile Core/Radio elements (i.e. RAT elements and 5G/4G Core Network Functions).

The Management and Orchestration layer communicates with the Coordination layer via two reference points, one that allows the onboarding of the NS descriptors at the NFV MANO Catalogue and another that connects to Slice Manager in order to accept network slice creation configuration and service deployment requests.

A brief summary of the particular functionalities of the aforementioned components is provided in the following section.

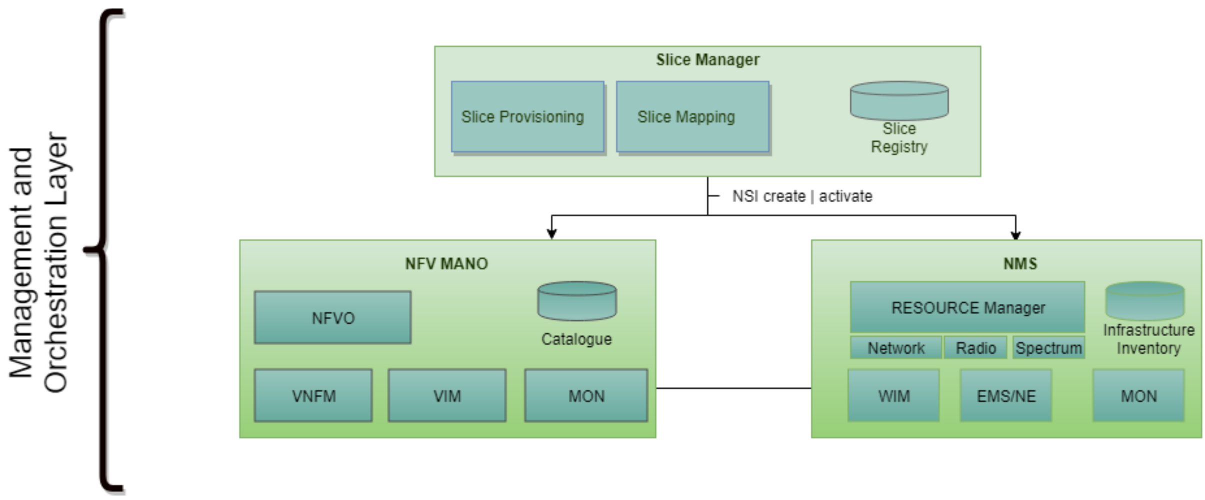

Figure 16: MANO layer components

3.2.2.1. Slice Manager

As discussed in Section 2, the network slicing concept is one of the most prominent features of the 5G architecture. The challenges that are imposed to the Management and Orchestration layer relate to the optimised provisioning of the resources E2E across heterogeneous technological domains in order to create an isolated, E2E virtualised network instance (seen as a pool of resources providing specific performance guarantees) for the deployment of diverse communication services, as requested by different vertical industry cases.

The Slice Manager receives the requests from the upper layer and instructs NFVO about how and where an experiment should be deployed, including the networking part, provisioning the slice with the resources indicated by the Mapper, that gathers the information of the available resources and its location from the NMS and calculates the placement for each of the items to be deployed within the virtualized infrastructure.

The sub-components comprising the 5GENESIS Slice Manager are:

- Slice Registry – This component maintains a catalogue of available Network Slice templates that may be used by the coordinator in order to be offered to the experimenters to deploy their services. Moreover, the Registry also maintains and monitors the already deployed slice instances over the infrastructure.
- Slice Provisioning – This component is responsible for the provisioning of the required resources within each technological domain (i.e. Transport, NFV, MEC, RAT) in order to allocate and make available the resources to the slice construct.
- Slice Mapper – This component is responsible for the sub-network slice stitching and configuration for traffic classification in order to be admitted to the create slice. The slice created in each technology domain is considered as a sub-network slice, in this sense the end-to-end slice is created by the stitching of sub-network slices together.

In addition, the Slice Manager will expose and also use internally a well-defined information model for the specification of network slices (network slice template). This info model will be exploited also at the Coordination layer in order to be used by the experimenters during their service deployment requests.

The Slice Manager communicates southbound with the other two components of the M&O layer in order to manage and coordinate the slice creation and lifecycle. Two reference points are considered. The first one towards the NFV MANO, in order to request operations related to Network Services (i.e. interfacing with the NFVO) and allocate per tenant resources (i.e. interfacing with VIM). In fact, this reference point encapsulates functionality that is described by the specifications governing the Oss-Ma-Nfvo reference point of the ETSI NFV MANO recommendations [29]. However, the details of this particular reference point will be further defined during the implementation of the Slice Manager component. The second reference point connects to the NMS components with the purpose of allocating and provisioning network resources that provide x-haul connectivity or transport connections between NFV infrastructures.

3.2.2.2. NFV MANO

This component has been detailed in the previous section (Section 2). The role in 5G and provided functionalities are well established. In order for this section to be self-contained a summary is provided here, but the reader is advised to redirect to Section 2 and the Annex 6.1 if more details are required.

The NFV MANO components is responsible for the instantiation of NSs consisted of VNFs within specific infrastructures that support compute, storage and network virtualisation. A specific interface is exposed northbound in order to accept the requests, for NSs that have been previously onboarded in it NS catalogue. The NFV MANO comprises the following components:

- NFV Orchestrator (NFVO) - Responsible for performing the orchestration of NFVI resources across multiple VIMs with the help of the WIM component when necessary, as well as for managing the lifecycle of Network Services.
- VNF Manager (VNFM) - Responsible for the lifecycle management of VNFs under the control of the NFVO, which it achieved by sending instructions to the VIM for instantiation, scaling, updating and upgrading, as well as termination of VNFs. For the 5G architecture, the most critical issue is the interface with the EMS for each VNF/PNF.
- Virtualisation Infrastructure Manager (VIM) - Responsible for managing the virtualized infrastructure of an NFV-based solution (including keeping inventory of the allocation of virtual resources to physical resources, supporting the management of VNF forwarding graphs, managing a repository of NFVI hardware and software resources, supporting discovery of the capabilities and features to optimize the use of such resources, performing the necessary LCM operations triggered by the VNFM). This component is actually between the M&O and the Infrastructure layer. The interfaces to the infrastructure elements (i.e. NFVI, WAN) are well defined in [30].

In the case of an NS distributed across various NFV infrastructure, the NFVO is capable of directly interfacing with the WAN infrastructure manager (WIM) in order to orchestrate the provisioning of resources between two or more NFVIs. In our view, however, this capability is also offered via the NMS.

3.2.2.3. NMS

NMS is a commonly used management structure for the management and control of the network resources available in the infrastructure layer of 5GENESIS platforms. NMS is essentially an application or set of applications that lets network administrators manage a network's independent components inside a bigger network management framework. NMS may be used to monitor both software and hardware components in a network. It usually records data from a network's remote points to carry out central reporting to a system administrator.

NMS is a framework that comes in useful when the resources are not reconfigured regularly, i.e. for static provisioning, or when a Network Controller with programmatic interfaces is not available for these resources. In this case, the configuration is either done manually or through a proprietary interface.

