VertIcal demos over Common large scale field Trials fOr Rail, energy and media Industries

D2.4 5G-VICTORI end-to-end reference architecture

This project has received funding from the European Union's Framework Programme Horizon 2020 for research, technological development and demonstration

5G PPP Research and Validation of critical technologies and systems

Project Start Date: 1st June 2019 | **Duration**: 36 months

Call: H2020-ICT-2019 | **Date of delivery**: 2022-04-11

Topic: ICT-19-2019 | **Version** 1.0

Project co-funded by the European Commission

Under the H2020 programme

Dissemination Level: **Public**

Grant Agreement Number:	857201
Project Name:	VertIcal demos over Common large scale field Trials fOr Rail, energy and media Industries
Project Acronym:	5G-VICTORI
Document Number:	D2.4
Document Title:	5G-VICTORI end-to-end reference architecture
Version:	1.0
Delivery Date:	2022-03-31 (**2022-04-11**)
Responsible:	IASA
Editor(s):	Anna Tzanakaki (IASA)
Authors:	Markos Anastasopoulos (IASA), Anna Tzanakaki (IASA), Tanya Politi (UoP), Christos Tranoris (UoP), Panagiotis Papaioannou (UoP), Alexis Birbas (UoP), Ioanna Mesogiti (COSM), Maria-Evgenia Xezonaki (ICOM), Dimitrios Kritharidis (ICOM), Vasileios Theodorou (ICOM), Nikolaos Tzanis (ADMIE), Eleftherios Mylonas (ADMIE), Paris Flegkas (UTH), Nikos Makris (UTH), Louay Bassbouss (FhG), Troudt, Eric (FhG), Jesús Gutiérrez (IHP), Marius Iordache (ORO), Catalin Brezeanu (ORO), Sofia Pison (EUR), Hung Nguyen (EUR), Raymond Knopp (EUR), Navid Nikainen (EUR), Shadi Moazzeni (UNIVBRIS), Hojjat Baghban (UNIVBRIS), Constantinos Vrontos (UNIVBRIS), Hamid Falaki (UNIVBRIS),

	Kostantinos Katsaros (**DCAT**), Peter Lundh (**Alstom**), Ed Dening (**ZN**), Anthony Karydis (**MATI**), Eleftherios Kazanis (**MATI**), Robert Sugar (**UHA**), Adriana Fernández-Fernández (**I2CAT**), Miguel Catalán-Cid (**I2CAT**).
Keywords:	5G Networks, Vertical Industries, Architecture, 5G-VIOS, 5G RAN, 5G Core, 5G Use Cases, 5G Network infrastructures, Communication Systems, 5G KPIs.
Status:	Final
Dissemination Level	**Public**
Project URL:	https://www.5g-victori-project.eu/

Revision History

Rev.	Description	Author	Date
0.0	Draft Table of Contents (ToC)	Anna Tzanakaki (IASA)	2021-11-20
0.1	Finalisation of ToC	Anna Tzanakaki (IASA)	2021-12-03
0.2	Section 5 first content on the 5G-VICTORI deployment options per cluster (Patras, Berlin, France/Romania and Bristol)	Tanya Politi (UoP), Marievi Xezonaki (ICOM), Ioanna Mesogiti (COSM), Nikolaos Tzanis, Eleftherios Mylonas(ADMIE), Paris Flegkas (UTH), Nikos Makris (UTH), Louay Bassbouss, Eric Troudt (FhG) Jesús Gutiérrez (IHP) Marius Iordache, Carmen Patrascu (ORO) Navid Nikaein (EUR) Hojjat Baghban, Constantinos Vrontos (UNIVBRIS)	2021-12-21
0.3	Section 5 revised content on the 5G-VICTORI deployment options per cluster (Patras, Berlin, France/Romania and Bristol)	Tanya Politi (UoP), Marievi Xezonaki (ICOM), Ioanna Mesogiti (COSM), Nikolaos Tzanis, Eleftherios Mylonas(ADMIE), Paris Flegkas (UTH), Nikos Makris (UTH), Louay Bassbouss, Eric Troudt (FhG) Jesús Gutiérrez (IHP) Marius Iordache, Carmen Patrascu (ORO) Navid Nikaein (EUR) Hojjat Baghban, Constantinos Vrontos (UNIVBRIS)	2022-01-10
0.4	Revision of section 5.3	Peter Lundh (Alstom)	2022-01-27
0.5	Input sections 3 and 4	Anna Tzanakaki, Markos Anastasopoulos (IASA)	2022-01-21
0.6	Revised section 5.5	Hojjat Baghban, Constantinos Vrontos (UNIVBRIS)	2022-01-29
0.7	Input section 5.6, Interdomain descriptions	Kostas Katsaros (DCAT)	2022-01-31
0.8	Section 5 revised content on the 5G-VICTORI deployment options per cluster (Patras, France/Romania and Bristol)	Tanya Politi (UoP), Ioanna Mesogiti (COSM) Marievi Xezonaki (ICOM), Ioanna Mesogiti (COSM), Nikolaos Tzanis, Eleftherios Mylonas(ADMIE), Paris Flegkas, Nikos Makris (UTH), Marius Iordache, Carmen Patrascu (ORO) Navid Nikaein (EUR) Hojjat Baghban, Constantinos Vrontos (UNIVBRIS)	2022-02-11
0.9	Acronyms added, Mapping of Rail Signaling and CCTV services over 5GC. General comments	Peter Lundh (Alstom)	2022-02-21
0.10	Input to section 2 and revised input to section 3 and 4	Markos Anastasopoulos, Anna Tzanakaki (IASA)	2022-03-10
0.11	Section 5 revised content on the 5G-VICTORI deployment options for the Patras cluster	Tanya Politi (UoP), Marievi Xezonaki (ICOM), Ioanna Mesogiti (COSM),	2022-03-11

		Nikolaos Tzanis, Eleftherios Mylonas(**ADMIE**), Paris Flegkas, Nikos Makris (**UTH**),	
0.12	Additional input section 2	Ioanna Mesogiti (**COSM**)	2022-03-21
0.13	Executive Summary, Sections 1 and 6	Anna Tzanakaki (**IASA**)	2022-03-25
	Additional input section 5.5 inter-facility demo descriptions and revision of section	Markos Anastasopoulos, Anna Tzanakaki (**IASA**)	2022-03-28
0.14	Review of the document and referencing	Anna Tzanakaki, Markos Anastasopoulos (**IASA**)	2022-03-29
0.15	Review of the document	Kostas Katsaros (**DCAT**)	2022-03-31
0.16	Final revision of the document	Anna Tzanakaki (**IASA**), Jesús Gutiérrez (**IHP**)	2022-03-31
1.0	Submission of the document	Jesús Gutiérrez (**IHP**)	2022-04-11

Table of Contents

List of Figures

List of Tables

Executive Summary

This document summarises the requirements the 5G-VICTORI infrastructure aims to support, focusing on the “Business level use case requirements”, as well as on the “5G-VICTORI Infrastructure Operation System (5G-VIOS) architectural requirements”. In addition, this deliverable provides an overall description of the 5G-VICTORI functional architecture focusing on the functionalities, features and characteristics that the 5G-VICTORI platform is designed to offer. Following this, it includes a detailed description of the overall project 5G end-to-end (E2E) reference architecture used for the instantiation and integration of the various verticals and corresponding infrastructures at the different facility locations.

The proposed and adopted flexible network architecture has been inspired by standardised 5G architectural approaches (ETSI, 3GPP, IEEE and O-RAN), adding to these innovative features. A key innovation relates with the concept of the functions repository to enable service provisioning in support of Vertical use case (UC) requirements. This functions repository allows verticals to define and implement their own functions as well as to access and deploy a set of functions developed by other verticals available in the same repository. Another architectural innovation is the introduction of a thin inter-domain orchestration layer that resides on top of the orchestration solutions of the individual facility, referred to as 5G-VIOS. This orchestration layer enables dynamic inter-site connectivity, inter-domain orchestration and on-boarding of inter-domain services as well as E2E slice monitoring and management for the deployed E2E services. These capabilities enable a common platform over which a variety of Vertical industries are able to provide their service offerings independently and in isolation, deploying resources and functions available through the common 5G-VICTORI infrastructure and functions repository. Furthermore, this document provides the details of the various project architectural deployment options at the different facility locations, i.e. the specific 5G architectures adopted at each of the 5G-VICTORI facility infrastructures (Patras in Greece, Berlin in Germany, France/Romania in Romania, and Bristol in the UK). More specifically, this information includes the description of the specific architectural structures, platforms and technologies deployed per facility, details on how the Vertical services that will be demonstrated per facility as part of the planned UC) are mapped over the available 5G infrastructure and some discussion on the required interfaces. Finally, 5G-VICTORI offers the necessary tools offered by 5G-VICTORI to provide services across the different facilities involved in the project. In the context of the project, two inter-cluster scenarios are considered based on the Vertical application deployment options.

1 Introduction

In support of the overall 5G vision, aiming to offer services to a variety of new industrial stakeholders (referred to as Vertical industries), and to support new business models and opportunities, 5G-VICTORI has proposed a novel architectural approach to facilitate a 5G platform with increased functionality and flexibility. The proposed approach aims to transform traditionally closed, static and inelastic network infrastructures into open, scalable and elastic ecosystems that can support a large variety of dynamically varying applications and services. In this context, the overall project activities focus on bringing together technology players, vendors, operators and verticals orchestrating their interaction with the aim to open up new business models and opportunities for the ICT and Vertical industries and to enable cross-Vertical collaborations and synergies to offer further enhancement in value propositions.

Apart from a set of functional requirements that the 5G-VICTORI infrastructure aims to support, it targets to meet a set of stringent network Key Performance Indicators (KPIs) in accordance to the 5G defined KPIs, but also to provide a suitable framework in support of the greatly varying strict requirements of Vertical industries. In this context, it aims to support different types of applications, both human-centric and machine-type, exploiting the notions of end-to-end (E2E) network slicing, Software Defined Networking (SDN), and adopting concepts such as Service-Based Architecture (SBA) and Network Function Virtualization (NFV).

5G-VICTORI is adopting a flexible 5G architecture and a variety of advanced 5G technologies comprising and integrating together commercially available solutions, open-source platforms and innovative technologies developed in the framework of the project. It addresses large-scale trials for advanced use case (UC) verification in commercially relevant 5G environments. These large-scale trials will be executed in operational environments in a number of 5G platforms across Europe and for a number of verticals, while some specific UCs involving also cross-Vertical interaction. The project exploits extensively the existing ICT-17 5G Testbed Infrastructures interconnecting main sites of the 5G-VINNI, 5GENESIS, 5G-EVE and the 5G UK testbed in a Pan-European Network Infrastructure. Intensive 5G-VICTORI activities have focused on extending and upgrading these existing infrastructures to enable integration of the Vertical commercially relevant, operational environments [1] [2]. This activity has been key towards the demonstration of the large variety of 5G-VICTORI Vertical and cross-Vertical UCs focusing on **Transportation**, **Energy**, **Media** and **Factories of the Future**.

The proposed and adopted flexible network architecture has been inspired by standardised 5G architectural approaches (ETSI, 3GPP, IEEE and O-RAN) adding to these innovative features. A key innovation relates with the concept of the functions repository to enable service provisioning in support of Vertical UC requirements. This functions repository allows verticals to define and implement their own functions as well as access and deploy other functions developed by other verticals available in the same repository. Another architectural innovation that 5G-VICTORI has proposed is the introduction of a thin inter-domain orchestration layer that resides on top of the orchestration solutions of the individual facility sites referred to as the 5G-VICTORI Infrastructure Operation System (5G-VIOS). This orchestration layer enables dynamic inter-site connectivity, inter-domain orchestration and on-boarding of inter-domain services as well as E2E slice monitoring and management for the deployed E2E services. These capabilities enable a common platform over which a variety of Vertical industries are able to provide, independently and in isolation, their service offerings deploying resources and functions available through the common 5G-VICTORI infrastructure and function repository.

This document summarises the requirements that the 5G-VICTORI infrastructure aims to support focusing on the “Business level use cases and requirements” as well as the “5G-VIOS architectural requirements". Detailed service-, technology- and deployment-specific requirements have been already provided and discussed in detail in 5G-VICTORI deliverable D2.1 [3]. In addition, this deliverable report provides an overall description of the 5G-VICTORI functional architecture focusing on the functionalities, features and characteristics that the 5G-VICTORI platform is designed to offer. Following this a detailed description of the overall project 5G E2E reference architecture used for the instantiation and integration of the various verticals and corresponding infrastructures at the different facility locations is provided. Emphasis is put on the description of the 5G-VIOS role in support of the execution of UCs involving more than one facility. The details of the 5G architecture adopted at each of the 5G-VICTORI facility infrastructures (Patras in Greece, Berlin in Germany, France/Romania in Romania, and Bristol in the UK) is described providing information on the specific platforms and technologies deployed, the details of services mapping to the available 5G infrastructure and some discussion on the required interfaces.

1.1 Organisation of the document

This document comprises six (6) sections. Following the Executive Summary and Introduction sections:

Section 2 summarises the requirements that the 5G-VICTORI infrastructure aims to support focusing on the "Business level use case requirements" as well as the "5G-VIOS architectural requirements".

Section 3 provides a detailed description of the 5G-VICTORI functional architecture focusing on the functionalities, features and characteristics that the 5G-VICTORI platform is designed to offer and the overarching 5G architecture the project adopts.

Section 4 describes in detail the E2E 5G reference architecture that is used for the instantiation and integration of the various verticals and infrastructures in the four selected 5G facilities considered in the project.

Section 5 presents the different architectural deployment options per facility, i.e. the 5G architecture adopted at each of the 5G-VICTORI facility infrastructures (Patras in Greece, Berlin in Germany, France/Romania in Romania, and Bristol in the UK), providing information on the specific platforms and technologies deployed per site. In addition, details of the mapping of the services that will be demonstrated over the per site available 5G infrastructure is provided together with some discussion on the required interfaces.

Finally, Section 6 concludes the deliverable.

2 System Requirements

As discussed in detail in deliverable D2.1 [3], 5G-VICTORI aims at enabling new business models allowing Vertical stakeholders to create and access infrastructure slices in support of services that they can offer over the underlying 5G infrastructure. This approach will encourage and accelerate the level of adoption of 5G technologies on emerging markets and will create new business opportunities for small enterprises and large industries.

The main goal is the shift towards creating a network as a service model that will be realised through an open interoperable platform integrating together networking, compute and storage resources in a common programmable infrastructure. This infrastructure addresses business critical requirements of Vertical industries, as it has translated these business requirements into a set of technical specifications that the infrastructure is able to support including capacity, latency, reliability, security and guaranteed Quality of Service (QoS).

The 5G-VICTORI infrastructure will be accessed flexibly and will support the coexistence of multiple Vertical services that share common resources. These resources will be managed and accessed on demand by any service or application, enhancing resource efficiency and providing measurable benefits for the Vertical industries in terms of cost, scalability, sustainability and management simplification.

In 5G-VICTORI there are six (6) main UCs that are being implemented and demonstrated during the project lifetime, these are:

- “Enhanced Mobile broadband under high speed mobility”, Vertical: Transportation – Rail.
- “Digital Mobility”, Cross-Vertical - Transportation and Media.
- “Critical services for railway systems”, Vertical: Rail.
- “Smart Energy Metering”, Cross-Vertical: Energy and Rail.
- “Digitisation of Power Plants”, Vertical: Smart Factory.
- “CDN services in dense, static and mobile environments”, Vertical: Media.

The relevant network and service level technical requirements associated with the planned UCs have been presented and discussed in detail in deliverable D2.1 [3].

2.1 Business level use cases and requirements

5G networks can be considered as platforms where various stakeholders can operate in a layered service provisioning approach. Through various technical and business interfaces, these stakeholders eventually contribute to offer services to a **Service Customer (SC)**, such as an individual end-user, a Vertical industry customer, etc. Based on the 3GPP standard [4], which defines various service provisioning layers, the 5GPPP Architecture WG [5] has provided a representation of the processes and activities related to the 5G service provisioning. These have been grouped in coherent roles along with the relationships and interfacing options between them, as shown in Figure 2-1. These roles assume the management of relevant interfaces at business and technical level, an overview of which is provided in [5].

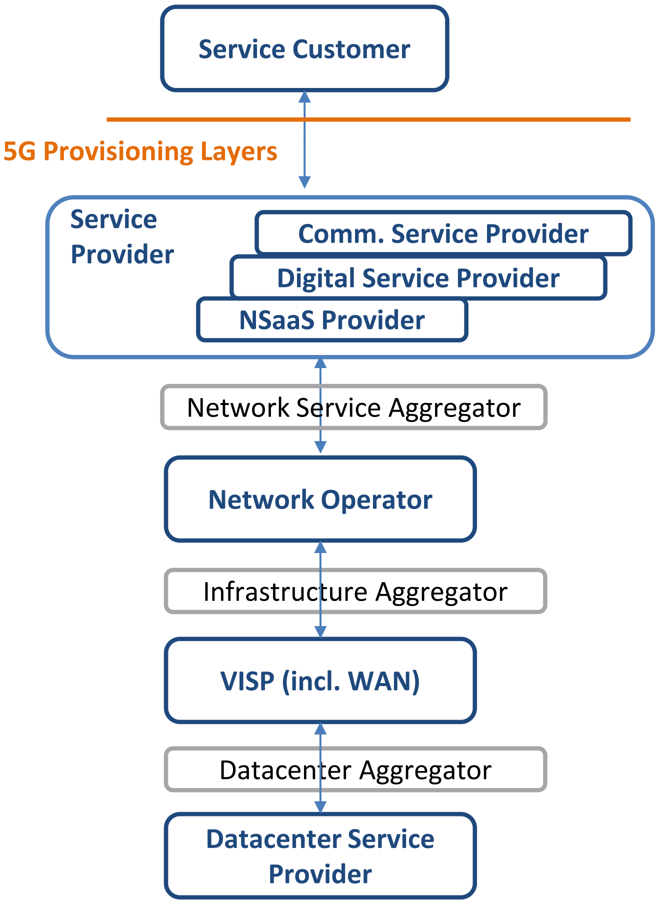


Figure 2-1 Roles and interfacing in 5G provisioning systems (based on 5GPPP [4])

The **Service Provider (SP)** is a principal role in the 5G system, which directly interfaces the SCs and obtains and orchestrates resources from **Network Operators (NOPs)**, **Virtualisation Infrastructure Service Providers (VISPs)** and **Datacentre Service Providers (DCSPs)** (collectively mentioned in parts of this document as **Infrastructure Providers**). The role of the SP can be distinguished into: i) **Communication Service Provider (CSP)**, entailing the activities for offering traditional telecom services, ii) **Digital Service Provider (DSP)**, entailing the activities for offering digital services such as eMBB and IoT to various Vertical industries, and iii) **Network Slice as a Service (NSaaS) Provider**, entailing the activities for offering a network slice along with the services that it may support and configure. These roles include, among others, the business services provisioning activities towards their interfacing roles, and are technically related to Business Support System (BSS)/Operations Support System (OSS) interfacing the virtual or actual infrastructure resources operated and maintained by the NOP role.