NMS consists of:

- ***Element Management (EMS)***: anchor point responsible for the FCAPS (Fault, Configuration, Accounting, Performance, and Security) of a VNF/PNF. It is anticipated that different RATs will utilise different EMs exposing different management and monitoring capabilities. Furthermore, 5GNC functions for configuration and management, as well 5G Radio elements may as well be managed via EMS systems.
- ***Resource Manager (ResMngr)***: aware of the available resources throughout the platform, communicating with the Element Managers per technology domain of Infrastructure and storing the updated information in the Infrastructure Repository. In case that specific resource provisioning is required (i.e. creation of a slice) the ResMngr is responsible of communicating with the EM of the elements to configure the requested resources.
- ***Wide-area Infrastructure Manager (WIM)***: manages the network between the NFVIs, the infrastructure gateway and the radio edge, which is distributed across the SDN-based WAN, interconnecting the different domains (i.e. Core NFVI and 5G NC), having an updated registry of the VIMs located in each domain. It is necessary in case the NS to be deployed within the NFVI is distributed among different Points of Presence (PoP). The component can either directly interface with the NFVO or indirectly via the NMS.

3.2.2.4. Management & Orchestration layer sequence diagram

Figure 17 presents the sequence diagram that depicts the interactions between the different components in the Management & Orchestration Layer, as well as towards the Coordination and Infrastructure layers. This sequence diagram corresponds with the diagram introduced in Figure 15 and includes a more detailed sequence of the messages interchanges between the Coordination layer and the Management and Orchestration layer. For the sake of economy, the messages between the experimenter and the coordinator are not shown here.

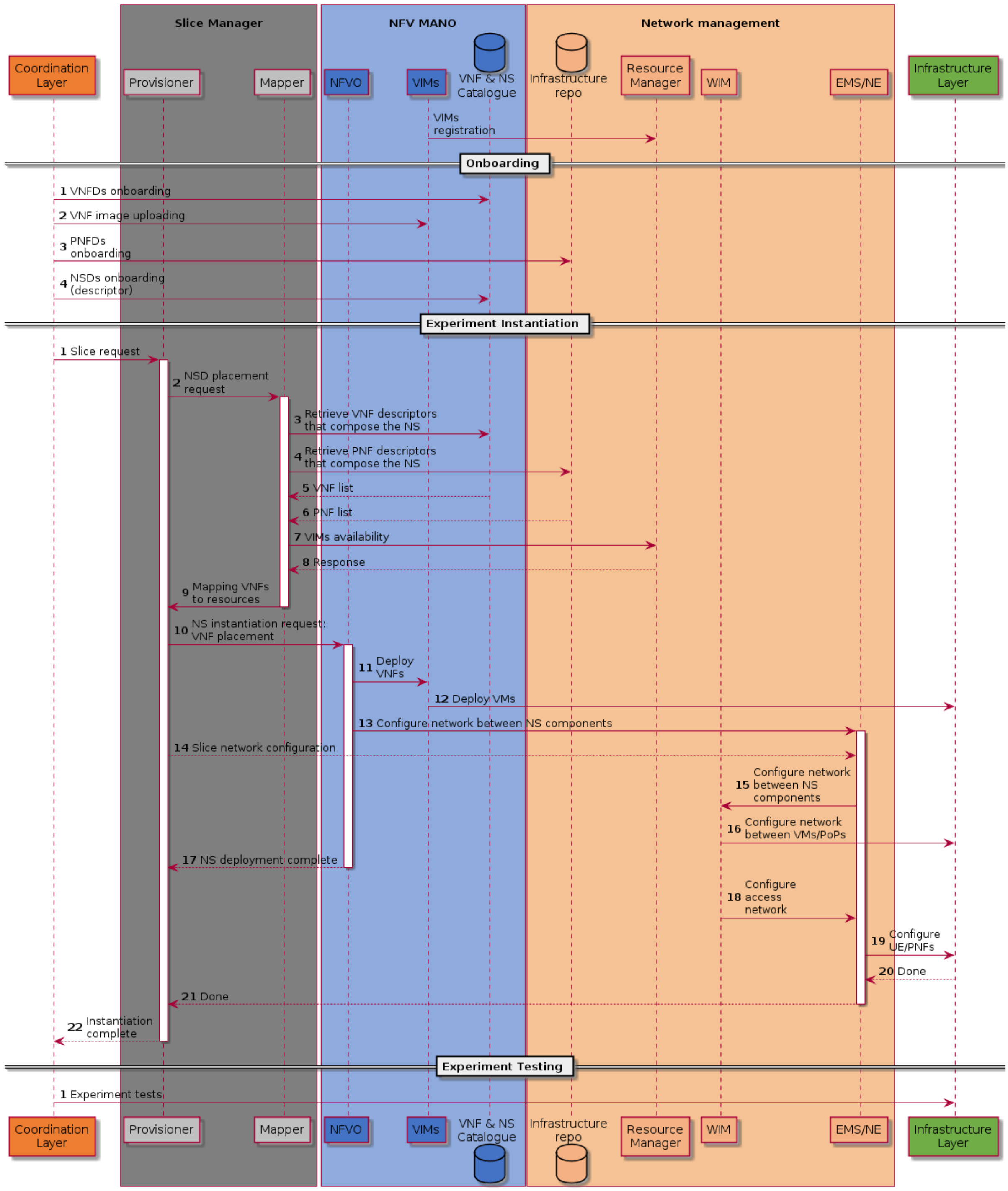

Figure 17: MANO Layer sequence diagram

3.2.3. Infrastructure layer

The components of the infrastructure layer essentially aim to constitute the end-to-end data path for the user traffic. Figure 18 below visualises the functional architecture of the 5GENESIS Infrastructure layer and highlights its key components. The functions in the outer blocks are assumed to be implemented as PNFs, while the enclosed blocks mostly represent VNFs, either at the Core or at the Edge.

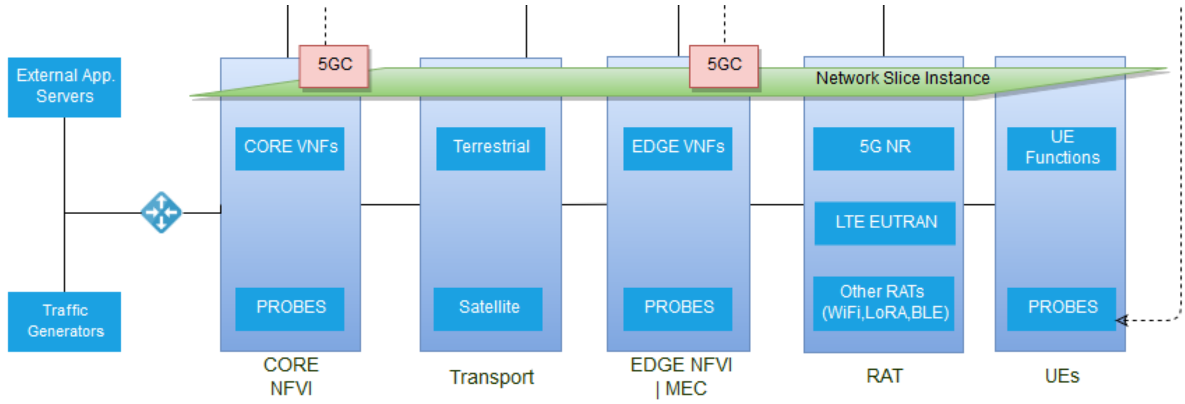

Figure 18: Functional architecture of the 5GENESIS platform infrastructure layer

The paragraphs to follow outline the expected functionality of each component of the Infrastructure layer. Most of these components are platform-specific and therefore not all platforms will support all the components in this layer.

3.2.3.1. Platform Gateway and traffic sources

User traffic will originate from external application servers and/or from traffic generators. The Platform Gateway (indicated with the router icon in Figure 18: Functional architecture of the 5GENESIS platform infrastructure layer) is the component residing at the Platform perimeter and handles the traffic to and from the external world (the internet and/or other peer platforms). It performs standard operations expected from such a component, such as L3 routing, stateful firewalling, basic traffic inspection, VPN/secure tunnel support, port mapping and address translation.

3.2.3.2. 5G NG Core (5GC)

The 5G core network employs unique features, one of the most important one being the separation of the user and control planes, which brings flexibility and agility as required by specific 5G use cases (e.g., URLLC). Furthermore, virtualization, ease in scaling and distribution to the edge of core network functionalities will allow to keep applications as close as possible to the users, improving service delivery and quality of experience.

The 5G core network, architecturally renewed by these key features, will enable new highly demanding services that pose requirements such as increased data rate, reduced end-to-end latency, massive connectivity, guaranteed QoS/QoE, higher availability and efficiency. As referenced in 3GPP TS 23.501, the control plane (CP) and user plane (UP) will be architecturally separated from the (R)AN between the interfaces N2 towards the Access and Mobility Management Function (AMF) and N3 towards the User Plane Function (UPF). The UPF is also the key core network component in MEC-based deployments, where the CP functionalities might reside in the central core or in the cloud. CP and UP separation and MEC deployments for traffic local break-out can be already adopted architecturally with the current available technology – LTE – as required by customers willing to leverage these features without waiting for the commercial availability of 5G.

3.2.3.3. Core NFVI

The Network Functions Virtualisation Infrastructure (NFVI), as referred to in Section 2.2.2, will be a core component of each 5GENESIS Platform, comprising the execution environment for **Virtual Network Functions (VNFs)** to be deployed at the core of the network. As defined in ETSI GS NFV-INF 001 [31], the NFVI will be able to support, as instructed by the MANO components, the execution of all the steps of the NFV lifecycle management, including onboarding, deployment, chaining, monitoring, scaling up and down, and termination. In each 5GENESIS Platform, the NFVI will comprise one or more PoPs, either co-located or distributed, each of which implements all the necessary functional domains:

- **Compute domain**, as per ETSI GS NFV-INF 003 V1.1.1 [32], comprising the servers and storage,
- **Hypervisor domain**, as per ETSI GS NFV-INF 004 V1.1.1 [33], enabling the abstraction of the hardware, allocating compute resources to the workloads, either VMs or containers, and managing the virtual network connections,
- **Infrastructure network domain**, as per ETSI GS NFV-INF 005 V1.1.1 [34], comprising the physical switches interconnected into the PoP backbone network.

3.2.3.4. Measurement probes

The goal in 5GENESIS is to design and deploy a measurement framework comprising of uniform measurement probes that can carry out the same experiment in a similar fashion in all platforms. The probes will be capable of measuring not only QoS parameters such as latency, availability and throughput, but also parameters related to the QoE of popular services that will run on 5G networks.

5GENESIS will rely on existing flexible lightweight software systems for the design and scheduling of experiments. The aim will be to measure latency, reliability, throughput, as well as application performance such as web and video streaming. The measurement probes will be deployed not only on the user equipment to measure the E2E performance, but also in the network when applicable, to explore the performance of different components in the system and troubleshoot when needed.

3.2.3.5. Transport/Backhaul network

I. **Terrestrial backhaul**

Regarding terrestrial backhaul, 5GENESIS will leverage radio links in the mmWave band at V-Band (60 GHz). The deployment of small cells at this carrier frequency is suitable for dense urban scenarios with a limited range of around 250 m. The mmWave backhaul architecture will feature multi-gigabit meshed backhaul technologies, targeting the channels from the IEEE 802.11ad standard, and making use of beam steering algorithms to establish different topology configurations. The expected features are Point-to-Multi-Point (PTMP) capabilities, support of beam-tracking and fast beam switching communications. The small cells will be enhanced with programmable network processors to allow network functions to be easily configured/modified or controlled by an SDN controller.

II. **Satellite backhaul**

5GENESIS will also employ satellite communications for the backhaul links, thus giving the possibility to extend 5G coverage to areas and use cases far beyond the typical coverage of terrestrial radio network architectures (e.g. underserved areas, long-haul transportation media etc.) The focus will be on multi-spot geostationary (GEO) satellites, operating at Ka-band for increased throughput. 5GENESIS will exploit and properly adapt satellite networks with technical enablers for more seamless integration with 5G, such as management APIs for network slicing and QoS control and SDN/NFV capabilities at both the satellite gateway and the terminal (edge). The terminals and antennas to be employed will support both stationary/portable use as well as mobile use, allowing the ad-hoc deployment of 5G “hot-spots” anywhere and anytime.

3.2.3.6. Mobile Edge Host & Platform (Edge NFVI)

5GENESIS will support execution and lifecycle management of applications at the edge of the network, as an essential component of 5G, employing Mobile Edge Hosts at the edge of the network, i.e. co-located with RAN components. As defined by ETSI MEC (see description in Section 2.2), the MEC hosts will provide (compute, storage, network) resources to the MEC applications and functions. They will also host the “MEC platform” function, which in turn will control the edge services and maintain the traffic rules for proper traffic steering. According to the specific requirements of the 5GENESIS platforms and associated use cases, the MEC platform may also support service advertisement/discovery and DNS resolution. In terms of physical infrastructure, the MEC host will be built on devices suitable for the platform and the use cases (i.e. compact and energy-efficient, especially in mobile usage scenarios).

3.2.3.7. Radio Access Technologies (RATs)

The 5GENESIS facility will rely on both software-defined radio (SDR) and hardware-based solutions for the implementation of 5G gNBs. Both solutions will be integrated with the NMS system in order to enable the NMS to manage and monitor them. Specific configurations will be allowed to be selected by the upper layers using configuration profiles.

The software-based gNB runs on general purpose computing systems together with software-defined radio platforms. Currently, the platform supports 3GPP Release 14, including LTE-M and NB-IoT and Release 15 5G NR is currently being implemented.

In its final version planned for the end of the 5GENESIS project, the gNB will support both NSA mode 3A configuration (LTE-assisted and EPC connected) and SA mode connected to a 5G core network.

The initial plan for the hardware gNB solution in 5GENESIS is to be based on NSA 3A configuration (LTE-assisted, and EPC connected). The gNB will include two main parts, the Physical layer part and the Protocol stack part. The Physical layer part will comprise two elements: the Distributed RAN (D-RAN) that implements the FEC process, LDPC for the UP data and Polar for the CP information, and many Remote Radio Heads (RRHs). To facilitate mobility within the RRH beams coverage area the sessions, DL data will be transmitted by all beams over the same resource elements. This introduces a cell-less coverage supporting mobility with no need for handover. The protocol stack part implements the 5G RAN protocol stack and will support the MAC, RLC, PDCP, SDAP and RRC layers. All these layers will share the same platform.

Two main interfaces will be provided at the gNB ends. On its front-end part, 3GPP Rel.15 3.5GHz TDD Air-Interface will be supported. On its backend, the SDAP layer will support a S1-U interface.