The **NOP** role implies operating a programmable (5G) network infrastructure, spanning from the radio and/or fixed access to the edge, transport and core network (CN), and it is extended to include the operation of virtual resources leased by other Infrastructure Providers through appropriate Application Programming Interfaces (APIs).

The **VISP** role performs activities related to offering virtualised network or cloud/edge computing resources available through APIs and it practically corresponds to the cloud/edge infrastructure provider.

The **DCSP** role performs activities related to offering raw computing resources in the context of the Information Technology (IT) world.

Additional roles can be identified such as the **Service Aggregators (SA)** at various layers, i.e. the **Network Service Aggregator**, the **Infrastructure Aggregator** and the **Datacentre Aggregator**. The role of SAs can assume the activities of service provisioning across multiple domains of a specific layer, namely: across multiple NOPs required, e.g. in cross borders (country/territory borders) or in multiple private and public network environments, across multiple cloud/edge providers for the deployment of a distributed service/Vertical application, across multiple datacentre providers for similar purposes.

The following requirements are taking into account the various business level requirements that emerge from the aforementioned service provisioning model, at various service provisioning levels and are also inspired and are in alignment with the requirements defined by 3GPP TS 28 530 V16.5.0 [4], 3GPP TS 28 535 V16.5.0 [6], TS 22 261 V16.16.0 (2021-12) [7], etc. The requirements below refer to the business interactions rather than the service requirements, since the service-, technology- and deployment-specific requirements have been provided in 5G-VICTORI deliverable D2.1 [3]

- ***Communication service management and assurance between the SC and the CSP***

The requirements defined below reflect the management control loop between the SC and the CSP. In general terms, the SC provides the requirements for an assured communication service to the CSP, the CSP provides the corresponding communication service and also provides feedback to the SC. The CSP adjusts the resources used by a communication service or the SC adjusts the Service Level Agreement (SLA) continuously to achieve the assured requirements. These requirements are inspired by 3GPP TS 28 530 [4] and 3GPP TS 28 535 [6], and address the common service provisioning phases being: Preparation phase, Commissioning phase, Operation phase, Decommissioning Phase.

  - ***Preparation phase and Commissioning phase***

Req.ID	Description
P-1	Automation in the description of the compute and network resources required for the deployment of the Vertical application provided by the CSP, on a 5G System (5GS).
P-2	Automation of the onboarding of the Vertical application, which will use communication services provided by the CSP, on a 5GS.
P-3	The 3GPP management system –of the CSP/DSP/NSaaSP- shall have capabilities to receive communication service requirements from the Vertical application.
P-4	The CSP shall be capable of defining and providing Communication Services of various Types (uRLLC, eMBB, mIoT) with the required QoS.

  - ***Operation and De-commissioning Phase***

In particular, the operation phase, which is the one affecting the most the experienced service performance, includes also Monitoring, Analysis, Decision and Execution activities. The following requirements are posed in these activities/cycles.

Req.ID	Description
OD-1	The 3GPP management system shall have capabilities to monitor, collect and report to the Vertical applications information related to the degree of fulfilment of committed communication service requirements of Vertical application. This includes degree of satisfaction of an SLA in business terms, experienced quality in terms of user satisfaction, etc.

OD-2	The 3GPP management system shall have capabilities to take actions to adjust the 5GS in order to meet the communication service requirements of the Vertical application and maintain their fulfilment.
OD-3	The 3GPP management system shall be adjustable to accommodate the requests/services coming from multiple Vertical applications.
OD-4	The management system shall be able to accept and execute requests for decommissioning of Vertical applications (NF and application level).

- ***Communication service management and assurance between the CSP and the NOPs***

The below defined requirements reflect the management control loop between the CSP and the NOPs. In general terms, the communication service provided by CSP requires the network capabilities from one or multiple NOPs. These requirements are inspired by [8], and address the operation phase and specific Monitoring, Analysis, Decision and Execution requirements posed by a Cross Facility Management and orchestration (MANO) layer. The requirements below reflect the various scenarios / services that are requested from CSP by NOPs.

  - ***Requirements for KPIs monitoring***

Req.ID	Description
SM-1	The facility operators shall be able to perform KPIs definition and performance data collection.
SM-2	The facility operators shall be able to request and provide with KPIs measurement data to the Vertical application developers and the cross facility management orchestration platform.

  - ***Requirements for NF performance measurement***

Req.ID	Description
PM-1	The facility operators shall be able to perform Network Function (NF) performance data collection.
PM-2	The cross facility orchestrator shall be able to request and be provided with NF measurement data by the facility operators. The facility operators – responsible for controlling the NF measurement job shall have the capability to allow the cross facility management orchestration layer – to request creation of a measurement job to collect the performance data of NF(s).
PM-3	The facility operators- responsible for NF performance data file reporting shall have the capability to allow the cross facility management orchestration layer to fetch the performance data file of NF(s)- and create analytics.

  - ***Requirements for Network Slice and Network Slice subnet performance measurement***

Req.ID	Description
AR-4.13.2-a	The facility operators shall be able to perform Network Slice performance data collection.
AR-4.13.2-b	The facility operators- responsible for controlling the Network Slice Instance performance data collection and reporting shall have the capability to allow the cross

	facility management orchestration layer to obtain its own Network Slice Instance performance data especially in the NSaaS scenario.
AR-4.13.2-c	The facility operators shall be able to perform Network Slice Subnet Instance performance data collection.
AR-4.13.2-d	The facility operators- responsible for controlling the Network Slice Subnet Instance performance data collection and reporting shall have the capability to allow the cross facility management orchestration layer to obtain its own Network Slice Subnet Instance performance data especially in the NSaaS scenario.

2.2 5G-VIOS Architectural Requirements

As described in D2.1 [3], the 5G-VICTORI solution aims at supporting both ICT and Vertical services through the deployment of 5G and Vertical NFs. This is achieved by taking advantage of the capabilities that the overall 5G architecture offers in support of the Vertical service requirements. The 5G-VICTORI architectural enabler that supports this vision is the creation of repositories comprising programmable NFs both 5G and Vertical service specific (i.e. synchronisation, positioning, signalling, etc.), as well as Vertical industry specific Application Functions (AFs). Combinations of the functional elements of these repositories that may be associated with different facilities and geographical locations will form one common repository through which they can be accessed and deployed for service provisioning at any location of the 5G-VICTORI infrastructure.

To make Vertical applications deployable over the 5G-VICTORI platform, suitable application packaging is provided through the development of AFs and Network Services (NS) descriptors. These descriptors facilitate applications to be deployed in a single domain/site but will be also extended to enable platform NSs. This functionality is supported through 5G-VIOS, the inter-domain orchestrator developed in the framework of the project and described in detail in deliverable D2.6 [9]. The role of 5G-VIOS in the overall 5G-VICTORI architecture is further discussed in section 4.2. In summary, 5G-VIOS enables management of slices, resources, and orchestration of services across different 5G sites/platforms. It provides NS deployment across different facilities, inter-site service composition and on-boarding, E2E slice monitoring and management for the deployed E2E services and facilitates end-users (facility administrators and Vertical users) to interact with the 5G-VICTORI infrastructure and services. Facility administrators are able to onboard their facilities onto 5G-VIOS and expose the capabilities they offer through a common service repository that can also host AFs developed by the external Vertical SPs, which can then be used to deploy new NS to other facilities. In addition, 5G-VIOS is responsible to automate the life-cycle management (LCM) of these inter-domain NSs.

In this context, the 5G-VICTORI needs to satisfy specific requirements that dictate the functionality and performance of the inter-domain/inter-platform orchestration that are summarised below.

2.3 Common Application Repository and Application Programming Interfaces (APIs)

These requirements are inspired and in alignment with the requirements defined by ETSI TS 123 222 V16.10.0 (2021-07)) [10].

- ***High level Architectural Aspects***

Req.ID	Description
CAPIF-1a	5G-VICTORI will provide mechanisms (e.g. publish service APIs, authorisation, logging, charging) to support service API operations (as well as operations from trusted 3rd party API providers).

CAPIF-1b	5G-VICTORI will enable the common AF to discover and communicate with service APIs from the API providers
CAPIF-1c	Reference points between local facility orchestrators, AFs hosted in 5G- VICTORI and external applications will be provided as APIs.
CAPIF-1d	Reference points internal to 5G- VICTORI may be provided as APIs.

- ***Service API publish and discover***

Req.ID	Description
CAPIF-2a	5G-VICTORI will provide a mechanism to publish the service API information to be used by the AF to discover and subsequently invoke the service API.
CAPIF-2b	5G-VICTORI will provide mechanisms to apply restriction policies for specific published service API information and based on these to allow restricted discovery of the published service API information by the AF providers.

- ***Security***

Req.ID	Description
CAPIF - 3a	5G-VICTORI will provide mechanisms to hide the topology of each individual trust domain (independent 5G-VICTORI facility) from the AF accessing the service APIs from another 5G-VICTORI facility.
CAPIF – 3b	5G-VICTORI will provide authentication mechanisms for AFs prior to accessing the service APIs and upon service API invocation.
CAPIF – 3c	5G-VICTORI will provide mechanisms to authorize and validate authorisation of AF providers to access the service APIs. These authorisation mechanisms need to be mutual between the 5G-VICTORI platform and the API invoker.
CAPIF – 3d	5G-VICTORI will provide mechanisms to control the service API access for every AF and the communication between the 5G-VICTORI platform and the AFs needs to be confidentiality protected.
CAPIF – 3e	The communication between 5G-VICTORI and the AFs will be integrity protected and the 5G-VICTORI platform needs to provide authentication and authorisation mechanisms for the service API publishers to publish and manage the service API information.

- ***Operations, Administration and Maintenance***

Operations, Administration and Maintenance (OAM) requirements that the 5G-VICTORI solution needs to address include performance monitoring, fault monitoring, policy configurations, and certain lifecycle management aspects such as running status of service APIs monitoring and related operations.

Req.ID	Description
CAPIF – 4a	5G-VICTORI will provide mechanisms to monitor the status of AFs, e.g. starting and stopping access of the Vertical services as well as monitor and report the performance.
CAPIF – 4b	5G-VICTORI will provide mechanisms to monitor and report the fault information about the service APIs or change of API related events e.g. service APIs relocation
CAPIF - 4c	5G-VICTORI will provide mechanisms to configure policies related to service APIs.

- ***Vertical applications monitoring***

The 5G-VICTORI Platform needs to support a set of monitoring functions. These enables the Vertical application developers the performance of their applications, determine critical aspects such as system load, API usage information, uncover potential overload and attack (e.g. DDoS) conditions.

Req.ID	Description
CAPIF – 5a	5G-VICTORI needs to provide mechanisms to capture service API invocation events and make them available to the AF provider.
CAPIF – 5b	5G-VICTORI needs to provide mechanisms to notify in case of events related to overload and threat conditions (e.g. system load, resource usage information).

- ***Onboarding API invoker***

A set of indicative requirements related to the onboarding API invoker that the 5G-VICTORI solution needs to support are summarised below.

Req.ID	Description
CAPIF – 6a	The 5G-VICTORI platform will provide mechanisms to enable Vertical applications developers to onboard new AFs to the common repository.
CAPIF– 6b	5G-VICTORI will support offboarding of an AF from the platform.
CAPIF–6c	5G-VICTORI will support updating an AF API list e.g., following the discovery of new API(s).

- ***Policy configuration***

In terms of policy configuration, 5G-VICTORI solution needs to support the following requirement.

Req.ID	Description
CAPIF–7	5G-VICTORI will support policy configurations (e.g. related to the protection of platforms and network, specific functionalities exposed, message payload size or throughput).

- ***Protocol design***

In order for the 5G-VICTORI solution to be common across the variety of all present and future AF providers, a common protocol stack model is needed. This can be summarised as follows.

Req.ID	Description
CAPIF–8a	5G-VICTORI will support a minimum common protocol stack model for all API implementations
CAPIF–8b	5G-VICTORI will support a common security mechanism for all API implementations for confidentiality and integrity protection.

- ***Interconnection between the 5G-VICTORI facilities***

Two different 5G-VICTORI facilities may need to interoperate to allow AF providers from one trust domain (individual 5G-VICTORI facility) to utilise service APIs from the second 5G-VICTORI facility.

Req.ID	Description
CAPIF–9	5G-VICTORI will provide mechanisms to enable the AF providers of one 5G-VICTORI facility to discover and invoke the service APIs of another 5G-VICTORI facility.

3 5G-VICTORI Functional Architecture

The 5G-VICTORI architecture is designed in accordance to the overall 5G vision, the relevant service requirements and KPIs described above. 5G-VICTORI aims at providing a Vertical-optimised common platform aiming to address the requirements and business needs of the telecom and Vertical industries. In this context, 5G-VICTORI aims to design and prototype an open 5G infrastructure capable of instantiating and co-hosting applications for various Vertical sectors. A central objective of the project has been the integration of commercially relevant, operational environments that are required for the demonstration of the large variety of the 5G-VICTORI Vertical and cross-Vertical UCs. In this context, transforming current closed, purposely developed and dedicated infrastructures into open environments, where resources and functions are exposed to the telecom and the Vertical industries, has been identified as a key enabler. This, as already discussed, can be facilitated through the creation of a common repository that can host the required functions both from the network and the Vertical perspective offering the potential of co-creation and sharing of services among different players in a controlled and secure environment where authentication and different authorisation levels can be applied.

3.1 5G VICTORI Functional Architecture Definition

More specifically, the 5G-VICTORI infrastructure interconnects main sites of all ICT-17 infrastructures, i.e. 5G-VINNI, 5GENESIS and 5G-EVE and the 5G UK testbed in a Pan-European network infrastructure as illustrated in Figure 3-1.

This infrastructure is used to demonstrate a set of Vertical and cross-Vertical UCs focusing on Transportation, Energy, Media and Factories of the Future, relying on an open environment where resources and functions are exposed to the telecom and the Vertical industries and can be accessed and shared on demand for efficient and flexible service provisioning. 5G-VICTORI is also developing an open data management platform for scalable data collection, aggregation and processing across the various project infrastructure sites adopting machine learning (ML) and artificial intelligence (AI) techniques to offer optimised Vertical services.

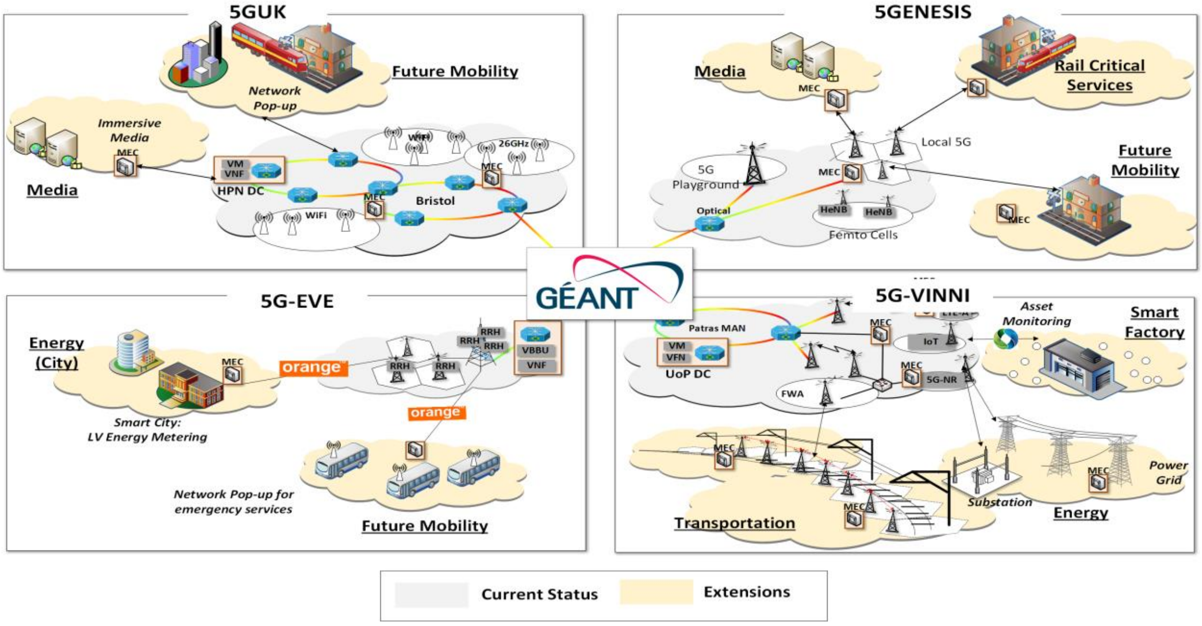


Figure 3-1 5G-VICTORI facilities and associated extensions

5G-VICTORI activities have focused intensively on extending the available **ICT-17 5G infrastructures with emphasis in Vertical sector operational environments** in order to facilitate the integration of the Vertical components required for the demonstration of the Vertical and cross-Vertical UCs planned as part of the project activities.

The 5G-VICTORI infrastructure has been designed to instantiate and co-host various Vertical sectors and is based on leading industry and open source technologies supporting very diverse service requirements with guaranteed QoS levels. This developed and deployed infrastructure operates a truly Open, and Extensible 5G NFV-based ecosystem that integrates verticals into existing interconnected 5G Platforms enabling practical infrastructure sharing through slicing and virtualisation.

The proposed and adopted flexible network architecture has been inspired by standardised 5G architectural approaches, i.e. ETSI, 3GPP, IEEE and Open Radio Access Network (O-RAN) [11], adding to these innovative features. A key innovation proposed relates with the concept of the functions repository to enable service provisioning in support of Vertical UC requirements. This functions repository allows verticals to define and implement their own functions as well as access and deploy other functions developed by other verticals available in the same repository. Another architectural innovation that 5G-VICTORI has proposed is the introduction of a thin inter-domain orchestration layer that resides on top of the orchestration solutions of the individual facility sites referred to as 5G-VIOS. This orchestration layer enables dynamic inter-site connectivity, inter-domain orchestration and on-boarding of inter-domain services as well as E2E slice monitoring and management for the deployed E2E services. These capabilities enable a common platform over which a variety of Vertical industries are able to provide independently and in isolation their service offerings deploying resources and functions available through the common 5G-VICTORI infrastructure and function repository. 5G-VIOS implements suitable drivers to communicate with the Northbound Interfaces (NBIs) of the site orchestrators, while also provisioning and orchestrating the necessary Layer 3 (L3) or Layer 2 (L2) dynamic connectivity across the data plane of the sites. To take advantage of the technology, resources and services offered across facilities in the common 5G-VICTORI repository, slices can be composed across platforms taking a cross-platform infrastructure slicing approach.

Flexible service provisioning over cross-platform slices relies on the combination and orchestration of a set of NFs through service chaining over the integrated programmable infrastructure. Cross-domain infrastructure slicing, service chaining and orchestration is be facilitated merging together the SDN reference architecture and the ETSI NFV standard and leveraging on existing developments including the 5G-XHaul control plane (CP), and the orchestrator from the Phase-2 5G-PPP project 5G-PICTURE.

To make the application of Verticals deployable over the 5G-VICTORI platform, suitable application packaging will be provided through the development of Virtual Network Functions (VNFs) and NS descriptors. These descriptors facilitate applications to be deployed in a single domain/site and have been extended to enable cross-domain/platform NSs.

5G-VIOS supports a lightweight multi-site active inventory that is be responsible to maintain virtual resources along with their interrelated logical entities exposed by the underlying facilities. The lightweight multi-site inventory system is dynamically updated to reflect changes in hardware/software resources of the underlying facilities. It also provides to Vertical SPs a self-configured SDN CP approach capable of reacting rapidly to traffic demand changes, network failures and requests for the creation of new services from the service orchestration layer.

The 5G-VICTORI lightweight multi-site inventory is able to keep the current state of the virtual and logical network layers, and their interrelationships with the underlying 5G platforms. This is critical for the provisioning of services for Vertical industries as in many cases the created service chains rely on network slicing and inventory data that typically cross several network domains. Given that Verticals require services with very high reliability, the 5G-VICTORI multi-site inventory also provide tools for performing root-cause analysis of service impacting network faults and configuration issues that manifest themselves at higher network layers or in other network domains. To achieve this, the multi-site inventory interacts with that testing system that allows full root-cause analysis and rapid fault resolution across the whole system.

In addition to this, it provides access to service catalogues available at the various sites acting as single marketplace adopting suitable authentication mechanisms and authorisation schemes to ensure that privacy and security requirements are satisfied as appropriate. This repository allows users to search, select, purchase and deploy, under specific SLAs, slice templates offered by third party providers. Third party providers and users will be able to develop their own components or services through the VNF developer kit. SLAs are offered with respect to the relevant service policy imposed be the various site facilities.

Figure 3-2 provides a pictorial representation of the 5G-VICTORI architecture including the proposed layered approach detailed in D2.1 [3] and the different platforms that are being integrated.

3.1 Overall 5G Architectural Approach

5G Networks (5GNs) introduce new ways of interconnecting the involved network elements compared to the previous LTE EPC technology. As the Control Plane and User Plane Separation (CUPS) is a crucial concept in 5G, two different approaches are adopted to support each. More specifically, the Control Plane (CP) NFs interact through the SBA, whereas the User Plane (UP) elements communicate through traditional point-to-point interfaces.

In the case of the Service Based Interfaces (SBIs), i.e. the API based communication that can take place between VNFs, each NF offers one or more services to other NFs in the network. These services are made available over NF interfaces that are connected to the common SBA. In practice this means that NFs are accessible by other NFs over an API. The defined communication method for 5G Core (5GC) is the HTTP Representational State Transfer (REST) API. It is important to be noted that the SBA is used for signaling functionality and not for the transfer of actual user data. The SBI concept is expected to make network capabilities easier to extend compared to the traditional point-to-point architecture, which relies on detailed and extensive protocol specification efforts.

When two NFs interact over the 3GPP SBA, a role is assigned to each one of them. The NF that requests a service has the role of a Service Consumer (being the entity to make use of the NF (at upper service provisioning layers the service consumer is essentially the service customer of Figure 2-1), while the NF offering the service is assigned the role of a Service Producer. Service Discovery, i.e. when a Service Consumer needs to locate a certain Service Producer, is realised by making use of the **Network Repository Function (NRF)**. The NRF is, as the name suggests, a repository where all available services of all NFs are registered and it is in charge of connecting the NFs in order for a service to be delivered.

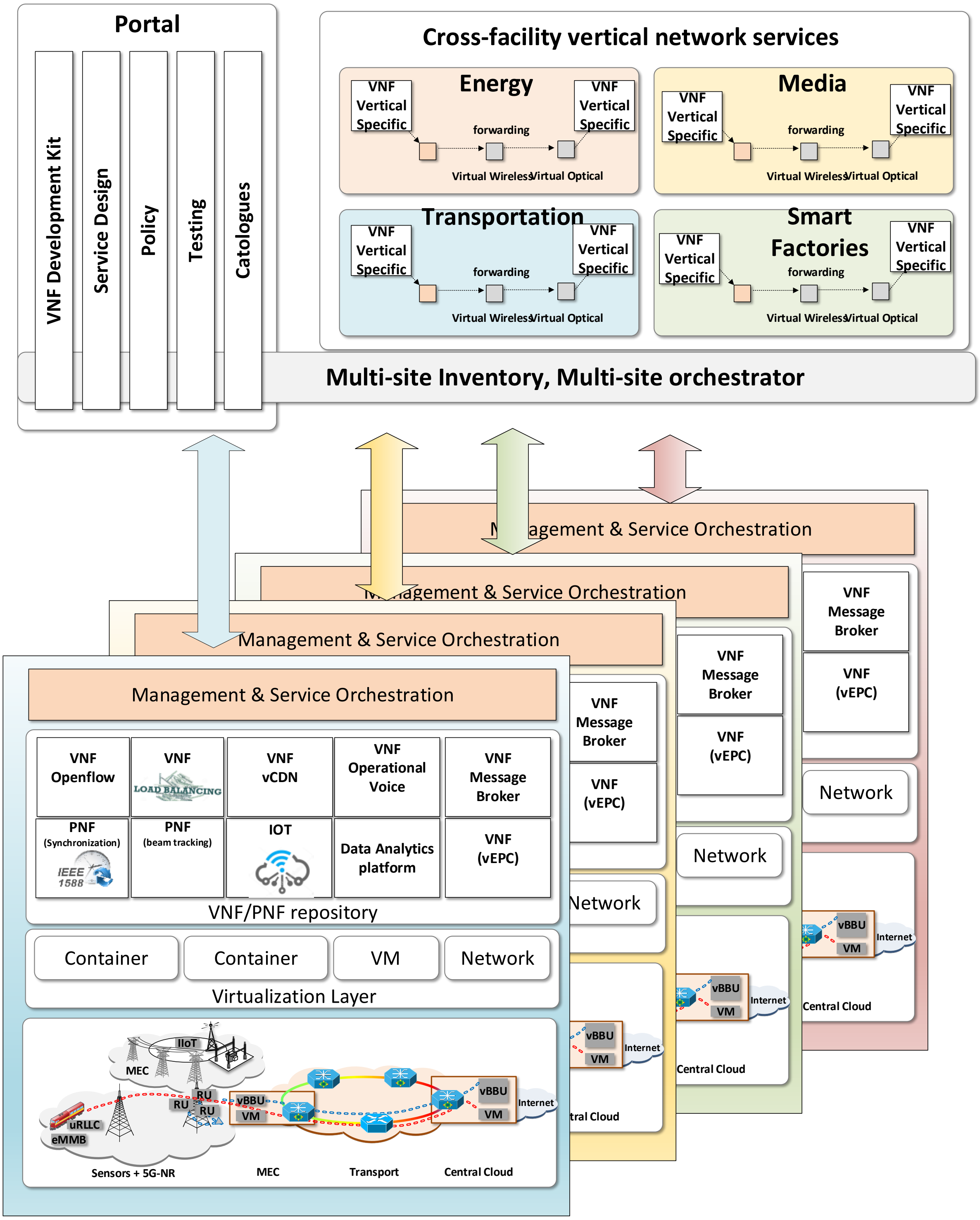


Figure 3-2 5G-VICTORI functional architecture

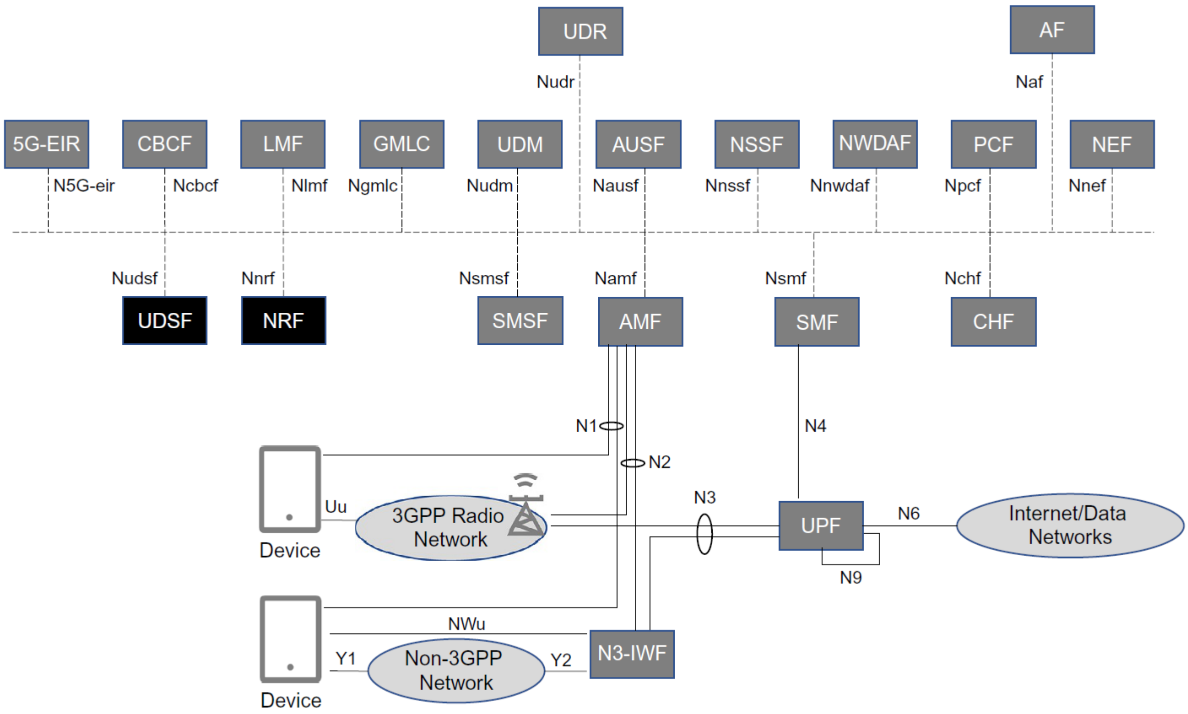


Figure 3-3 5G non-roaming architecture

As for the interaction between the UP elements (UE-RAN-UPF-DN) as well as between some CP NFs (SMF, AMF) and the UP components, communication is achieved through their point-to-point interfaces. The most commonly used point-to-point interfaces are:

- N1: Connects the UE with the AMF entity of the CN for NAS messages.
- N2: Used for the signaling between the RAN and the CN (AMF) through the NGAP protocol.
- N3: Used for data connectivity between the RAN and the UPF through a GTP tunnel (GTP-U protocol).
- N4: Used for communication between the SMF and the UPF over the PFCP protocol.
- N9: Interconnects different UPF entities across a given CN.
- N6: Interconnects the Anchor UPF with the external Data Network (DN).

3.2 5G Core Network Functions (NFs)

We will now briefly describe the most important NFs involved in the 5G architecture. These are the following:

- **Access and Mobility Management Function (AMF):** The AMF is involved in most of the signaling call flows in a 5G network, and it supports encrypted signaling towards device, allowing them registration, authentication, and moving between cells. It interacts with Radio Network over the N2 interface (NGAP), and with the devices over the N1 interface with NAS 5G Mobility Management (5GMM) messages. Connections with all other NFs are realised via SBIs.
- **Session Management Function (SMF):** The SMF is on the one hand responsible for setting up the connectivity between the UE and the DNs, and on the other hand for managing the user plane functionality for that connectivity. It manages the end device Protocol Data Unit (PDU) sessions such as establishment, modification and release of individual sessions, and allocation of IP addresses per session. It connects with other NFs via the N4 interface and also with its SBI. The SMF is designed with the flexibility

to support various types of end-user protocols, different options to ensure service continuity, as well as a flexible user plane architecture. Additionally, it interacts with the PCF to retrieve policies for the PDU sessions which it then passes to the UPF, and it is responsible for collecting charging data.

- **User Plane Function (UPF)**: Its main task is to process and forward user data using the N3 interface and its functionality is controlled from the SMF. It connects with external IP networks and acts as a stable anchor point for the devices toward external networks, hiding the mobility. This means that IP packets with a destination address belonging to a specific device is always routable from the Internet to the specific UPF that is serving this device even as the device is moving around in the network. Moreover, it performs different types of processing if the forwarded data. It also generates traffic usage reports for the SMF, which then includes them in charging reports to other NFs. The UPF can also apply packet inspection, to analyze the content of user data packets, which it can use either as input to policy decisions, or as a basis for traffic reporting. Additionally, it can redirect traffic or apply different data rate limitations. It also acts as buffer when a device is in idle state or unreachable from the network. It applies QoS marking of packets towards the radio network or to external networks. This can be used from the transport network to prioritize packets in case of congestion inside the network.
- **Unified Data Management Function (UDM)** executes functions requested from the AMF. It also generates the data used to authenticate attaching devices. Moreover, it authorizes access to specific users based on subscription data, for example, applying different access rules for roaming subscribers and home subscribers. The UDM also keeps track of which instance is serving which device, in case of more than one AMF and SMF existing in the network.
- **Unified Data Repository (UDR)**. It is basically a database that stores various types of data such as, subscription data and data defining various types of network or user policies. The data stored in the UDR are commonly offered as services to other NFs, namely, UDM, PCF and NEF.
- **Authentication Server Function (AUSF)**: It has a limited but important functionality, which is to provide the service of authenticating a specific device, in that process utilizing the authentication credentials created by the UDM. Moreover, it generates cryptographical material to allow for secure updates of roaming information and other parameters in the device.
- **Policy Control Function (PCF)**: The PCF is a key element in the 5GC and it interacts with various NFs. It is in charge of providing policy control of functionality for the SMF, AMF, UE access selection and PDU session selection. It can also support Negotiation of future data transfers. In relation to the SMF, the PCF provides QoS and charging control for SDFs (Service Data Flows), as well as policy control and event reporting for the PDU sessions. In relation with the AMF, it offers access and mobility policy control, including management of service area restrictions and of the RAT/Frequency. Selection Priority (RFSP). Finally, the PCF interacts with the UE via the AMF to provide policy information such as discovery, Session continuity mode selection, network slice selection and more.
- **Network Repository Function (NRF)**: The NRF is a repository that keeps the profiles of all NFs available to the network. Each time a NF (Service Consumer) needs to receive some service from another NF (Service Provider), will simply have to look the NRF to find the most suitable NF. Newly deployed or changed NFs have to report their new profile information to the NRF. Profile information updates can either be triggered

by the NF itself or by another entity on behalf of the NF. NF profiles in the NRF include information such as the NF type, address, capacity etc.

- **Network Exposure Function (NEF)**: The NEF is responsible for the exposure of events and capabilities from the 5GS to the applications and NFs of the operator's network or a third party network. Events such as the UE location, reachability, roaming status and loss of connectivity can be monitored by the NEF and then be made available to specific applications and NFs. Authorised applications by the network can use the NEF for specific requests, such as QoS and charging policies.
- **Application Function (AF):** Applications that are considered trusted, either inside the operator's network or outside of it, can communicate directly with the other Core NFs and influence some of their aspects, e.g. an application that runs on a Mobile Edge Compute (MEC) server may influence the traffic routing decisions. These applications are depicted in the 5G architecture as AFs. AFs can interact with the Core NFs either directly or via the NEF.
- **Network Slice Selection Function:** In 5GS, different networks can be virtually divided to isolated slices. For example each UC (eMBB, uRLLC, mMTC, IoT) can be served by a different slice. The NSSF is aware of the existence of all network slices and the AMF(s) that are dedicated to each slice, and selects the set of slices and AMF(s) that should serve the UE.

4 5G-VICTORI multi-domain Architecture

4.1 5G-VICTORI End-to-end Architecture

5G-VICTORI provides a Vertical-optimised common platform supporting in an attractive, cost and energy efficient way, the requirements and business needs of Vertical industries. To enable the offering of a single E2E platform across multiple facility sites, 5G-VICTORI provides interconnection and interworking capabilities creating a common infrastructure of integrated network and compute/storage resources. This is a key aspect of the 5G vision as these resources will be able to be managed and accessed on demand by any service or application, enhancing resource utilisation efficiency and providing measurable benefits for the Vertical industries in terms of cost, scalability, sustainability and management simplification.