3.2.3.8. Other RATs

The 5GENESIS platforms will also support legacy EUTRAN (4G) for backwards compatibility. 4G radio will also be exploited at the first integration cycles, when 5G NR features will not yet be available.

Depending on the needs of the verticals, some platforms will also support other RATs, such as WLAN, LoRA and BLE, particularly for IoT scenarios.

3.2.3.9. User equipment

An experimental 5G UE will be employed in 5GENESIS, developed by ECM, based on the OpenAirInterface software. Until commercial 5G UEs become available, 5GENESIS will engage a software-driven solution, based on software-defined radio platforms. The UE will support the 5G NR physical layer (3GPP 38.211-38.214) with certain restrictions. The RRC will support Release 15 NR (38.331) and LTE (36.331) specifications and will support both 5G-NR NSA as well as SA mode.

3.2.3.10. Non-3GPP network integration

5GENESIS will support 5G/WiFi aggregation, by following the relevant standards, as described in Section 2.2.4.1. The 3GPP specification to be taken into account to interconnect 3GPP and non-3GPP network, Release 15 compliant, are: TS 23.402 and TS 33.402 for the NSA case, TS 23.501 for SA.

5GENESIS will primarily focus on the NSA model deployment, because according to 3GPP Release 15, it is the only which is fully completed. However, the project will follow Release 16 and future Releases in order to achieve SA deployment as well.

The key components to achieve the interoperability, as also shown in Figure 19 below, are:

- Access Point (A.P): The functionality of the access point is basically the creation of wireless networks. It will redirect wireless data traffic toward the operator network. It is managed by the controller
- AAA: Authentication server, authenticates users and devices
- Controller: It is the entity that controls the creation of each of SSID thus each network slice
- Manager: This is not mandatory module, it could appear or not and its aim is just to simplify controller configurations.

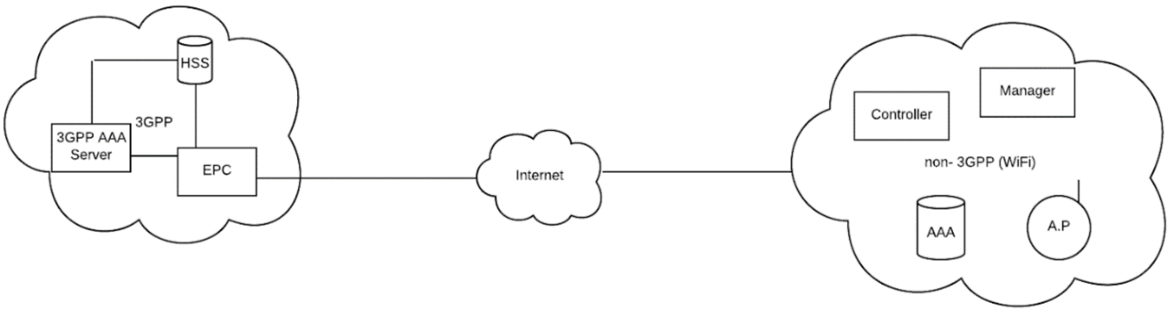

Figure 19: Components involved in 5G/WiFi aggregation

3.2.3.11. Platform- and vertical-specific infrastructure enablers (Core, Edge, UE)

Link aggregation functions

The objective of link aggregation functions is to leverage the availability of multiple backhaul links in order to improve the overall user QoE, especially in situations where the 5G link quality is poor. In 5GENESIS, a pair of link aggregation functions will be placed on the N3 interface between the RAN and the CN, thus aggregating all the backhaul links (satellite and terrestrial) in 2 separate points. These functions will steer, switch and split incoming data flows over available backhaul links using algorithms that take into account the actual link characteristics, as well as the size of the transmitted objects (e.g. PSBOL). The project will also implement aggregation of LTE, WiFi and 5G NR to increase throughput and reliability following the LWIP approach (see [35]).

Spectrum management functions

As already mentioned, several vertical spectrum-sharing methods have emerged in the context of mobile communications. Unlike horizontal sharing solutions, where several networks are allowed to access the spectrum with the same priority (e.g. WiFi, Multfire), vertical sharing allows the several networks to access the spectrum with different priorities (e.g. TV white spaces (TVWS), Licensed Shared Access (LSA), Citizens Broadband Radio Service (CBRS)). When the networks use several bands, each band may adopt a different type of sharing (e.g. LTE-Unlicensed, Licensed Assisted Access (LAA), LTE-WLAN aggregation (LWA)).

The 5GENESIS project will conceive a framework that allows deploying any one of these sharing schemes in a dynamic way. Knowing the QoS requirements of the slices to be instantiated, the details of the infrastructure deployed in the service area of interest, and the usage level and sharing constraints of the IMT bands of interest, the spectrum management framework will be able to select, for each slice, the appropriate band and radio technology. However, as the network load might evolve during the slice lifecycle, either because the terminal is moving or because the number of active slices has been changed, there might be a need to select a better cell for a given UE, adapt the channel bandwidth or activate carrier aggregation in a given slice.

In addition to selecting the better cell for a UE, the framework will also be able to select a best slice for a given UE. For example, this will be useful when there exist two slices configured to support the same service: one slice with wide coverage to support links at any place in the network, and a second slice with local coverage to support device-to-device communications between in range terminals. Moreover, in case the network will be using wireless backhaul, the framework will also be able to allocate spectrum for the backhaul, as if the backhaul were an additional network slice.

Resulting from the above analysis, the spectrum management framework considered in 5GENESIS will be flexible enough to take decisions with different time scales, and different geography scopes. For this reason, “spectrum management functions” must be able to run in the CN, MEC platform, gNB and in the user terminal. The decision on the selection and placement of the spectrum management functions will be made by a coordinating spectrum management service running in the MANO layer.

IoT interoperability functions

These functions aim to provide interoperability between heterogeneous IoT implementation systems at different layers of the IoT stack, including device, network, platform, application and semantics. The functions can be deployed at several physical locations of the Platform.

An open and modular IoT gateway function gathers the sensor data from different sensors, physically connected through several access networks, including, WiFi, LoRa, etc. This function will be presumably located at the edge of the network and close to the devices, and will be entirely lightweight to be installed in resource-constrained environments.

Additionally, the interoperability at network level will be further supported through functions deployed at the core NFVI. These functions will provide capabilities such as IoT protocol translations (MQTT, CoAP, HTTP, etc.) in order to provide a homogeneous communication protocol to deliver the data onto the core platform. In addition, a middleware function will achieve interoperability at platform and semantic level, creating bridges among different IoT platforms, using the specific protocols implemented in those platforms and extracting their data and accessing their services. This involves semantic translation from the different semantics that each Platform may have.

Policy Manager

One of the ambitions of 5GENESIS is to enhance E2E performance by taking advantage of policy and context information from the 5G network, for protocol and algorithm selection on the UE side. This will allow higher layer protocols to be aligned and configured in accordance with the requested services, extending E2E slice management to also incorporate higher layer protocol selection and configuration.

The policy manager is an entity on the UE that is responsible for providing this functionality within the 5GENESIS infrastructure layer and for interacting with the 5GENESIS Management and Orchestration framework. In general, the policy manager needs to consider three inputs for its decisions on how to configure a given transport connection: the application requirements, the configured polices and the current network characteristics. The latter two will be integrated with and take advantage of policy and context information from the 5G network. The application requirements will be captured through standard interfaces such as the TAPS [36] interface currently under standardization within the IETF.