To achieve this goal, the 5G-VICTORI platform allows third party SPs to create their own Vertical applications, upload them to a common repository and make them available for deployment at the different 5G-facilities. In their turn, using open APIs, facility owners can decide how their infrastructures can be discovered, reached and accessed by SPs. This may span from a simple 5G network connectivity offering up to full exposure of virtualised infrastructure slices that can be used to provide E2E services to the customers with guaranteed QoS levels. This concept is very much aligned with the way cloud providers operate creating significantly more revenues for the facility owners. Using the 5G-VICTORI solution, 3rd party SPs have now access to the appropriate tools that can assist them to tightly integrate their services with the underlying infrastructure taking advantage of the unprecedented capabilities of 5G Networks. The open, accessible, and programmable environment adopted by 5G-VICTORI enables the development of a new class of services going beyond standard uRLLC, eMBB and mMTC slice offerings.

To achieve this objective, the 5G-VICTORI architecture relies on a set of components and interfaces addressing the requirements of the various stakeholders involved in the 5G ecosystem including facility owners, Vertical application providers and users. A key enabling technology is a thin inter-domain orchestration broker that operates on top of the orchestration solutions of each facility. This orchestrator implements suitable drivers allowing communication of services with the 5G functions that are available in every facility. As a result, service developers have programmable access to the 5G system components allowing them to create a new class of novel applications and offer them to the Vertical industries. Traditionally, Vertical industries (such as rail and energy) operate complex services that require specific expertise and knowledge which is unlikely to be found to a single SP. The exposure of APIs per facility with the right security and authentication mechanisms to a single place that is accessible by multiple third party SPs creates new collaboration opportunities. Based on its expertise, each player can create its own VNFs, combine its VNFs with other functions available in the common repository and, orchestrate the VNFs with the necessary Layer 3 (L3) or Layer 2 (L2) resources in the various facilities thus maximising its role and revenue across the service delivery chain.

The 5G-VICTORI platform also acts as a single cloud-based contact point for multi-national system developer teams and integrators. This eases the development process and reduces time-to-market as APIs and service development kits (SDKs) are offered using a programming language understandable to cloud-service developers. This brings significant advantages to the service development and deployment process as:

- It is not necessary service developers to be aware of the multiple programming interfaces (APIs and SDKs) that are supported per technology component / per facility. On the other contrary, developers have access to the programmable assets of each facility through a single Open API gateway.

- Multi-vendor CNs that are available across the different facilities (e.g., open5GS in UK, Open5GCore in Germany, etc.) are exposed through a single gateway. To further simplify the service development process, overlapping functionalities (i.e., APIs) are aggregated and exposed as a single item [12].
- The platform acts as a trusted neutral mediator between facility owners, service developers and Vertical users minimizing contractual, legal and communication overheads. Through a secure edge proxy combined with authentication/authorisation mechanisms, each facility owner can decide the level of information it wishes to expose, set up the rules about how untrusted applications may access the APIs.

In addition to cross platform service exposure and Open API capabilities, the 5G-VICTORI platform also provides tools to manage services throughout their entire lifecycle. To achieve this, the platform relies on a set of dedicated components that have been developed to perform a set of actions including, monitoring and configuration of the underlying infrastructure as well as maintenance of the managed servicers.

To monitor the network status, the 5G-VICTORI platform:

a) interacts with the local monitoring mechanisms that are available per facility,
b) monitors the interconnection points of the different facilities, and
c) collects logs and statistics that are used for the lifecycle management (LCM) of the services.

The latter is achieved through purposely developed cross-facility network analytics and operation optimisation functions. Specifically, the 5G-VICTORI platform uses monitoring data (exposed by facility owners subject to specific authorisation) to verify that:

- all network components (PNFs and VNFs) have been configured and connected correctly to create the E2E infrastructure slices.
- the E2E cross-facility infrastructure slices that will be used to provide service function chains have been set-up and configured correctly.
- the E2E service slices operate as expected based on the set of predefined KPIs.

The collection of high-level information above ensures the correct initialisation of the system. In addition to this information, more detailed metrics are also collected from the different facilities to continuously optimize the operation of the whole system. Based on authorisation granted by the facility owners to expose the relevant metrics, the 5G-VICTORI monitoring system subscribes and collects both high (E2E service related such as throughput, packet latency, jitter, etc.) and low-level statistics (network/compute resource utilisation, bit error rate, packet error rate, power consumption). These statistics are then exposed to other NFs that are hosted in the 5G-VICTORI platform, such as the cross-facility network data analytics and the profiling engine functions. These functions provide recommendation services related to error detection, localisation, root-cause analysis, and error resolution.

These statistics are also used as input by the 5G-VICTORI service management entity to take specific actions to ensure proper operation of the offered services. This includes actions related to repair/restore of a broken service chain due to a failure of a specific component, provisioning, and re-provisioning of specific parts/components of a service chain such as, instantiation of additional virtualised 5G NFs when the underlying resources are not sufficient to support the requested services, modification of the 5G deployment options, etc.

Depending on the specific agreement between facility owners, Vertical application developers and end-users, the 5G-VICTORI platform may either handle these issues indirectly by contacting the local facility orchestrators to repair/restore/instantiate an entity in the 5G system (restart a 5G CORE/RAN NF, scale out a container hosting the virtualised 5G functions) or manage the network directly. In any case, any configuration changes to 5G NFs are executed in a controlled manner to prevent faults and service disruptions, and to minimise the risk of violating SLAs. Typical actions that are supported by the APIs include:

- Creation/restart/update/partial update of the virtualised 5GC and 5G RAN functions.
- Creation/restart/update/partial update of the virtualised compute and network resources (i.e., containers, VLANs) used by the NFs.
- Backup/restore of individual 5G NFs.
- Backup/restore of 5G network slices.
- Initiation/deployment/termination of an application NFs, E2E network slice also including the corresponding network connectivity (VLANs).
- Migration of a NF from one location to another.

Emphasis in 5G-VICTORI is also given on providing mutual authentication and authorisation between:

- facilities exposing their APIs to the 5G-VICTORI platform,
- the 5G-VICTORI platform and service developers, and
- Vertical users (consumers of the developed services) and the AFs.

Therefore, any entity requesting access to any information or resources that is exposed by the facilities is first authenticated and authorised. Apart from the standard internal authentication/authorisation process that is available per facility and described by the relevant standards [13], 5G-VICTORI introduces an additional authentication layer. The additional mechanism ensures that unauthorised users or applications that reside outside the trusted area of each facility cannot request or provide services in the common repository and make use of resources hosted at different facilities. A 5G facility can authenticate/admit a new Vertical application provided that this has been already authenticated/admitted by the 5G-VICTORI platform.

Confidentiality and integrity for both control and data plane information flows interconnecting the different entities is achieved through a variety of mechanisms installed at the exposure points (perimeter) of the 5G-VICTORI platform ensuring confidentiality and integrity of communication between service-consuming and a service-producing NF. Aspects related to:

a) network access security (security features that enable a UE to authenticate and access services within a facility as described in **3GPP TS 33.501** [14]),
b) network domain security (set of security features that enable network nodes to securely exchange signalling data and user plane data [14], and
c) user domain security: the set of security features that secure the user access to mobile equipment.

are out of the scope of 5G-VICTORI as these issues are handled separately by every facility. Furthermore, application domain security aspects (security features that enable applications in the user domain and in the provider domain to exchange messages securely [14]) are handled by Vertical application developers.

On the contrary, 5G-VICTORI provides appropriate tools to provide:

- SBA domain security: the set of security features that enables NFs of the SBA architecture to securely communicate within the serving network domain and with other network domains. Such features include NF registration, discovery, and authorisation security aspects, as well as the protection for the service-based interfaces [14].

- Visibility and configurability of security: the set of features that enable the user to be informed whether a security feature is in operation or not.

Specifically, at the network exposure points of each facility, the following security requirements are considered by the 5G-VICTORI platform:

- Support of Integrity protection, replay protection and confidentiality protection for communication between the network exposure points and the AF.
- Mutual authentication between the network exposure points and the AF.
- Internal 5GC information per facility is not transmitted externally.
- Every facility decides whether an AF is authorised to interact with the relevant NFs hosted in every facility.

To satisfy these requirements and *protect control plane information* that is exchanged either between facilities or between facilities and the 5G-VICTORI platform, Security Edge Protection Proxy (SEPP) gateways are installed at the perimeter of the CN of each facility. SEPP gateways protect CP messages exchanged between NF hosted at the different facilities using the N32 interfaces. The SEPP implements application layer security for all the service layer information exchanged between NFs across two different facilities. *To protect user plane information*, Inter-Public Land Mobile Network (PLMN) UP Security (IPUPS) is proposed and located at the perimeter of the facility. IPUPS is a functionality of the UPF that enforces GTP-U security on the N9 interface between UPFs of the visited and home PLMNs. Finally, to protect the exposure of capabilities of each platform to the common 5G-VICTORI platform, the common API framework (CAPIF) recently developed by 3GPP has been considered in the design of the relevant interfaces [15]. A detailed description of this framework is provided in the following section.

4.2 5G-VICTORI Operation System and Interfaces

The overall 5G-VICTORI multi-domain architecture is shown in Figure 4-1. 5G-VIOS, shown on the top part of the figure, has a key role in the 5G-VICTORI architectural as it enables management of slices, resources, and orchestration of services across different sites. 5G-VIOS described in detail in D2.6 [9] provides NS deployment across different facilities, dynamic layer-2 (L2) or layer-3 (L3) cross-domain service interconnections, inter-site service composition and on-boarding, E2E slice monitoring and management for the deployed E2E services. The design of 5G-VIOS follows a SBA and considers the current status of the MANO platform and 5GCN at each facility in order to integrate with the individual components as required. This thin orchestration layer builds on top of the orchestration solutions of each facility and their 5G systems, to provide E2E services across the different sites. More details on the architecture and functionality of 5G-VIOS is included in D2.6 [9].

The role of 5G-VIOS is to facilitate end-users (facility administrators and Vertical users) to interact with the 5G-VICTORI infrastructure and services. Facility administrators are able to onboard their facilities onto 5G-VIOS and expose the capabilities they offer. Vertical users can then define experiments utilizing a common service repository to deploy services across different domains. This common network and service repository enables 5G-VIOS to host NRFs from different facilities or provide message forwarding services, grant access to 5G-functions available to other facilities and forward NRF messaging across facilities. In addition, it hosts the AFs developed by the external Vertical SPs that can be used to deploy new NSs to other facilities.

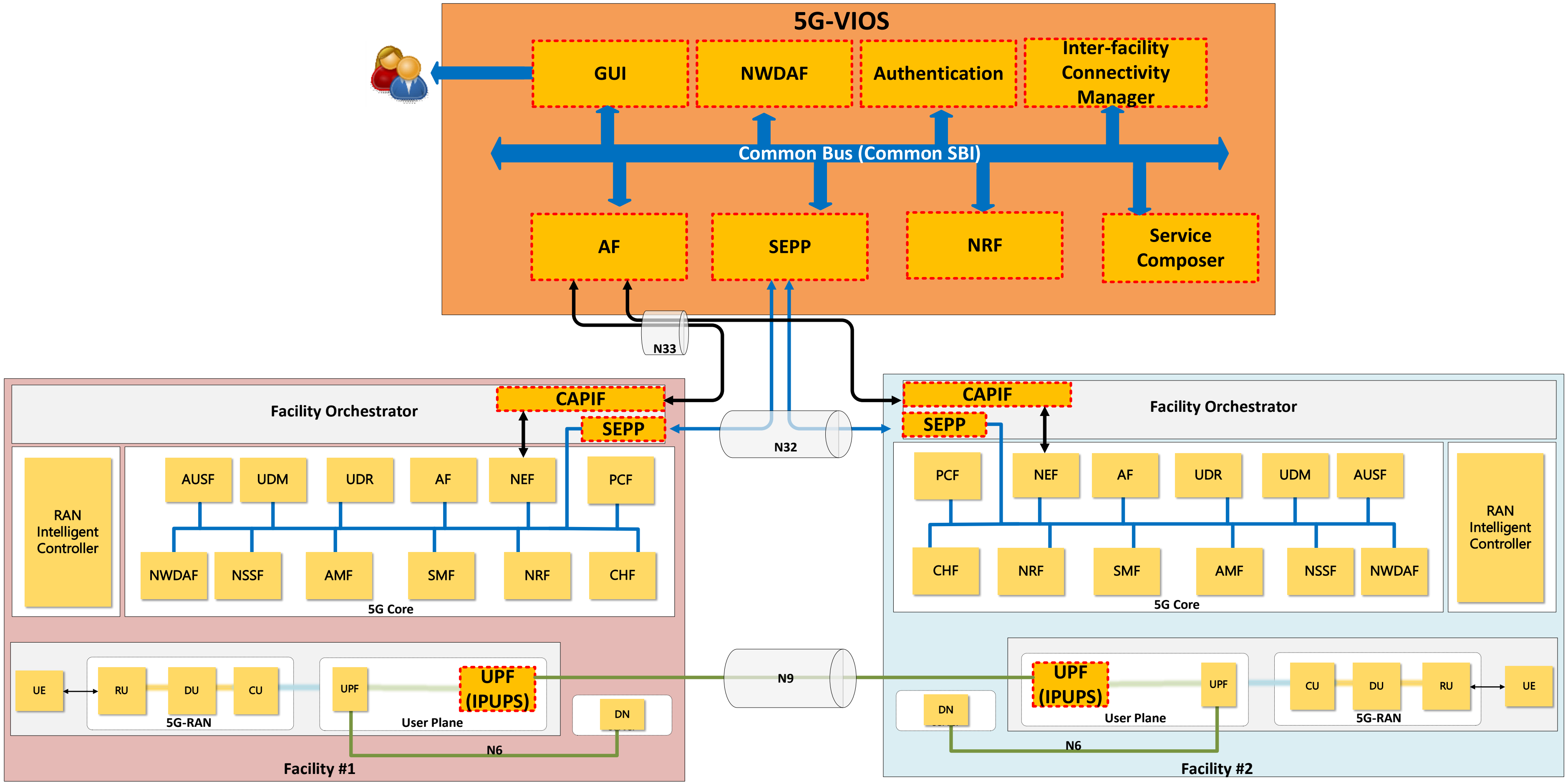


Figure 4-1 5G VICTORI multi-domain architecture

5G-VIOS is responsible to automate the LCM of these inter-domain NSs. The 5G-VIOS deploys at the edge of each facility appropriate interfacing mechanisms supporting the connectivity with 5G-VIOS and the remote 5G facilities. The Inter-edge Connectivity Manager (ICM) is responsible to establish secure connections between the different facilities. Dynamic Multipoint VPN (DMVPN) is used to enable this connectivity on top of which appropriate interfaces are overlaid based on exposed functions i.e. N32 for the control messages, N9/N6 tunnels for UPF(IPUPS) -UPF(IPUPS)/ UPF-DN connectivity, N33 for the exposure of the capabilities of each facility through NEF to the AF hosted in VIOS. Furthermore, 5G-VIOS offers a centralised data monitoring and analytics platform, extending the Network Data Analytics Function (NWDAF), with data collected across facilities from different components, including the 5GC NWDAF, MANO, and application specific monitoring data. AI and ML algorithms are employed to analyse and generate performance profiles for NSs used to optimize the deployment of such services across the facilities. Finally, a common exposure function provides access of the AFs available to the facilities. Information is shared per facility through the local orchestrators that interact with the local 5GC systems and expose the necessary information to 5G-VIOS.

The key building blocks of the 5G-VIOS interfacing the individual facilities include:

- the edge proxy providing interfaces for SEPP and CAPIF. SEPP is part of the roaming security architecture enabling 5GCN signalling traffic to be transferred across remotely located 5G facilities. CAPIF is used to expose functionalities of each facility through NEF to the common AF repository hosted in 5G-VIOS. To implement SEPP and CAPIF an authentication mechanism is required that enables effective filtering of traffic coming from the interconnect between different facilities and 5G-VIOS. SEPP to SEPP and NEF to AF through CAPIF is implemented through a new application layer security solution on the N32 and N33 interfaces, respectively, providing protection of sensitive data attributes while still allowing mediation services throughout the interconnect. 5G-VIOS Edge Proxy and API Gateway implement basic SEPP and CAPIF functionalities and extending it to communicate with the NFVO and other services running at each facility.
- A NRF providing a single record of all NFs available in each facility, together with the profile of each and the services they support. It supports the following functions:
    - Maintains the profiles of the available NF instances and their supported services in the 5GCN.
    - Allows consumer NF instances to discover other providers NF instances in the 5GCN.
    - Allows NF instances to track the status of other NF instances.

  The common repository component implemented in 5G-VIOS, is able to interact (upon approval by facility owners) with individual NRFs and thus facilitate inter-domain NSs. It registers itself with local NRFs as another NF allowing it to discover available NFs instances on each facility. In addition, it maintains a repository of NS descriptors advertised by the NFVO at each facility.
- A network data analytics function (NDWAF) colleting high and low level statistics and aggregating monitoring data across the different facilities from individual sub-systems including 5GC and MANO. Then through AI/ML algorithms implemented generating performance profiles for individual NSs that are used during the LCM of those services.
- The NEF providing the tools to Vertical application developers to securely and developer-friendly expose the services and capabilities provided by 3GPP NFs (3GPP TS 29.522). This access is provided by a set of northbound RESTful APIs from the

network domain to both internal (i.e. within the NOP's trust domain) and external applications. This functionality is expanded to multi-domains with the aid of the Service Broker (SBR) components in 5G-VIOS. SBR enables different edge facilities to expose their capabilities and services in a common infrastructure (5G-VIOS) that can be used to instantiate inter-domain services in collaboration with the service composer and other 5G-VIOS components. Particularly, as part of the experiment LCM, which relates to a network slice LCM, Network Slice Management Function (NSMF) and Network Slice Subnet Management Function (NSSMF) can be exposed in order to perform the appropriate operations.