3.3. Cross Platform Interface

5GENESIS architecture considers loosely coupled cross-platform interconnections as part of the Facility's Coordination layer. In the context of 5GENESIS, evaluation of use cases running on two interconnected Platforms (i.e., Athens and Malaga) is planned as a proof of concept. This is a first step towards more complex inter-connections between platforms in future projects. The results will provide useful insights for future projects to determine how to run distributed use cases across platforms.

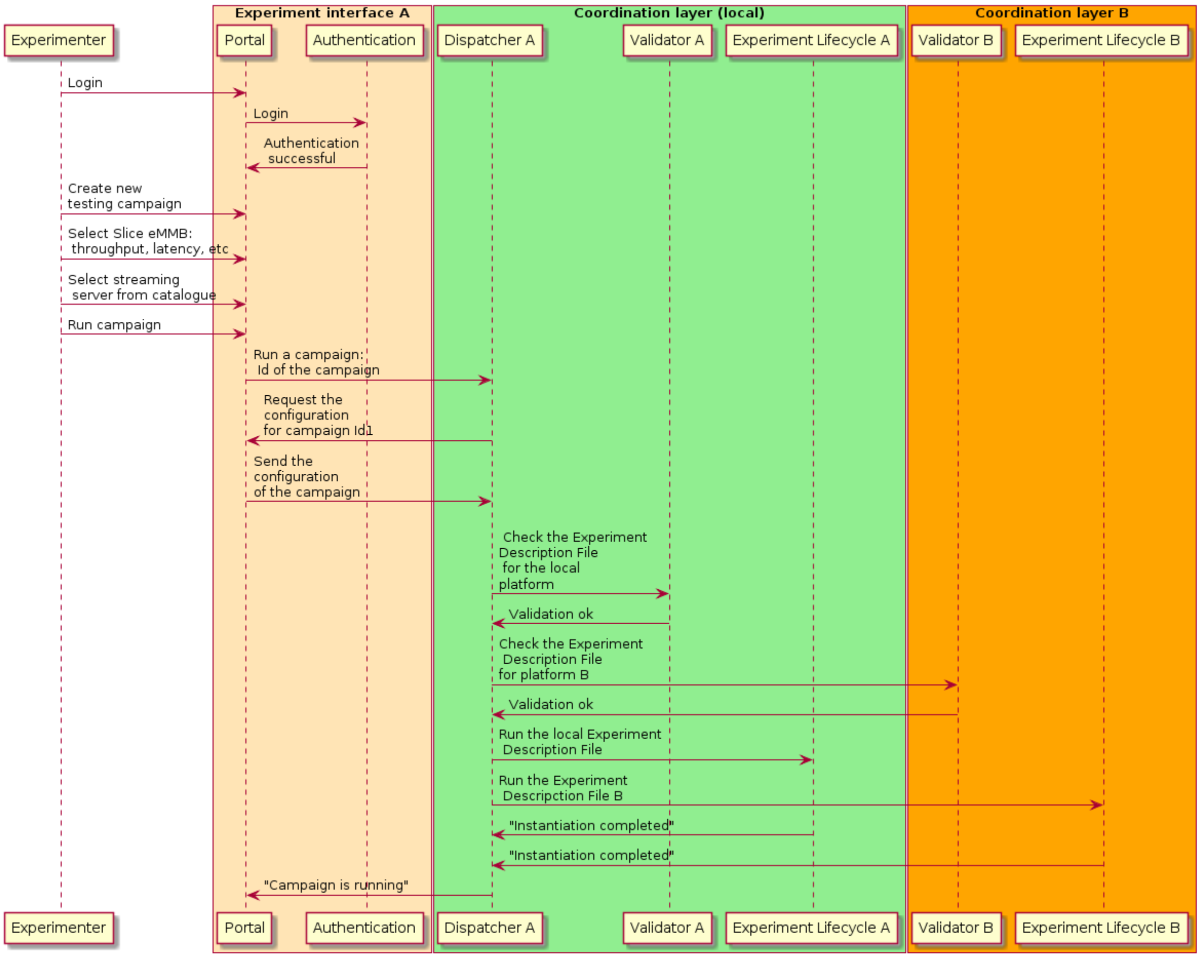

Figure 20: Sequence diagram for interconnection between platforms

The interconnection proposed implies two steps, as shown in Figure 20. In the first step, the experimenter provides the experiment description using the local portal. The Coordination layer on the first Platform makes the processing (dissection) of the local part and sends the rest of the descriptor to the remote Platform, that processes the received experiment descriptor as if it were a local experiment. The sequence diagram shows how the "interconnection with another platform" is inserted into the flow.

When the experiment has been deployed in both Platforms, users are connected and run the services, potentially communicating with UEs in both platforms. In this phase, the gateway is responsible to connect the data planes in both Platforms, providing end-to-end connectivity and service continuity.

Note that the sequence diagram does not include reporting measurements; however, from the remote platform this is done also through the "interconnection with another platform", to be aggregated with the local reports in order to be presented to the experimenter.

4. Summary Of 5GENESIS Individual Platform Features

The five Platforms formulating the 5GENESIS Experimentation Facility have worked to present in an easy-to-read format the mapping of the 5GENESIS Facility features, that reside at each architectural layer, to the platforms, as presented in **Error! Reference source not found.**. In each cell of the table a colour-code has been applied as follows:

- Green: Feature that will trigger an upgrade of the corresponding platform in order to support it;
- Yellow: Feature that is platform-specific and adaptations will be required to be interoperable with 5GENESIS Facility;
- Purple: Feature that will be used as is;
- *White*/Empty: Feature that is not supported.

Table 3: Mapping of the 5GENESIS Facility features reside at each architectural layer to the platforms

Facility feature	Athens	Berlin	Limassol	Malaga	Surrey
Infrastructure Layer					
Rel15-5GNR in Non- Standalone Alone (NSA) mode					
Rel15-5GNR with Rel15-5GCore in Standalone Alone (SA) mode3					
Rel16-5GNR and 5GCore (NSA or SA)					
5G NR					
Edge Computing (MEC)					
Integration of additional gNB to ICT-17 facility					
3.5 GHz 5G Radio					
26 GHz 5G Radio					
mmWave backhaul					
Satellite backhaul					

Facility feature	Athens	Berlin	Limassol	Malaga	Surrey
Fiber network backhaul					
Switching infrastructure backhaul					
Dynamic spectrum management					
Backhaul link aggregation					
LTE-WiFi aggregation (MEC)					
WiFi					
NFVI - VIM					
SDN Control					
Monitoring					
EPC solutions (4G)					
4G eNodeBs /Small Cells					
Platform GW					
UE devices (4G)					
UE devices (5G)					
Vertical-specific functions					
Management and Orchestration Layer					
Network Slicing as a service					
Network Management System					
NFV MANO (NFVO)					
Customized network slice (e.g. SFC, security, enhanced Cloud access)					

Facility feature	Athens	Berlin	Limassol	Malaga	Surrey
Hosting of 3rd party VNFs					
Coordination Layer					
Experimenter UI					
Package Validator					
Experiment Lifecycle Management					
Analytics					
Automatic testing framework					
Interworking with other ICT17 facilities					
Distributed Data fabric service for analytics					
End User Testing					

Further to the features' mapping, Table 4 provides for each feature a description with the currently available capabilities per platform (not necessarily already integrated but readily available to be used), as an effort to reflect the current status of the platforms at the time this document is released.