4.3 Vertical Applications Deployment Options

The 5G-VICTORI offers the necessary tools to support the development, deployment and management of Vertical apps throughout their entire lifecycle. Based on the capabilities of each facility different scenarios can be supported with respect to placement of the AF controlling the Vertical application and the Application Server (AS) hosting the application. The role of AF in the provisioning of services with enhanced Quality of Experience (QoE) is critical as based on the feedback that it receives from the applications it can influence traffic routing and steering decisions of the SMF, select of the DN where the corresponding AF is hosted, trigger rate adaptation, publish statistics to the analytics function etc. In multi-domain scenarios, exposure of information to the AF is performed through CAPIF. Based on the maturity (in terms of 5GCN functionalities) different application deployment scenarios can be supported by the 5G-VICTORI platform:

<u>Scenario 1: 5G-VIOS installed at the premises of a trusted (i.e., public operator) facility providing services to a non-trusted (private operator) facility with Apps available on both sites</u>

In this deployment scenario we assume a scenario combining a private/public network located in the same region (Figure 4-2). Each facility has a MEC platform (DN) hosting the Vertical application, namely AppX. This scenario can be used to support services with low latency requirements. The control of the application (AS functionality) is hosted in 5G-VIOS. The remaining functionalities of the 5G-VIOS are not depicted for simplicity purposes. Network metrics and statistics are exposed by each facility to the monitoring and network analytics modules of 5G-VIOS through SEPP. The private network also relies on the CAPIF core functionalities (publish of service APIs, discovery of service APIs and charging of service APIs invocations, etc. [10]) that are available at the trusted public operator site to reach the Vertical AppX AF hosted in 5G-VIOS. Based on the collected measurements and the QoE of the Vertical application the AF assists in traffic routing, steering and MEC selection process. Specifically, when the user is located at the private facility, it contacts the SMF of the private facility to steer traffic to the local MEC. However, as the user moves to the public facility analytics modules hosted in 5G-VIOS take actions (notifies the public SMF) in order to migrate the AppX to the server of the new public facility.

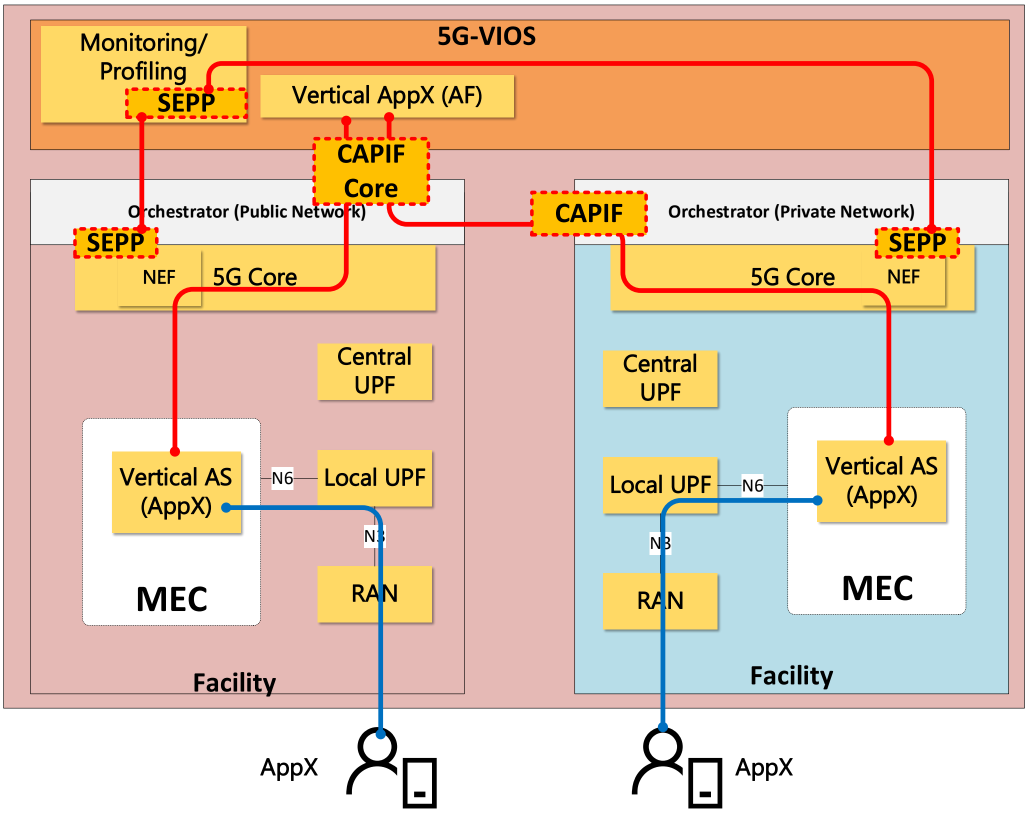


Figure 4-2 5G-VICTORI used to provide a Vertical apps.

Scenario 2: 5G-VIOS installed at the premises of a trusted (i.e., public operator) facility providing services to a non-trusted (private operator) facility with Apps available on a single facility

The second scenario, depicted in Figure 4-3, assumes that the Vertical application (AS) is hosted in the DN of a single facility. As before, the AF is hosted in the 5G-VIOS. In this case, data plane connectivity is established through an N9 interface interconnecting the two UPFs of the two facilities. The UPFs in this case support the IPUPS while connectivity between the two sites is orchestrated through 5G-VIOS. In this case, a 5GC implementation with limited capabilities can be installed in facility #2 as the NEF functionality and its associated exposure interfaces (CAPIF) are provided through facility #1.

In case IPUPS connectivity is not available, 5G-VIOS can be also used to provide inter-domain connectivity between the two facilities over a controlled IP network.

The data traffic related to the MEC of AppX is offloaded through the local UPF of facility #2 towards the DN of facility #1, where the AS of AppX is located directly via a controlled IP network between the two facilities. The controlled IP network is established by means of local 'pairing' links between operators' premises. The local 'pairing' links are terminated by gateways (GWs) that can play the role of border GWs to DNs and can have some functionality (e.g. NAT GW functionality) supporting inter-domain connectivity over the controlled IP network [16].

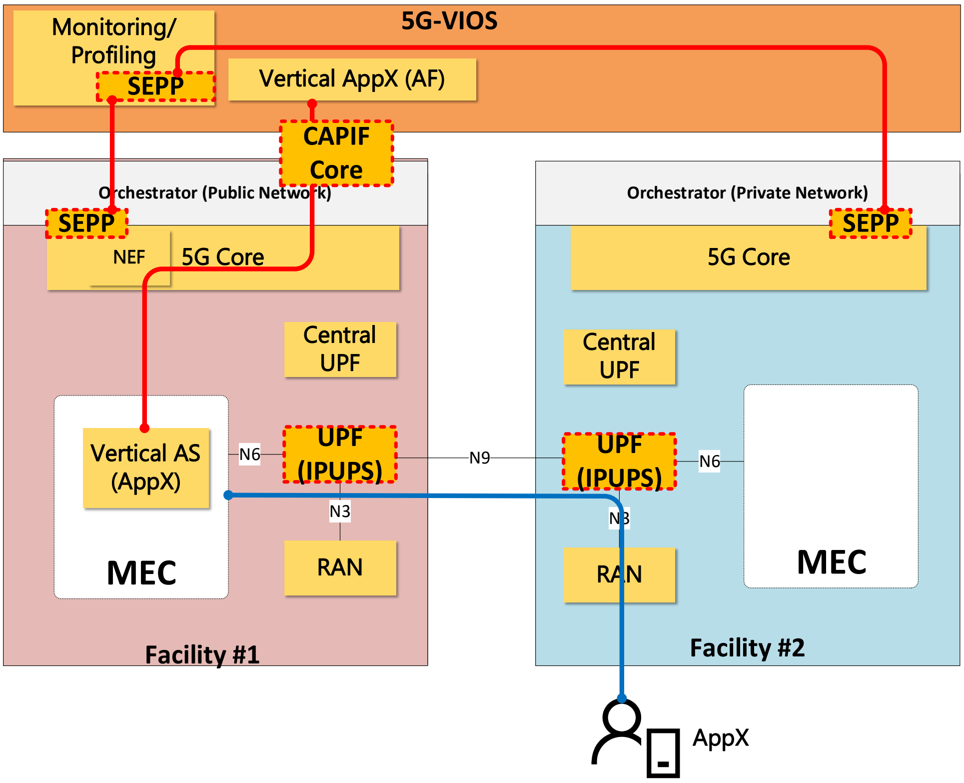


Figure 4-3 5G-VICTORI used to provide a Vertical app hosted in a single location.

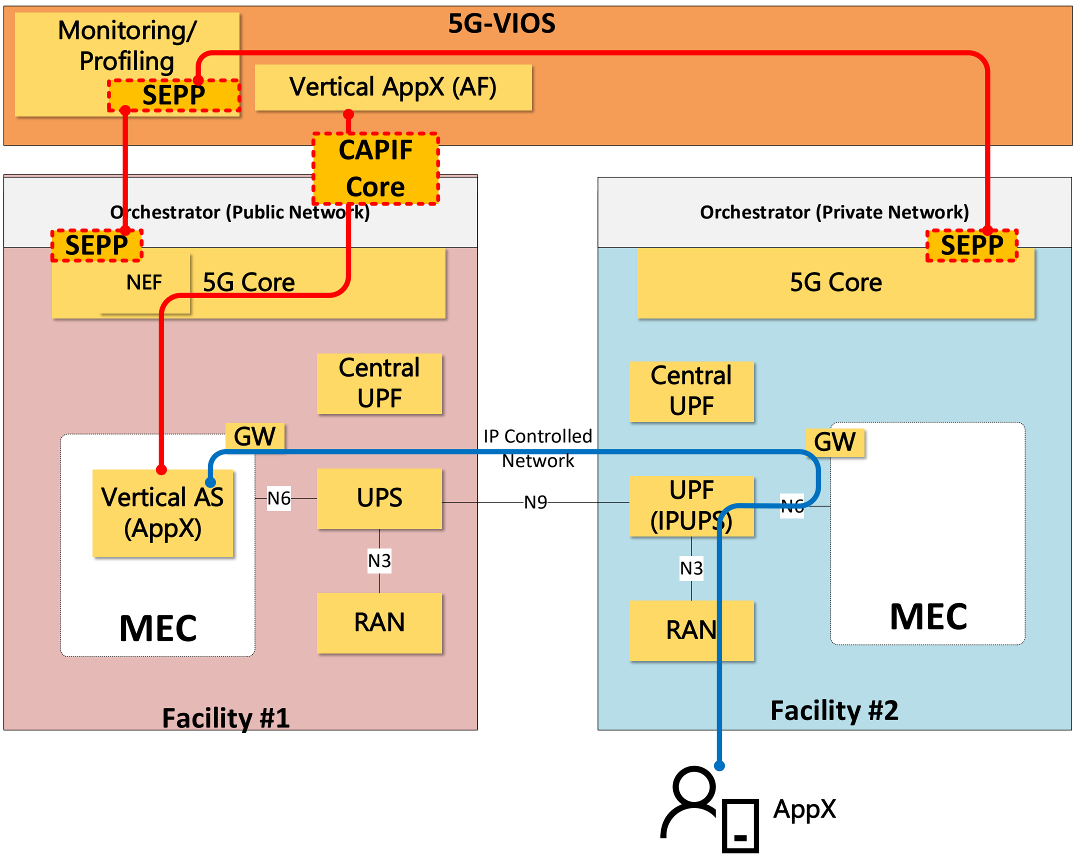


Figure 4-4 5G-VICTORI used to provide a Vertical app hosted in a single location.

5 Deployment options

5.1 5G-VINNI / 5G-VICTORI facility – Patras

5.1.1 Detailed 5G architecture description

The 5G architecture at Patras5G that enables the Greek cluster testing and UCs has three flavors. In all three flavors most of the installed components are offered as Open Source but there are also dedicated components and services to support 5G and IoT scenarios. This variety creates a unique 5G playground for KPI validation and support for future verticals [17]. The overall facility description is shown in Figure 5-1.

Although only 5G related technologies are illustrated, the platform allows experimentations with 4G and various Non-StandAlone (NSA) variations. The Greek cloud facility can be used to (co)host third parties software and hardware and provide access to the 5G facility for testing and experimentation:

- Providing 5G standard-conformant components and CN infrastructure as extension of the FhG Open5GCore toolkit, but also other 5GC implementations as will be detailed.
- Provide Intracom Telecom (ICOM) mmWave backhaul to link the access to the CN, and Fixed Wireless Access to provide broadband services to the facility. These variety of transport networks allows the Patras5G facility to extend to various locations in the city of Patras area.
- Integration of FhG Open5GCore with Limemicro SDR platform and the Software Radio Systems (SRS) UE and g/eNB as an E2E solution.
- Integration of Amarisoft solutions with various 5G and Customer Premises Equipments (CPEs) for indoor and outdoor testing.
- Enabling the E2E deployment of multiple customised-slices over the whole network – access, transport and CN.

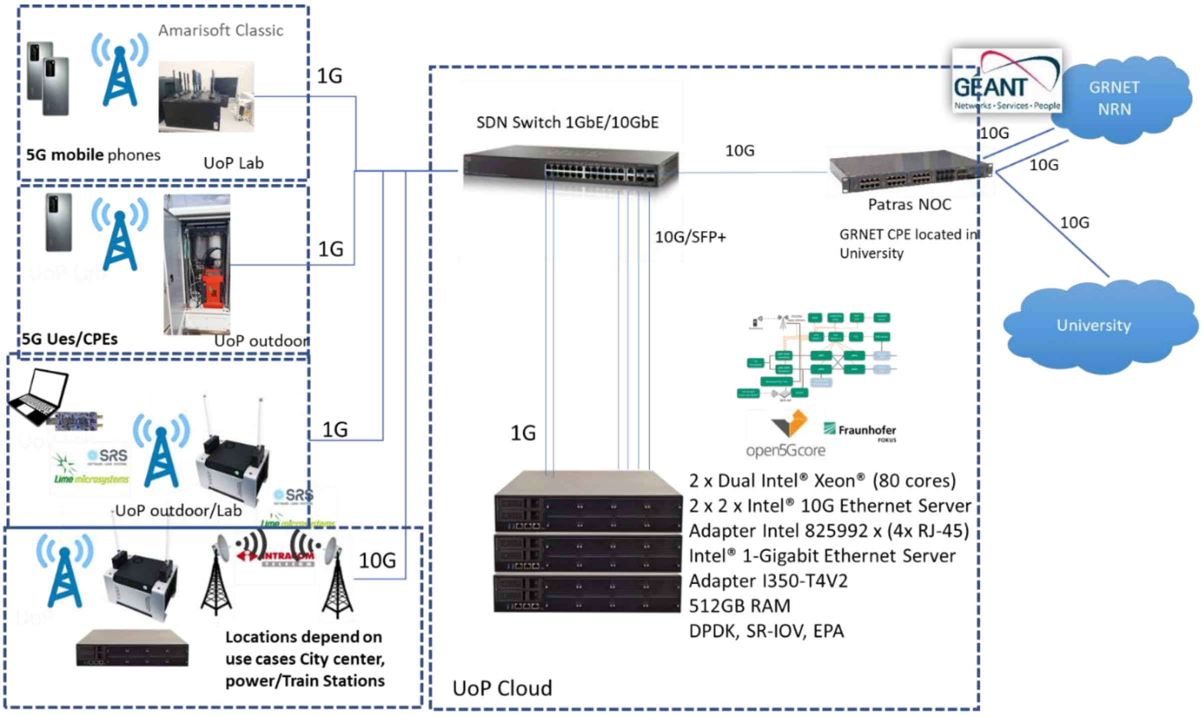


Figure 5-1 5G-VINNI / 5G-VICTORI facility

- Supporting MEC deployment, orchestration and mobility management features for the support of interactive mobile streaming edge services.
- 5GC and EPC solutions that are available and can be orchestrated in the facility: FhG Open5GCore, AMARISOFT EPC/5G, SRS EPC/5G, etc.
- 5G and 4G RAN: AMARISOFT 5G RAN (Classic boxes), 5G RAN open source radio (Lime, SRS)-700-800MHz, 3.5.-3.8GHz, 4G NB-IoT, LTE-M (FhG NB-IOT core) based on AMARISOFT, Various SDR equipment (Ettus Research).
- UEs based on Limemicro's SDR and SRS software, as well as commercial UEs: Mobile phones LG and Samsung, Huawei CPE, Various SDR equipment, a Drone for uRLLC testing.
- Monitoring is available through: Grafana, Prometheus, Netdata while Open Source MANO (OSM) also configure with VNF telemetry support.

To ensure that all services described in the next section can be delivered, the Patras5G deploys a specific set of 5G architectural features. In Figure 5-2 we illustrate the generic 5G architecture components deployed in Patras5G including the RAN and the CN supporting connectivity of mobile users and wireless devices (UEs), various wired and wireless transport technologies, the central cloud located at the University of Patras premises and edge cloud solutions that can be located closer to the users

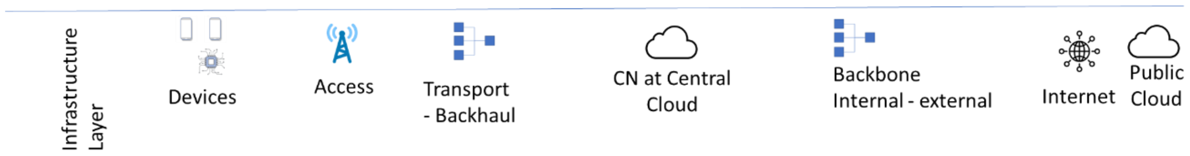


Figure 5-2 Patras5G Infrastructure building blocks

5.1.1.1 SA 5G architecture based on Amarisoft solutions

For non-public NSs, similar to a 4G LTE network architecture, the 5G RAN and gNodeB are typically close together, often at the base of a cell tower. The monolithic 5GC solution is ideal for testing and providing non-public networks (see Autonomous Edge below). In Patras 5G we deployed the Amarisoft solution that although architecturally follows the 3GPP standards, all softwarised NFs are integrated on the same hardware. This monolithic aggregated solution is successfully used for standalone (SA) deployments of services that require private networks and/or traditional services. In all scenarios orchestration is provided by OSM for NFV nodes, which are controlled by a Virtualised Infrastructure Manager (VIM) (VIM interface) and host VNFs (VNF interface), and then allows access to the hosted VNFs for day 1 and day 2 configuration, as well as in-life management of the hosted VNFs and SDNs, which are accessed and controlled via a SDN controller (SNDC interface).

Testing and initial results are taken utilising solutions based on the Amarisoft software suite that offers technology running the full RAN, including physical layer, on generic hardware, the RAN can be seen as NVF and utilised in the case where virtualised RAN (vRAN) and private mobile networks are required. The specific technology has been used for extensive testing with a variety of UEs and modes:

- Test in both NSA and SA mode.
- Various bandwidths tested (20, 40, 50 MHz).
- TDD pattern (ul/dl slots).
- Modulation (64QAM, 256QAM).
- Iperf (TCP/UDP) and Speedtest.

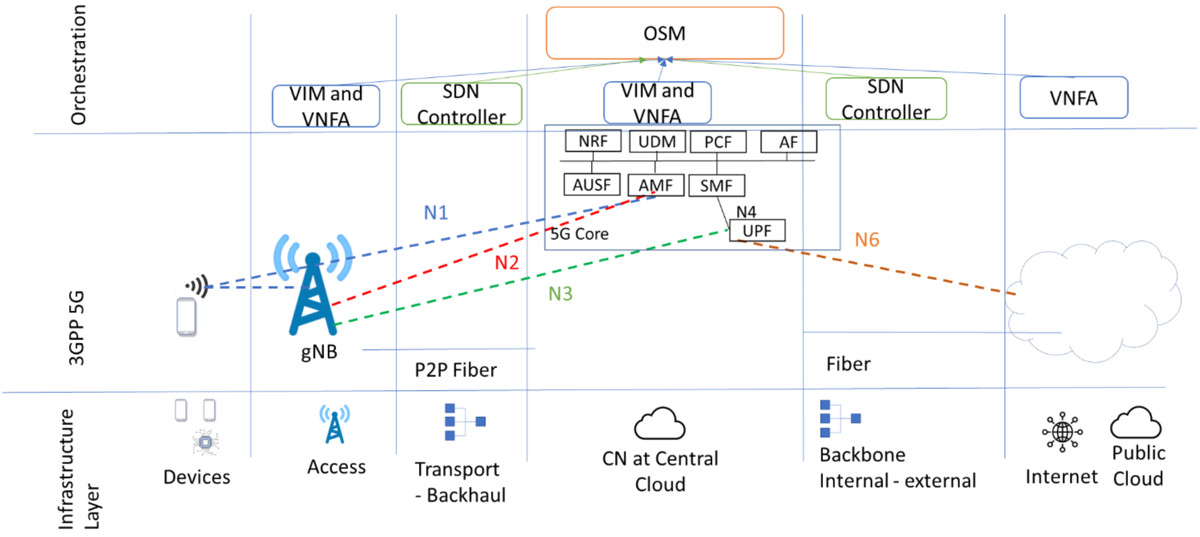


Figure 5-3 5G architecture based on aggregated solutions at Patras5G

5.1.1.2 SA 5G architecture based on decentralised 5G Core

In Patras5G the deployment of a 5G Service Based Architecture (SBA) solution is deployed. This breaks apart the monolithic core and implements each function so that it can run independently from each other on common, off-the-shelf server hardware. This allows the 5GC to become decentralised 5G nodes and very flexible. For example, 5GC functions can now be co-located with applications in an edge datacenter, making communication/data paths short and thus improving E2E speed and latency.

This stems from flexible deployment of the 5G SBA where various functions can be located at the edge. In Figure 4-4 a UPF is responsible for packet routing and forwarding, packet inspection, etc., in the 5G architecture it is deployed as a VNF at the edge, thus providing ultra-fast packet forwarding without disturbing compatibility with all the user plane functionality – currently deployed as virtual machine (VM) or container.

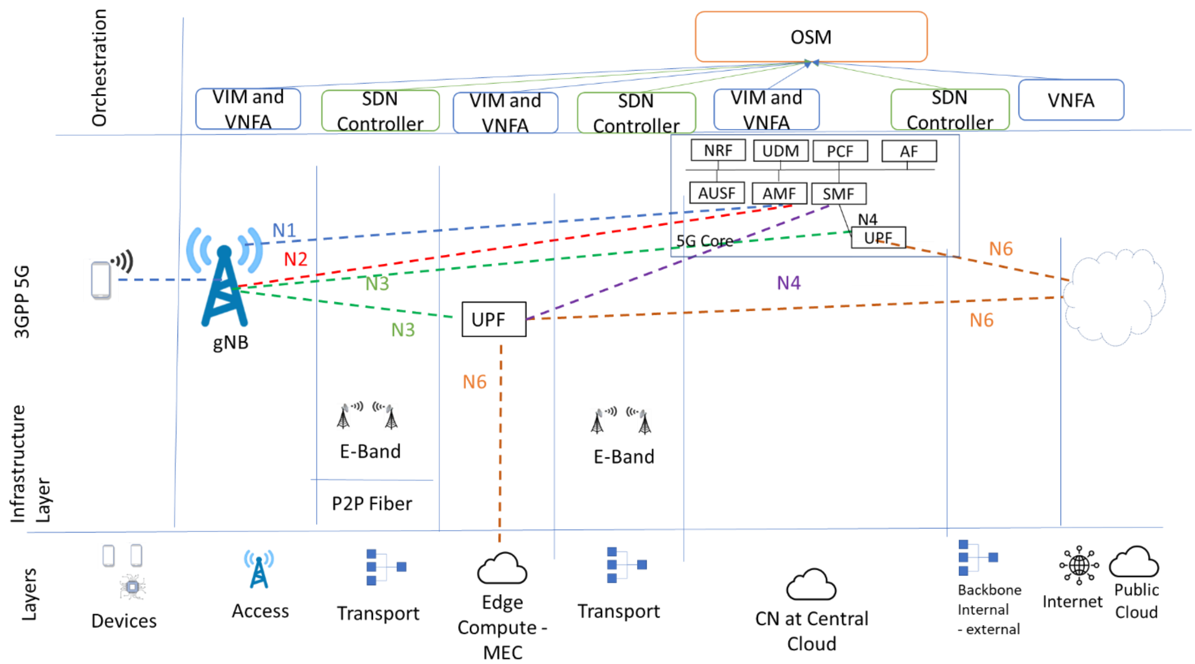


Figure 5-4 5G architecture based on disaggregated solutions at Patras5G

It is noted that the example above allows slicing: services with numerous UPF capabilities and distinct performance requirements to be implemented under the same 5GC, i.e. the UPF can be co-located with local and central data centers at both locations. This enables MEC, which delivers resources at the edge to support new low-latency 5G services (see 5.1.2).

It is evident that the above architectural aspect of OSM deployment does not necessarily capture all capabilities that related to services discussed below like for example network slicing, and containerised network functions (CNFs). As will be provided next orchestration may be simplified if a network slice encapsulates a larger set of functionality, as a single entity. The slice can be a single orchestrated component, to which it can add VNFs hosted in the MEC environment and in central NFV nodes.

The 5GCN deployment comprises the following NFs after Open5GCore [18] developments from the Berlin cluster (see also Section 3.3):

- Network Repository Function (NRF).
- Access and Mobility Management Function (AMF).
- Session Management Function (SMF).
- Authentication Server Function (AUSF).
- Unified Data Management (UDM).
- User Plane Function (UPF).

The rest of the function deployment will follow the developments of FhG's Open5GCore.

5.1.1.3 Fully Disaggregated architecture for mobility UCs

The Greek cluster is extending the fully disaggregated 5G architecture depicted at a high level in Figure 5-5. Here the initial concept of splitting the data and control functions at both gNodeB and the 5GC are delivered following the paradigm of 5G PICTURE, where, apart from increased flexibility, it offers enhanced scalability, upgradability and sustainability potential. The cell disaggregation is based on the 3GPP Option-2 split, which splits the base station stack to the Central Unit (CU), implementing the Packet Data Convergence Protocol (PDCP) and above layers, and the Distributed Unit (DU) integrating the Radio Link Control (RLC), Medium Access Control (MAC) and Physical (PHY) layers. The concept of flexible functional splits is supported and specifically as shown in Figure 5-5 at the point between CUs that incorporate the functionality of the layers from the PDCP layer and upwards, whereas DUs support the functionality of the RLC layer and downwards in order to allow incorporation of other lower layer splits inside the DU. On the other hand, several technologies can be aggregated through a single point at the base station level inside the PDCP layer. This paradigm is followed here with numerous advantages that serve the UCs in the Greek cluster:

- To facilitate handover in mobility UCs: this is related to the small coverage cells resulting in more frequent handovers and by disaggregating DU and CUs this can be handled efficiently as intra-gNB mobility
- To facilitate slicing in mobility UCs: The user plane of CU can be sliced into multiple CU-UPs to support network slicing and multiple CU-UPs can be deployed in independent locations while single CU-CP is deployed in the central site.

Related to slicing, allocating resources variably for the CU enables adaptation to the traffic patterns which varies according to the offered services. For our onboard train 5G network, the traffic pattern traversing the CU/DU pair is considered to be unpredictable because of the newly introduced services with different usage patterns. Conventional dimensioning typically designed for mobile service traffic pattern cannot adapt to these various traffic patterns of the new services. For example, uRLLC may have high control traffic load and low user traffic load. On the other hand, eMBB services have low control traffic load and high user traffic load.

Flexible dimensioning and scaling of virtualised and disaggregated RAN well adapted to various traffic patterns can bring resource efficiency as well.

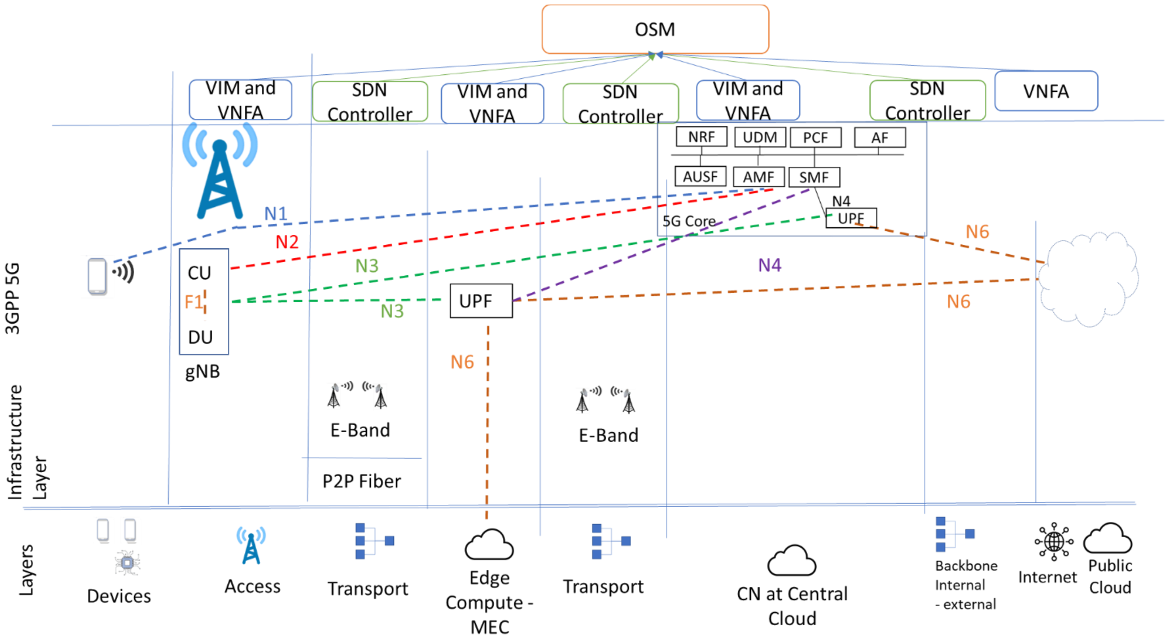


Figure 5-5 5G architecture based on aggregated solutions at Patras5G

5.1.2 Mapping of services over the 5G architecture

5.1.2.1 5G VICTORI services mapped over Private 5G network

Summary of Smart Factory services: Real-time monitoring of High Voltage (HV) power cable refers to real-time synchronisation of measurements from **ADMIE** sites in Rio and various sites in the area (e.g. Antirio). The sites are interconnected via submarine HV cables the status of which is monitored via sensors planted in both sites. The measurements from both sites will be collected, synchronised and stored in a common time-series database. 5G NR is used to interconnect legacy sensors and other monitoring devices. Then the health status of the HV cable and/or other devices will be estimated and control signals will be sent in case of emergency.

In case of an emergency (e.g. low oil pressure at the HV cable), the controller may provide some closed loop action to the system (low latency action no-man in the-loop). In case of emergency the specific service is of high priority. In Figure 5-6 a 5G Autonomous Edge developed at **UoP** provides a SA private 5G network (i.e. not connected to the main facility core services), in a mobile box that can be used for the specific UC.

5G Private networking based on the first architectural aspect of Patras5G offers the following characteristics:

- Support of the low latency requirements imposed by the nature of the application as storage, computation and packet processing is performed at an edge server in one of the two sites.
- Security and low latency are guaranteed by the Private network established in each of the sites

Summary of HV Energy services: In a similar way, the service developed within the Energy UC where high frequency power data sampling from two major verticals (here **TRAINOSE** and **ADMIE**) should be compared, processed and analysed in order to feed possible demand – response related services. Here, the Railway Management System (RMS) and the Energy

Management System (EMS) are executed as two completely isolated applications with real time monitoring and data acquisition from sensors on board (for the train i.e., power consumption, speed, position, 3-axial accelerometers, vibration sensors, frame grabbers monitoring the status of the electrification lines, etc.). The monitoring system collects measurements with rates exceeding 50 KSamples/Channel/Sec. Fully synchronised/timestamped measurements should be transmitted to the trackside adopting standard IoT messaging protocols (i.e., MQTT) over the private 5G network that will be deployed at the Corinth station.

Figure 5-6 shows the mapping of the 5G enabled services on the overall architecture described in section 5.1.1.1. It is noted that the SA private network that is deployed at ADMIE (see D2.3 Autonomous Edge) integrates all Application components by interfacing the 5GC through standardised interfaces.

5.1.2.2 Low latency services with flexible 5G architecture (Smart Factory)

A smart private network of energy efficient sensors and the corresponding management system, able to support preventive maintenance techniques, is demonstrated. Preventive maintenance applications requiring high frequency timestamped sampling will be considered. Due to the large volume of data, originating from different sensors spread at the facilities, needed to support the preventive maintenance applications, low-cost and low-power devices without strict latency requirements must be used.

5G NR is used for the transmission of the collected data to the ADMIE central facility where the ADMIE data management platform will coordinate the correlation and analysis of the collected time-stamped information from various sites. 5G NR will interconnect the UEs of technicians that look after the area. Figure 5-7 illustrates how the specific services are mapped on Patras5G architecture and how it is orchestrated by the OSM at UoP premises. Specifically, as shown in the figure, the MEC enabled Factory of the Future gives access to the ADMIE personnel to access the ADMIE digital infrastructure (application and data) via two types of services corresponding to two UPFs and two slices that will be discussed below.