Table 4: Candidate technologies for component design and development

Platform Capabilities	Athens	Berlin	Limassol	Malaga	Surrey
Infrastructure Layer					
Rel15-5GNR in Non-Standalone Alone (NSA) mode	ATH 5G Core	Open5GCore	-	ATH 5G Core	5GIC 5GC (in house product) (NSA mode) – 5GNR from Huawei
Rel15-5GNR with Rel15-5GCore in Standalone Alone (SA) mode3	ATH 5G Core	Open5GCore	-	ATH 5G Core	5GIC 5GC (in house product) (NSA mode) – 5GNR from Huawei.
Rel16-5GNR and 5GCore (NSA or SA)	-	-	-	-	Rel-16 5GC (in house product by 2020)
5G NR	D-RAN (RUN)	-	-	D-RAN (RUN)	HUAWEI 5G NR (eMBB & URLLC cells)
Edge Computing (MEC)	NFV based deployment with experimental local break out.	-	-	Cord-based Edge computing node	ETSI Complaint Virtual MEC & DASH standard
3.5 GHz 5G Radio	SDR based	-	-	SDR based gNB planned	HUAWEI 5G NR
26 GHz 5G Radio	-	-	-	Spanish regulator open to provide experimental licence	Layer 1 SDR based
mmWave backhaul	-	60 GHz; integration required	-	-	60 GHz; supported
Satellite backhaul	-	-	AVA satellite network	-	Hylas Avanti supported
Fiber network backhaul	Fiber networks in place between NCSRD and COS spots	-	-	MoM and UMA fiber networks in place	DWDM based carrier grade backhaul

Platform Capabilities	Athens	Berlin	Limassol	Malaga	Surrey
Switching infrastructure backhaul	-	Upgrade to distributed spine-leaf infrastructure required	-	-	SDN based
Backhaul link aggregation	-	-	EKI link aggregation functions	-	-
LTE-WiFi aggregation (MEC)	Dual connectivity via MPTCP	-	-	LWIP like aggregation of LTE-WiFi	-
WiFi	COTS supporting VAPs and 802.11ac	Commercial Aps	-	Commercial APs	Commercial APs
NFVI - VIM	Openstack and K8s supported and deployed	OpenStack	OpenStack	OpenNebula (MEC)	ETSI complaint docker container (OpenStack)
SDN Control	ODL, RYU, VAN (HPE)	OpenStack (Neutron)	ODL	ONOS (MEC)	ODL, RYU
Monitoring	Prometheus, OpenNMS, Gnocchi, SNMP	Monroe node (to be integrated)	OpenNMS	Ad-hoc solutions	Ceilometer (OpenStack)
EPC solutions (4G)	Amarisoft, OpenAirInterface	Open5GCore	ATH EPC	Polaris EPC, including ePDG/ANDSF	5GIC Core (developed in-house)
4G eNodeBs /Small Cells	SDR based (Amarisoft, OpenAirInterface) HW based (Nokia)	LTE EUTRAN indoor cells	SDR-based (OAI)	LTE emulators & indoor small cells band 7. Outdoor placement for NSA validation	LTE TDD EUTRAN outdoor & indoor cells
Platform GW	Connected to GEANT2	-	Connected to PLC backbone	Connected to GEANT2	SDN GW
UE devices (4G)	Commercial UEs (Samsung), USRP (OAI), USB Dongles	Commercial 4G UEs (cell phone)		Commercial 4G UEs, USRP -OAI based UEs	Commercial 4G UEs
UE devices (5G)	SDR based (ECM)	-	-	SDR based (ECM)	CPE/ experimental 5G UEs

Platform Capabilities	Athens	Berlin	Limassol	Malaga	Surrey
Vertical-specific functions	-	-	IoT interoperability functions	-	IoT interoperability functions
Management and Orchestration Layer					
Network Slicing as a service	-	-	-	-	Supported
Network Management System	LibreNMS EMS (PNFs)	-	-	Ad-hoc per physical component	5GICE (developed in-house)
NFV MANO (NFVO)	OSM, 5GTANGO	OpenBaton	OSM	OSM	ONAP & OSM
Customized network slice (e.g. SFC, security, enhanced Cloud access)	Currently simple NS supported via 5GTANGO implementation	-	-	-	-
Coordination Layer					
Experimenter UI	5GTANGO Validation and Verification	-	-	Triangle Web Portal to be adapted	5GICE
Package Validator	5GTANGO descriptor validator	-	-	-	5GICE
Experiment Lifecycle Management	5GTANGO Validation and Verification (VnV) framework	Monroe Platform (to be integrated)	-	Full end-to-end automation with Keysight's TAP framework	5GICE
Analytics	-	-	SHIELD DARE (based on Apache Spot)	-	UDWA (developed in-house), Apex for dynamic analytics-based policy
Automatic testing framework	5GTANGO VnV	-	-	Full end-to-end automation with	-

Platform Capabilities	Athens	Berlin	Limassol	Malaga	Surrey
				Keysight's TAP framework	
Interworking with other ICT17 facilities	GEANT2 connection	-	-	GEANT2 connection	JISC connection (through JANET)
Interconnection with other ICT17 facilities	-	DFN/GEANT connection available for setup	-	-	5GICE
Distributed Data fabric service for analytics	Cross-layer Monitoring based on Prometheus	-	-	-	Traffic QoE/QoS analysis software (RantCell)
End User Testing	-	-	-	QoS/QoE evaluation software tools	Traffic QoE/QoS analysis software (RantCell)

It is noteworthy to mention that these architectural components and planned enhancements will be refined in the context of the following work packages that address the design and implementation of the components, as well as integration and testing. Therefore, a more refined view will be presented in deliverable D2.4 of the project.

5. Summary and Conclusions

In the journey towards fully 5G-enabled Platforms, we have now reached the stage of experimentation, testing and KPI verification. To this end, 5GENESIS works towards the specification of the 5G Experimentation Facility, to be implemented and made available for vertical industry experiments at the end of the project.

This deliverable focuses on the specification of the all-encompassing reference architecture to be used as the basis for the 5GENESIS Facility implementation. This is accomplished by addressing the main relevant factors: (1) Prior work on requirements analysis, high-level architectural blueprint, necessary platforms enhancements, and use cases to be implemented, (2) the architectural landscape and existing standards and technologies, (3) well-defined guiding concepts and design principles. Based on these, the high-level blueprint architecture, already presented in deliverable D2.1, was extended with the actual components that constitute the architectural layers. The layer description is accompanied by the detailed description of the components, as well as the sequence diagrams for the information flow between them. Lastly, each Platform mapped the planned enhancements per component per layer, and presented the existing technologies considered as initial, ready to board, candidate implementations.

The resulting architecture ensures that the five Platforms that form the 5GENESIS Experimentation Facility remain administratively independent, while being interoperable and presenting a common interface towards the Experimenters.

The reference architecture that was presented in this deliverable is the basis for the 5GENESIS further work. However, it is expected that more refinements will come out during the development of the different components and the actual integration and testing; therefore, a more refined version (e.g., including interface definitions) of the reference architecture will be included in deliverable D2.4.