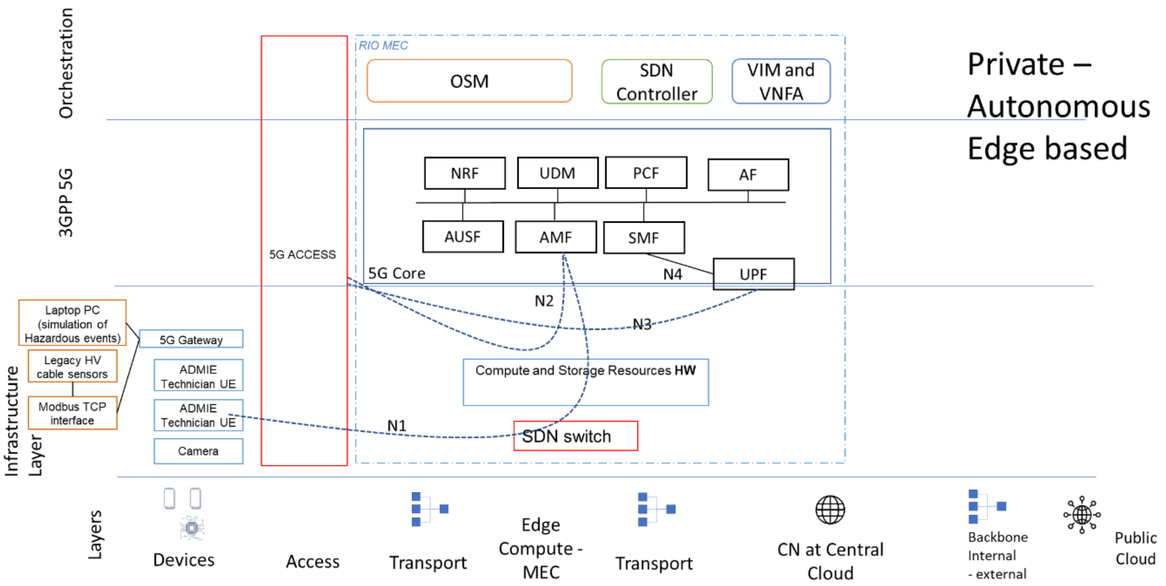


Figure 5-6 Smart Factory and Energy UC Services over Private Networks

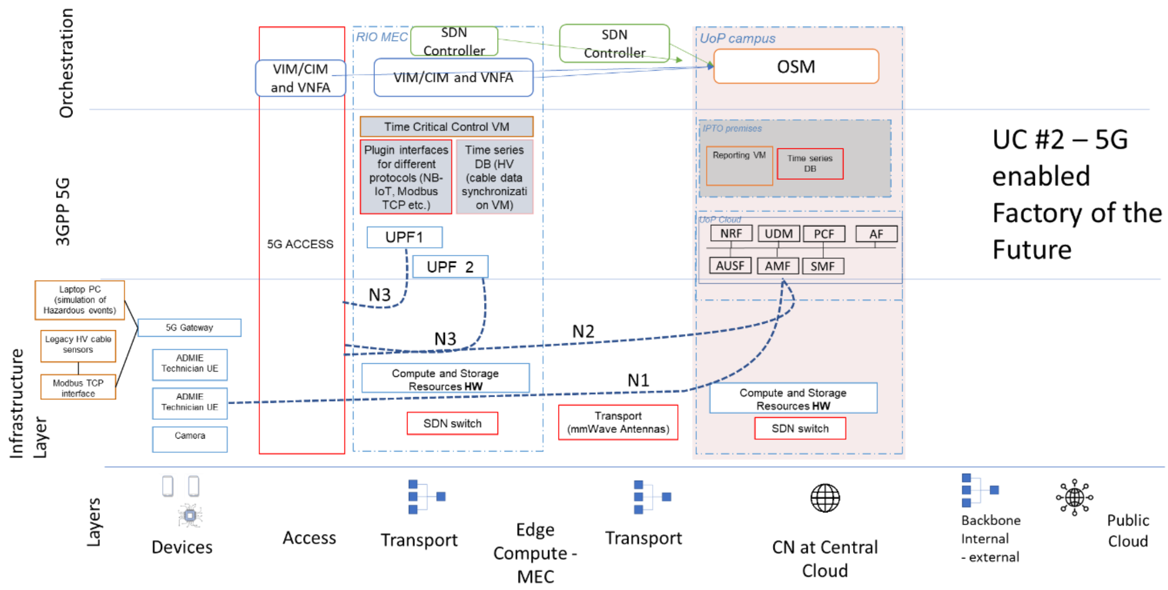


Figure 5-7 Preventive Maintenance Services over 5G VICTORI architecture

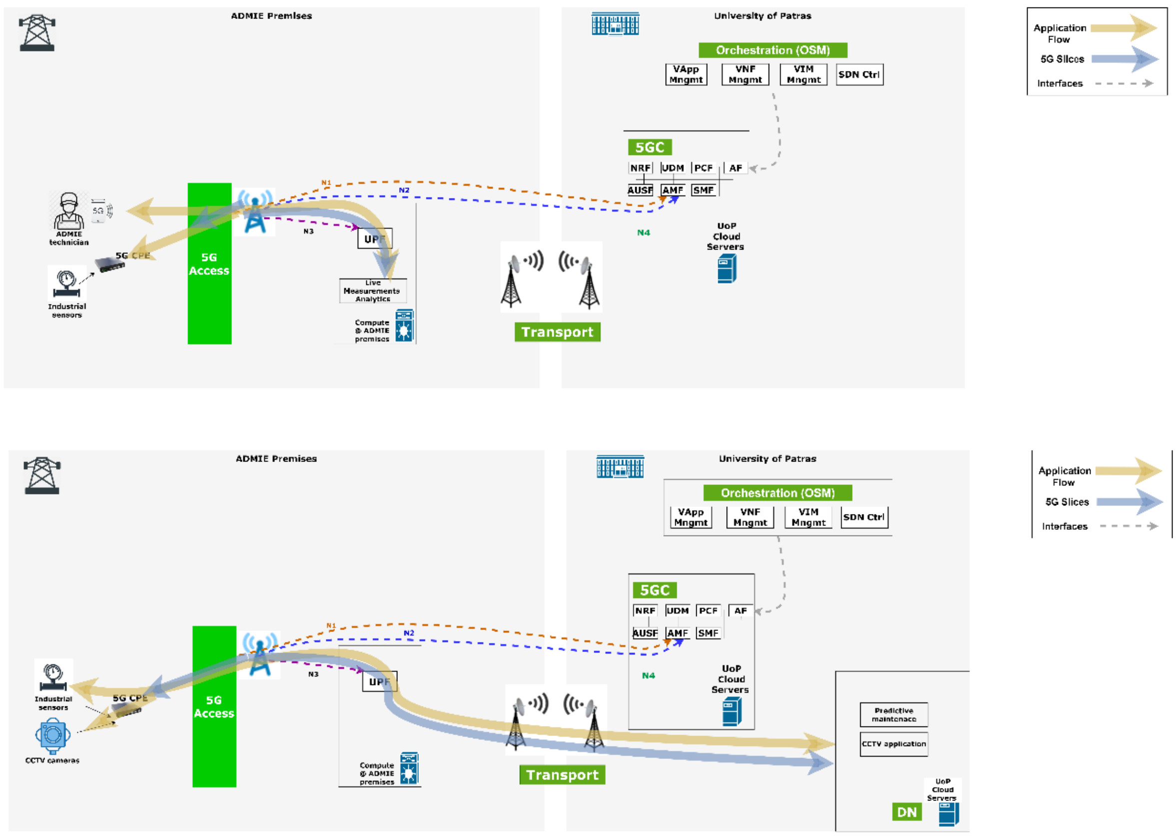


Figure 5-8 Application flows and 5G slices for Smart Factory services

In Figure 5-8 two services running on different slices as stems from the second variation of the Patras 5G architecture.

- The specific UC investigates how 5G technologies and the 5G service based architecture can facilitate the exploitation of 5G private networking for Energy sector/ factories of the future.

- The UC follows the newly established paradigm of allowing a specific UE that enters a Factory of the Future to have simultaneous access to two slices e.g. one restricted to the Factory premises and another providing access to the cloud.
- By placing Slice's UPF and processing close to the source (e.g. site) low latency requirements are met.
- In some cases part of the data may need to be forwarded at a central data center or even to the cloud depending on the application.

5.1.2.3 Disaggregated Architecture for eMBB services under high speed mobility

The specific deployment of a fully disaggregated 5G architecture is based on a backhaul (BH) network realised over heterogeneous wireless technologies, to support dedicated disaggregated virtualised access nodes on top of high-speed moving trains. The cell disaggregation is based on 3GPP Option-2 split [19], which splits the base station stack to the CU, implementing the PDCP and above layers, and the DU integrating the RLC, MAC and PHY layers. The proposed work builds upon the prior contributions of the 5G-PICTURE project [20] in demonstrating seamless E2E connections from a moving train through track-to-train communication links. Handover management for train and the heterogeneous track-to-train links is realised using the P4 programming abstractions [21]. P4-based switching allows the programmable configuration of the flows in the network, regardless of the technology that is connecting the train at any time point.

Regarding the on-board network architecture, a fibre network deployed on board interconnects access points, compute nodes and UC specific components (cameras, etc.) required for the execution of the UC. The high speed moving train carries the on board network deployment along the train to track connectivity nodes, without disturbing the interconnection between the CU and UPF/AMF and also without replicating traffic, while the train moves along the railtracks. As shown in Figure 5-9, the 5GC is placed at a remote location (e.g. NOPs Premises/UoP Cloud).

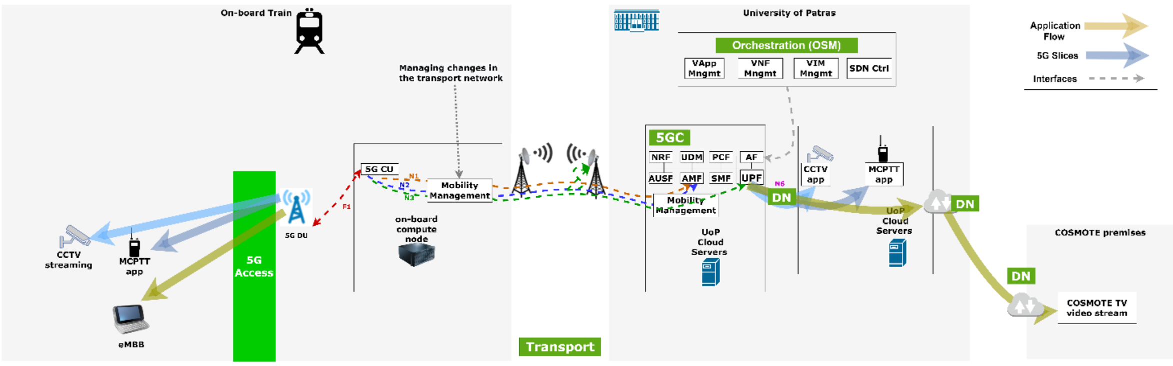


Figure 5-9 Application flows and 5G slices for Rail services

5.1.2.4 Disaggregated Architecture for CDN services at the station for Media services

The proposed deployment scenarios for the specific UC assume that a train approaches the **TRAINOSE** station and connects to the station through 5G NR in order to download streaming content in a "data shower" fashion, with the aid of **ICOM**'s CDN multi-level solution. The content includes **COSM** TV 4K Video on Demand content and COSMOTE TV linear services. Moreover, the train station is monitored through a 360° camera of high quality video. For this functionality at the end-user side:

- A 5G CPE will be on board the train along with an Edge server (on board).
- A 360° camera will be deployed at the train station for uploading content to an Operations Centre (e.g. University of Patras premises / train station).

For the integration with the 5G-VINNI facility, the CDN platform is based on a three-level hierarchical design. On top, there will be ICOM's central CDN Server (deployed at UoP premises), mainly responsible for receiving the (CDN) Source Content and preparing it to be delivered. At the MEC level, appropriate VNFs will be deployed and provide the necessary functionalities and elements to support the content delivery (storage and streaming) to end users. Also, an additional Edge server will be deployed on-board for preloading and caching large amounts of content and serving the passengers even during disconnection periods. The Content Origin point(s) is located on premises, (i.e. as a video streaming server at UoP premises hosting VoD COSM TV content) to emulate local streaming services, and/or remotely to emulate a Content Origin point of a real CDN network deployment (see Figure 5-10a).

A similar setup is envisioned for the case of the second scenario of the UC (video surveillance application), targeting both high data rate and low latency services. In this scenario, the 5G capabilities will be used to facilitate the monitoring of railway infrastructures by the railway security staff, located in a control center. A VR/360° 4K video camera will be installed at the train station, which remains equipped with a 5G base station (Figure 5-10b). The video streams produced by the camera will be locally processed and optimised, and then delivered to the control center through the 5G network. The camera client (operator) is served with HQ video footage for as long as his field-of-view is stable, and with lower quality footage but with low latency during field-of-view movement. This way, the new fields-of-view will arrive in time to the operator's screen and no motion sickness will be faced during the transition to the new field-of-view.

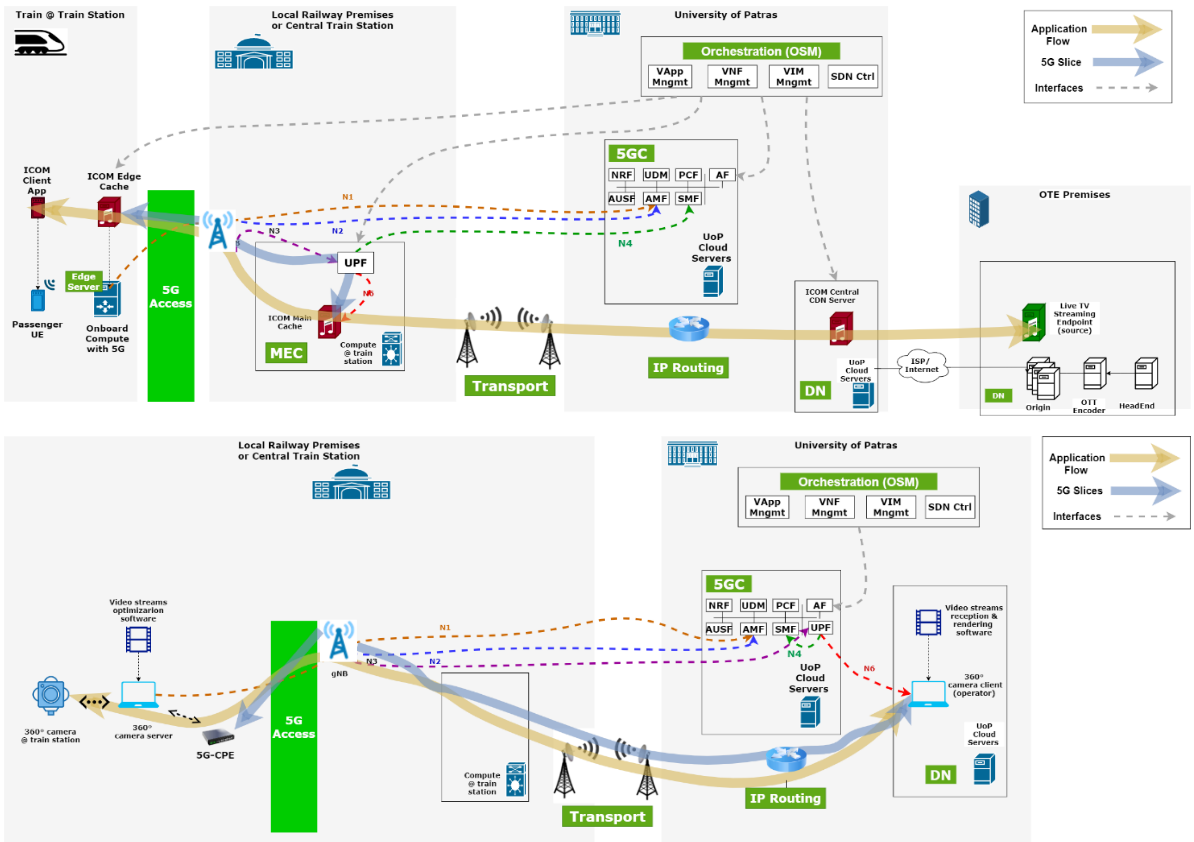


Figure 5-10 Application flows and 5G slices for the two CDN services

5.2 5GENESIS / 5G-VICTORI facility – Berlin

5.2.1 Detailed 5G architecture description

This section describes the four 5G elements outlined in Figure 5-11, these are:

- UE (User Equipment).
- RAN (Radio Access Network).
- 5G Core Network (5GCN).
- DN (Data Network), aka Service Network.

In addition, the section refers to the interfaces in-between nodes and functions.

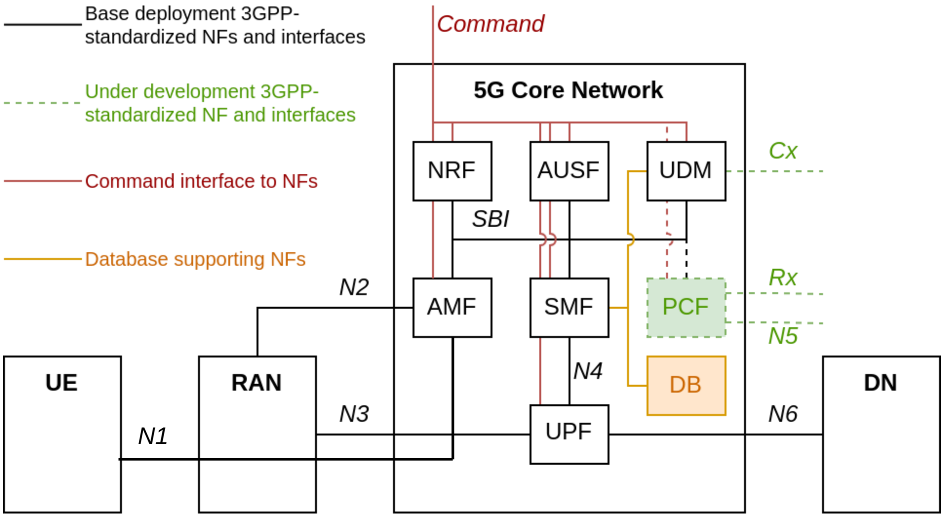


Figure 5-11 Overview of the Berlin 5G nodes with network functions and interfaces.

5.2.1.1 User Equipment (UE)

The UEs in the 5G deployment will be commercially available smartphones or CPE devices that are capable of connecting with 5G SA networks over 5G New Radio (NR). Depending on the nature and requirements of the UC service, the UE side of the application will run either directly on a smartphone or on a host with a cabled network connection to a CPE.

5.2.1.2 Radio Access Network (RAN)

The RAN will consist of one or more commercially available gNodeBs utilising the 5G SA architecture. The radio will use 5G NR at a band in the 3.7-3.8 GHz range allowed in Germany for campus networks. The coverage area of the radio is planned to serve UEs on a train that enters, stops and leaves a railway station, as well as some passenger areas.

5.2.1.3 5G Core Network

The Berlin cluster 5G-VICTORI 5G architecture is based on the 5GENESIS architecture, which is heavily tied to the Open5GCore software toolkit. The Open5GCore software includes an implementation of 3GPP-standardised 5GCN supporting 5G SA networks. The NFs are implemented to adhere to 3GPP specification in their function and in protocol stacks used by the network interfaces, however they are not complete implementations of all functionality and APIs.

The base 5GCN deployment comprises of the following NFs:

- Network Repository Function (NRF).
- Access and Mobility Management Function (AMF).

- Session Management Function (SMF).
- Authentication Server Function (AUSF).
- Unified Data Management (UDM).
- User Plane Function (UPF).

A potential extension to the base CN deployment (also depicted in Figure 5-11) includes the Open5GCore Policy Control Function (PCF), whose relevant functionality is currently being developed in parallel to project activities.

Each Open5GCore NF of the network deployment will be realised as an individual process and all will run on a single VM or container with the option to have the UPF separated from the CP NFs if user plane throughput demands require additional compute resources.

A MariaDB database (DB) server instance is required by the UDM and SMF to hold persistent network data. For the UDM, this includes subscriber authentication keys, subscriber access and mobility information, and subscriber session management information. For the SMF, this includes information about the DNs such as UE IP allocation ranges and UE static IP allocations.

5.2.1.4 Data Network (DN)

The DN will be a network where the exposed N6 interface of the UPF serves as a network gateway to the IPv4 address range assigned to UEs who have PDU Sessions to the DN. Any application that must be able to address the UE directly should have an interface in this network. Otherwise, a software router with an interface in the DN can be used to dynamically masquerade uplink UE traffic to external networks.