6. APPENDIX

6.1. Orchestrator Framework Review

NFV orchestration is used to coordinate the resources and networks needed to set up cloud-based services and applications. This process uses a variety of virtualisation software and industry standard hardware. The big advantage of NFV is that it uses industry-standard commercial off-the-shelf (COTS) hardware to deliver a service via software. Prior to the advent of NFV, operators built application-specific networks using proprietary hardware. Now, these services can be deployed as VNFs on an NFV platform. This includes popular software services such as virtual firewall, virtual load-balancing, or other software-defined wide area network (SD-WAN) services. Because of the greedy nature of the NFV in respect to virtualized resources, NFV requires a high degree of software management, referred to as orchestration. Orchestration coordinates, connects, monitors, and manages the required resources from the platform for the NFV services. Orchestration may need to coordinate with many network and software elements, including inventory systems, billing systems, provisioning tools, and OSSs. However, some of the existing orchestrating solutions are just tied to a specific networking environment, and moreover, some of them can orchestrate only a limited number of services [37]. This section presents an overview of the main orchestration frameworks, including open source and commercial solutions.

1. **Open source MANO orchestrator**

   Open source MANO [27] (2017) is an ETSI-hosted project that is developing an open source NFVMANO platform aligned with ETSI NFV information models and that meets the requirements of production for NFV networks. The project launched its fourth release [38] in May 2018 and presented improvements in performance, monitoring, modelling, network logic and a new North Bound interface. One of its main goals is to promote the integration between standardisation and open source initiatives. The OSM architecture has a clear split of orchestration functions between resource and service orchestrators. In its third release, it integrates open source software initiatives such as Riftware as network service orchestrator and GUI, OpenMANO as resource orchestrator (NFVO), and Juju 5 server as configuration manager (G-VNFM). The resource orchestrator supports both cloud and SDN environments. The service orchestrator can provide VNF and NS lifecycle management and consumes open information and/or data models, such as YANG. MANO architecture covers only single administrative domain.

2. **ONAP orchestrator**

   ONAP [39] (2017) is based on the union of two open source MANO initiatives, namely OPEN-O [40] and OpenECOMP [41] frameworks. ONAP software platform deploys a unified architecture and implementation, with robust capabilities for the design, creation, orchestration, monitoring and lifecycle management of PNFs and VNFs. ONAP's functionalities are expected to address automated deployment, management and policies optimisation, through intelligent operation of network resources using big data and artificial intelligence [42]. Authors in [43] identify two of the biggest challenges to merge two large sets of code using ONAP: (1) to define a higher-level common information model unifying the predominant data models used by OPEN-O (TOSCA) and OpenECOMP (YANG) and (2) to create a standard process so that end users can introduce onboarding and lifecycle management of VNFs using an automated process.

3. **X-MANO orchestrator**

X-MANO [44] (2017) is an orchestration framework to coordinate E2E network service delivery across different administrative domains. X-MANO introduces components and interfaces to address several challenges and requirements for cross-domain network service orchestration, such as business aspects with architectural considerations, confidentiality, and lifecycle management. In the business aspects case, X-MANO supports hierarchical, cascading and peer-to-peer architectural solutions by introducing a flexible, deployment-agnostic federation interface between different administrative and technological domains. The confidentiality requirement is addressed by the introduction of a set of abstractions (backed by a consistent information model) so that each domain advertises capabilities, resources, and VNFs without exposing implementation details to external entities. To address the multi-domain lifecycle management requirement, X-MANO introduces the concept of programmable network service based on a domain-specific scripting language, allowing network service developers to use a flexible programmable Multi-Domain Network Service Descriptor (MDNS), so that network services are deployed and managed in a customised way.

4. **Open Baton orchestrator**

Open Baton [45] (2017) is an open source reference implementation of the NFVO based on the ETSI NFV MANO specification and the TOSCA standard. It comprises a vendor-independent platform (i.e. interoperable with different vendor solutions), which is easily extensible for supporting new functionalities and existing platforms. Current Open Baton release 4 includes many different features and components for building a complete environment fully compliant with the NFV specification. Among the most important are a NFVO following ETSI MANO specification, a generic VNFM to deploy Juju charms or Open Baton VNF packages, a marketplace integrated within the Open Baton dashboard, a driver mechanism supporting different types of VIMs without having to re-write anything in the orchestration logic, and a powerful event engine for the dispatching of lifecycle events execution. Finally, Open Baton is included as a supporting project in the project Orchestra6. This OPNFV initiative seeks to integrate the Open Baton orchestration functionalities with existing OPNFV projects in order to execute testing scenarios (and provide feedback) without requiring any modifications in their projects.

5. **Agile reference Implementation of automation orchestrator**

Agile Reference Implementation of Automation (ARIA) TOSCA [46] (2017) is a framework for building TOSCA-based orchestration solutions to support multi-cloud and multi-VIM environments, while offering a command line interface (CLI) to develop and execute TOSCA templates with an easily consumable software development kit (SDK) for building TOSCA enabled software. By taking advantage of its programmable interface libraries, ARIA can be embedded into collaborative projects that want to implement TOSCA-based orchestration. For example, the Linux-based Open-O orchestrator uses the ARIA TOSCA codebase to create its SDN/NFV orchestration tool in the Cloudify framework.

6. **TeNOR orchestrator**

TeNOR [47] (2016) is a multitenant multi NFVI-PoP orchestration platform developed by project T-NOVA. Its main focus is on managing the entire NS lifecycle service and optimising the networking and IT resources usage. TeNOR proposes an architecture based on a collection of loosely coupled, collaborating services, known as micro-service architecture, which can ensure a modular operation of the system. Micro-services are responsible for managing, providing and monitoring NS/VNFs, in addition to enforcing SLA agreements and determining required infrastructure resources to support a NS instance. TeNOR architecture is split into two main components namely (1) network service orchestrator, which is responsible for NS lifecycle and associated tasks, and (2) virtualized resource orchestrator, which is responsible for the management of the underlying physical resources. To map the best available location in the infrastructure, TeNOR implements service mapping algorithms using NS and VNF descriptors. Both descriptors follow the TeNOR's data model specifications that are a derived and extended version of the ETSI name server daemon (NSD) and VNF descriptor (VNFD) data model.

7. **Tacker orchestrator**

Tacker [48] (2016) is an official OpenStack project building a generic VNFM and a NFVO to deploy and operate network services and VNFs on a cloud/NFV infrastructure platform such as OpenStack. It is based on the ETSI MANO architectural framework and provides a functional stack to orchestrate E2E network services using VNFs. The NFVO is responsible for the high-level management of VNFs and managing resources in the VIM. The VNFM manages components that belong to the same VNF instance, controlling the VNF lifecycle. Tacker also performs mapping to service function chain (SFC) and supports auto scaling and TOSCA NFV profile using heat-translator. Tacker's components are directly integrated into OpenStack and thus, provide limited interoperability with other VIMs. However, Taker combines the NFVO and VNFM into a single element, which means that its functionalities are limited and divided, and it works in single domain environments offering limited design flexibility.

6.2. Spectrum management

6.2.1. TV White Spaces

In the last two decades, several measurement campaigns demonstrated that spectrum licensing methods had to be changed, as they resulted in inefficient use of radio resources. While the appearance of software-defined radio and cognitive radio technologies provided the tools to adopt dynamic spectrum access schemes, the digital dividend, resulting from the migration to digital TV, provided an excellent first real-life test environment for introducing more efficient spectrum usage methods.

One of these methods, TV white spaces, originated in the USA in 2002 and was proposed by FCC [49] [50]. The method consists of sharing of the TV frequencies that were not used in certain areas (TV white spaces) by unlicensed low power devices. In TV white spaces, the TV receivers are called primary users, they have higher priority to transmit and are protected against interference. The unlicensed low-power devices are called secondary users, they have lower priority to transmit and are not protected from interference coming from the primary or the secondary users (i.e. several secondary users may use the same frequencies in the same place at the same time). To avoid interference with the primary users, before starting transmitting, the secondary users must consult a geo-location database to determine which spectrum is left available by the primary users at their current locations. In USA, final TV white space rules were published in 2010 [51] and updated in 2012 [52]. TV white spaces are commercially available to the public since the first database was approved by FCC in January 2012 [53].

In 2007, the UK also decided to regulate the use of TV white spaces by unlicensed devices [54]. After a period of preliminary studies, in 2009 UK selected geo-location databases as the more reliable method to protect primary users [55], and in 2013 proposed the complete TV white spaces rules [56] , which have been updated in 2015 [57]. TV white spaces are commercially available in the UK since this regulation entered into force, i.e. since December 2015 [58].

Europe started looking to TV white spaces in 2008 in the sequence of TV digital switchover [59]. As in the UK, several studies were made [60] [61], which culminated in the definition of regulatory guidelines very similar to those of the UK. These guidelines intended to harmonize the use of TV white spaces in European countries also using geo-location databases [62] [63]

Although USA and UK/Europe follow identical approaches, the implementation of the geo-location databases is very different in USA and UK/Europe. USA databases draw exclusion zones around the protected stations to define a region where no unlicensed devices, which are assumed as always transmitting at the maximum power, are allowed. On the other hand, UK/European databases divide the territory into squares with 100x100m, called pixels, and compute the maximum power that the unlicensed device may use so the protected TV service is not degraded more than a predefined threshold. To avoid different results from different databases, the UK regulator pre-computes the maximum power that may be used by a single unlicensed device in each TV channel in each pixel and sends this information to all database operators. Although more complex, the UK/European geo-location database allows for the sharing of the spectrum resources by a higher number of secondary users than the USA database.

6.2.2. Licensed Shared Access (LSA)

Since TV white spaces did not offer QoS to the secondary users, mobile telecom operators do not see this spectrum sharing scheme as a viable option for them to get additional spectrum. Therefore, in 2011 a different method called Authorized Spectrum Access (ASA) was proposed in Europe, specially tailored for mobile operators [64]. The ASA idea was that the spectrum owners, i.e. the incumbents, of underutilized bands could allow a limited number of mobile telecom operators to share the spectrum when the incumbent is not using it. The sharing conditions should be previously agreed between the spectrum owner (incumbent) and the new licensees (mobile operators), probably defining a monetary compensation paid by the new licensee to the incumbent. Initially, it is thought that the sharing agreement should also include a pre-defined channel plan allocating specific parts of the band to each mobile operator, thus avoiding the need for coordination among mobile operators. After signing the sharing agreement, whenever the new licensee needs spectrum, it should contact a database to see if the incumbent is planning to use the spectrum in a specific period in a given location. If it is not, the new licensee may use that spectrum in an exclusive way.

Meanwhile, the Radio Spectrum Policy Group (RSPG) and the European Conference of Postal and Telecommunications Administrations (CEPT) decided this concept should not be restricted to mobile networks, so they extended it to all radio services. The extended sharing scheme was called Licensed Shared Access [65] [66] [67]. Unlike TVWS, in LSA the new licensees are protected against interference and thus can access spectrum with the predictable quality of service. LSA is beneficial both for the LSA licensee because it can access an underutilized band in a cost-effective way while the band cannot be cleared/reformed, and for the incumbent who can be authorized to stay longer in the band and eventually to receive monetary compensation. The first band allocated in Europe to LSA was 2300-2400MHz band [68] [69] [70], and later the use of LSA in the band 3600-3800GHz was also suggested [71].

6.2.3. Spectrum Access System (SAS)

In the USA another sharing scheme, called Spectrum Access System was proposed in 2012 for the 3550-3700MHz band, as a means to get additional spectrum for mobile broadband [72] [73]. Unlike LSA, SAS shares the spectrum among two types of users (i.e. incumbents and LSA licensees). Also, SAS is a three-tier sharing scheme that allows three types of users to share the spectrum inside each administrative region: the federal users, the priority access licensed (PAL) users, and the general authorized access (GAA) users. The federal users take precedence over all the others and are protected against all types of interference, either through the definition of exclusion zones or by using the Environment Sensing Capability (ESC) networks that detect emissions from the federal users and inform the SAS, which will then instruct all other users to abandon the band. The PAL users will apply to geographic licenses through auctions. They may use the spectrum in an exclusive way when the federal users do not use it and are protected from interference from the other PAL and the GAA users, but not from the federal users. In the last priority level are the general authorized access users, which are unlicensed devices that use the spectrum opportunistically and are not protected against any interference. SAS final regulations were approved in April 2016 [74] .

6.2.4. Licensed Assisted Access (LAA)

Licensed spectrum should be the core 5G spectrum, but unlicensed spectrum can play a complementary role. Therefore, the two different ways of using unlicensed spectrum developed for 4.5G (LTE-Pro) should also be useful for 5G.

LAA is a new spectrum sharing scheme defined in 3GPP Release 13. Instead of alleviating radio network congestion by offloading cellular LTE traffic to wireless local area networks (WLAN) networks, LAA proposes to deploy inter-band carrier aggregation, using a primary LTE carrier component from a licensed band and a secondary LTE carrier component from an unlicensed band. LAA proposes to use the 5GHz unlicensed band opportunistically to boost data rate, ensuring coexistence with Wi-Fi devices already deployed in the band adopting a listen before talk scheme. LAA also proposes to use dynamic frequency selection in some regulatory domains, for coexistence with radar also deployed in the 5GHz band. In 3GPP Release 13, the secondary LTE carrier component in the unlicensed band can only be used in the downlink. In Release 14, LAA is being enhanced to allow using also in uplink the secondary LTE carrier component from the unlicensed band. In Release 13, the number of 20MHz component carriers that can be aggregated increased from five to 32. This will be of great value, especially for LAA to use large blocks of unlicensed spectrum in the 5GHz band. In Release 14, LAA was extended to the uplink.

6.2.5. LTE-WLAN Aggregation (LWA)

LWA is a new spectrum aggregation scheme defined also by 3GPP in Release 13. LWA proposes to connect a mobile terminal simultaneously to an LTE base station and a WLAN access point. In the downlink, packets going to a specific UE are split in the eNB, some of them are transmitted through the LTE air interface, others are directed to the WiFi access point, and are reordered and re-combined in the UE. Due to the unlicensed nature of WiFi, the packets going through WiFi use a secure IP (IPSec) tunnel. In Release 13, WiFi access point (AP) can be used for downlink only. In Release 14, LWA was extended to allow the use of WiFi AP also in uplink.

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