5.2.1.5 Interfaces

In the base deployment (see interfaces in **black** on Figure 5-11):

- N1 (AMF and UE): Control plane interface utilising the Non-Access Stratum (NAS) Protocol for 5G.
- N2 (AMF and NG-RAN Node): Control plane interface utilizing the Next Generation Application Protocol (NGAP).
- N3 (UPF and NG-RAN Node): User plane interface utilizing GTP-U tunneling protocol.
- N4 (SMF and UPF): Software-defined networking control interface utilising Packet Forwarding Control Protocol (PFCP).
- N6 (UPF and DN): un-encapsulated traffic between UEs and application servers. Open5GCore supports only IPv4 version.
- SBI (all CP NFs): Service-based Interfaces between 5G CN CP NFs utilising HTTP2 with JSON and binary payloads.
- Open5GCore command interface: non-standardised original equipment manufacturer (OEM) interface for Open5GCore utilising a logging and command system.

Potential extension (see interfaces in **green** on Figure 5-11):

- Cx: To be realised in the Open5GCore by collocating a subset of HSS functionality with the UDM. Utilises the Diameter protocol. This interface is still used by some IMS solutions for user authentication.
- Rx: To be realised in the Open5GCore via a dedicated translator between Rx and N5 requests/responses as for many UCs these map one-to-one. Utilizes the Diameter protocol.

- N5: 5G standardised interface between PCF and an AF. Implementation in the Open5GCore should cover the functionality to request QoS parameters for specific traffic filter set identifying a UE traffic flow for the application.

5.2.2 Mapping of services over the 5G architecture

5.2.2.1 General approach and development plan

In the base deployment, the UC services are enabled by E2E IPv4 connectivity provided by a UE-requested PDU Session. This assumes that the UC service applications is running directly on the UE (for the UE/client side) and on a host with an interface directly in the DN (for the DN/server side). Should that not be the case, there will most likely be an additional hop and some form of NAT.

Pending parallel developments of the Open5GCore PCF and related interfaces, a potential extension to the base deployment benefits the UC services with additional interfaces offered to the DN or server side of the application. Applications supporting the Rx or N5 interfaces should be able to utilise it to request that the 5G CN dynamically provision QoS parameters for a specific flow of traffic within the PDU session. Although the Open5GCore UPF will not enforce the QoS parameters, it should function in tagging downlink traffic to the RAN where the CN will have requested that the RAN honour these QoS parameters in the radio. This should enable a finer-grained control of QoS by the services.

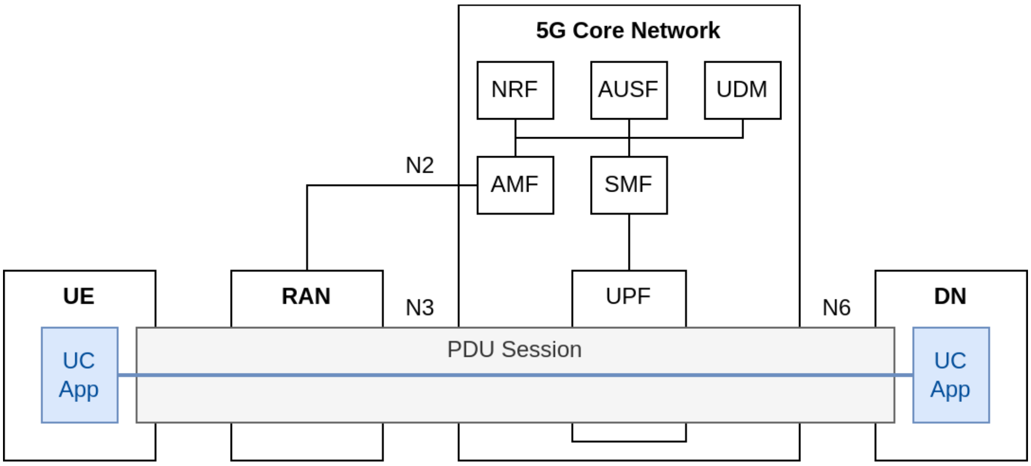


Figure 5-12 Base deployment in which E2E UC applications are enabled by PDU sessions

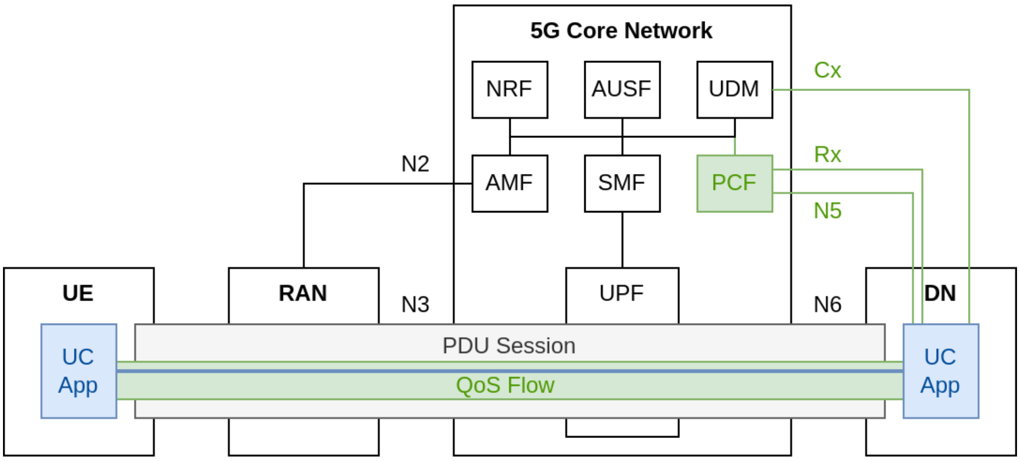


Figure 5-13 Target deployment in which E2E UC applications are enabled by PDU sessions with control of QoS parameters at the flow level

5.2.2.2 Specific UC Services

Figure 5-14 shows the services for the digital mobility, rail critical, and media content delivery UC to be demonstrated at Berlin Central station and how they utilise the 5G network to be deployed at the site.

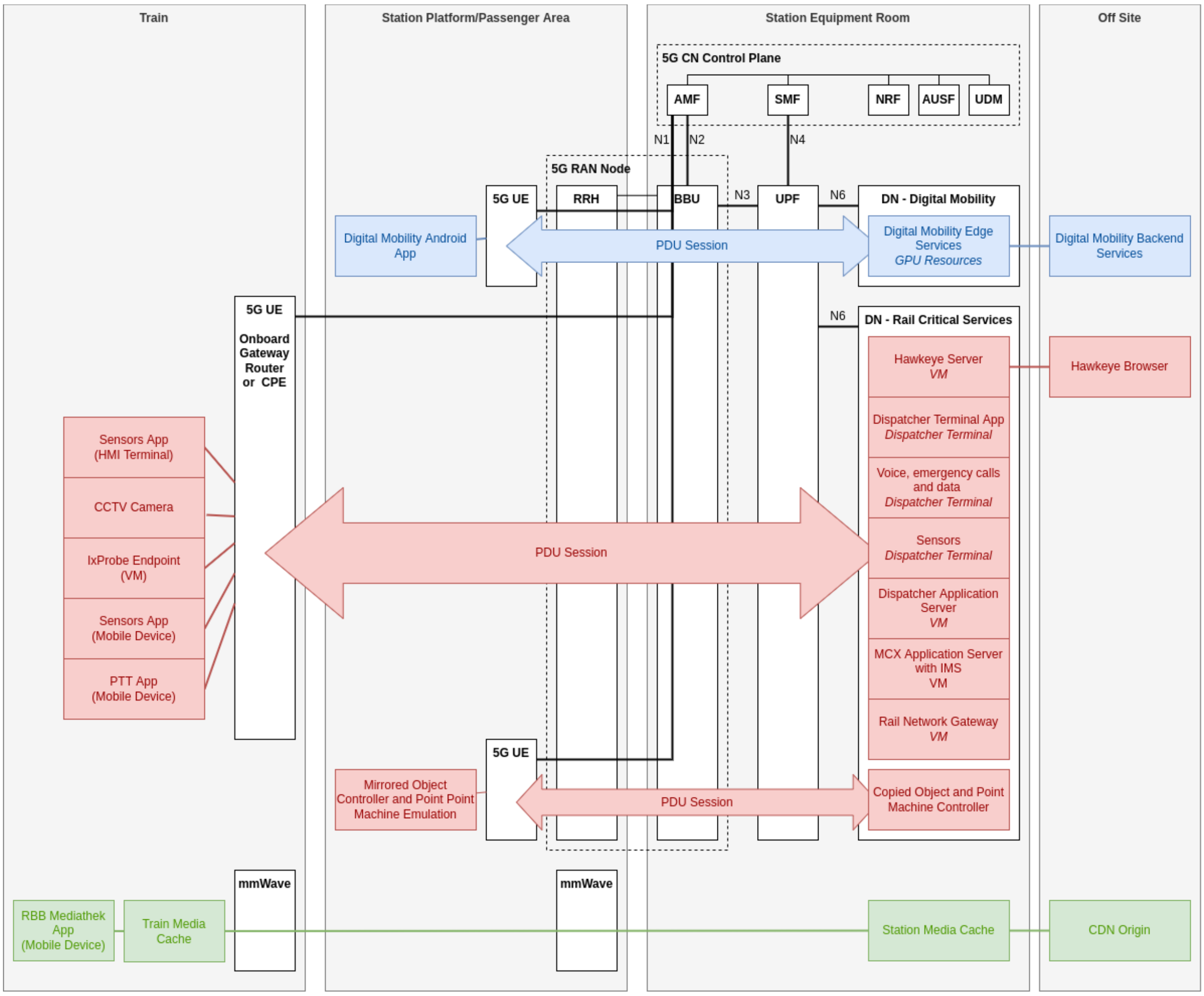


Figure 5-14 Berlin cluster UC services mapped to planned 5G infrastructure at Berlin Central Train Station

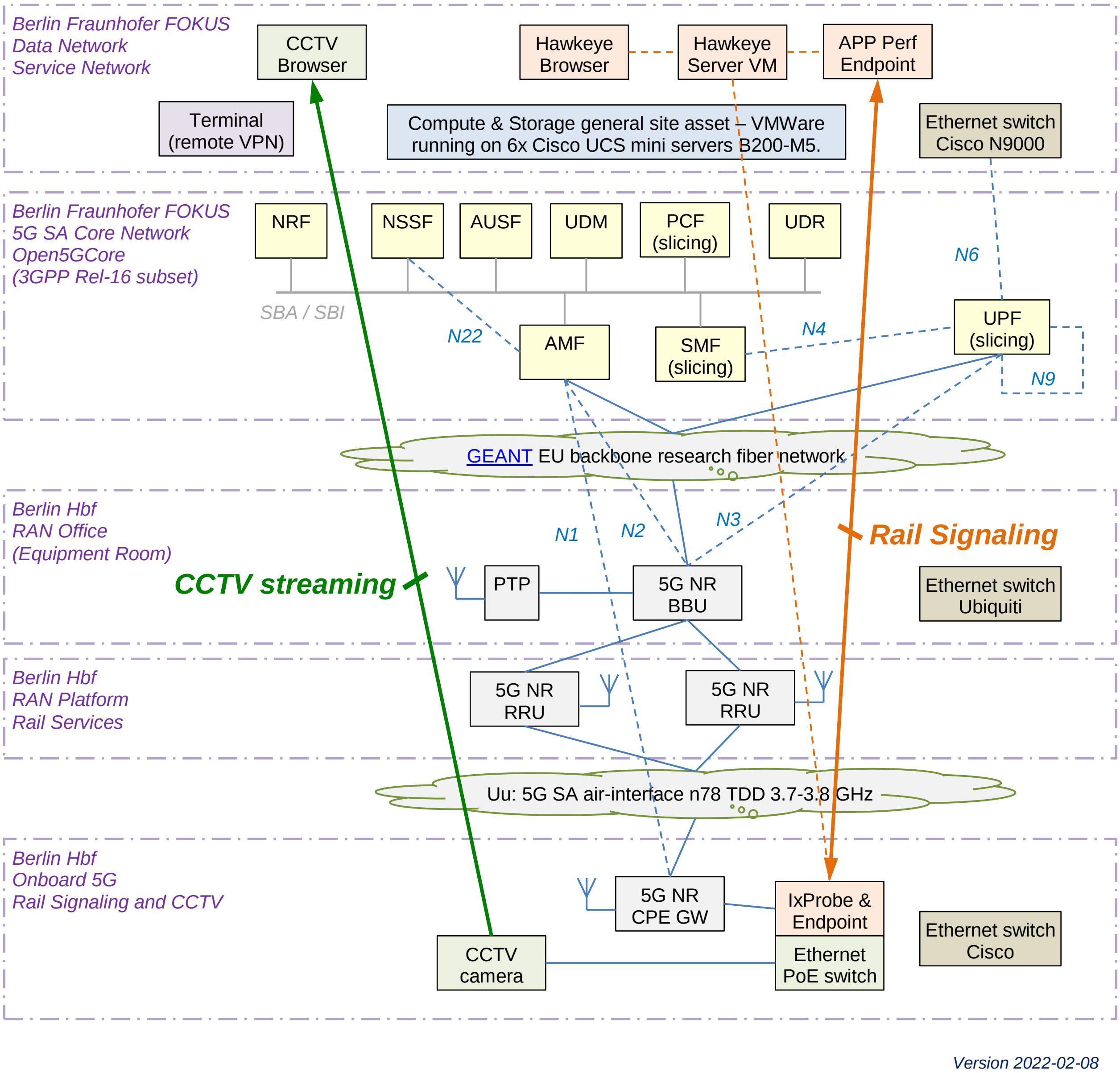
5.2.3 Mapping of Berlin Rail Signaling and CCTV services over 5GCN

See Figure 5-15 for an example overview of how the Rail Signaling boxes are connected and used in the Berlin cluster. The following subsections provide additional details.

5.2.3.1 Rail Signaling via 5GCN in Berlin – description

Rail Signaling in the 5G-VICTORI project for Berlin uses the IXIA software **Hawkeye**, which runs over Linux on a Compute and Storage server in the Fraunhofer FOKUS date center. This means that rail signaling is emulated with a bitrate and packet size that well represent rail signaling in real life.

The Hawkeye server needs a license which is related to the Host-ID of the computer (VM) it runs on. The project has only one user license and up to ten endpoints, which means that the license must be moved when Hawkeye is moved between computers. The Hawkeye server gets its IP address from a DHCP server, or uses a default IP address, or can be configured in a config file.



5G	5th Generation 3GPP defined cellular network	NS / NSSF	Network Slice / Network Slice Selection Function
AMF	Access and Mobility Function	PCF	Policy Control Function
AUSF	Authentication Server Function	PFCP	Packet Forwarding Control Protocol (TS 29.244)
BBU	Baseband Unit	PoE	Power over Ethernet
CCTV	Closed Circuit Television	PTP	Precision Time Protocol (IEEE 1588v2)
CN	Core Network	RAN	Radio Access Network
CPE	Customer Premises Equipment	RRU	Remote Radio Unit
GW	Gateway	SA	Stand Alone (=5G supporting signaling)
N1	Non-Access Stratum signaling (UE - CN)	SBA / SBI	Service Based Architecture / Interfaces
N2	Access Stratum signaling (RAN - CN)	SMF	Session Management Function
N3	RAN - UPF data plane	TDD	Time Division Duplex
N4	UPF - SMF signaling (PFCP protocol)	UDM	Unified Data Management
N6	UPF (IP anchor) – Data Network	UDR	Unified Data Repository
N9	UPF – UPF (interconnects UPF instances)	UE	User Equipment
NR	New Radio (compare with Old Radio – Ha ha!)	UPF	User Plane Function
NRF	Network Repository Function	VM	Virtual Machine (for example running on VMware)

Figure 5-15 Rail Signaling and CCTV via 5GCN in Berlin – block diagram

A web-browser at Fraunhofer FOKUS (or at Berlin Hbf) is used as GUI for the Hawkeye software, used for configuring traffic between endpoints, scheduling traffic, starting and stopping, and getting test result reports, etc. The web-browser uses the IP address of the Hawkeye server, where a login is needed.

When Hawkeye configures traffic between the involved endpoints, the Hawkeye server is not involved in traffic generation and termination. The Endpoints for rail signaling are a Performance Endpoint software in the Office and the IxProbe hardware endpoint on the train. When traffic stops, Hawkeye contacts the endpoints and extracts results E2E and presents results from the traffic, e.g. presenting latency, bitrate and frame drops.

When installing a Performance Endpoint, the IP address of the Hawkeye server is given during the installation process, and the endpoint then shows up in the Hawkeye GUI as a resource.

The IxProbe is used as Endpoint on the train for generating and terminating traffic. In this way no other computer is needed to host an Endpoint on the train, it is enough with the IxProbe. The IxProbe has two Ethernet ports A and B for traffic (A is northbound), and one Management port MGMT for configuring and monitoring in general of the IxProble. Thus, the IxProbe needs three Ethernet connections. The IxProbe can be moved around if needed, as it automatically connects to the Hawkeye server.

The 5GCN needs to be configured such that a UPF IP address shows up for the IxProbe, making possible for Hawkeye to reach the IxProbe.

5.2.3.2 CCTV via 5GCN in Berlin – description

See Figure 5-15 for an overview of how the CCTV boxes is connected and used in the Berlin project.

The CCTV network camera onboard a train in Berlin is of type **Axis P3935**. The camera is powered from a Power over Ethernet switch (or an insert box), using PoE IEEE 802.3af/802.3at Type 1 Class 3. The camera is connected via an RJ45 connector. The camera gets an IP address from a DHCP server or is configured with an IP address. The camera sends video using compression protocols H.264, H.265, or JPEG over Ethernet.

A web-browser at Fraunhofer FOKUS or at Berlin Hbf is used for monitoring pictures from the network camera. As only one camera is used, a web-browser is feasible (a software like AXIS Companion for showing pictures from several cameras is not needed). The web-browser runs over a compute and storage resource and needs a screen and keyboard. The web-browser surfs in to the IP address of the network camera and logs in to it (see D3.1 test-cases).

The 5GCN needs to be configured such that a UPF IP address shows up for the network camera, making possible for the web-browser to reach the network camera. The 5GCN needs to be configured such that the connection is always on, as the CCTV camera cannot setup 5G connections.

The IxProbe onboard the train can be used for generating traffic, both for additional CCTV emulated flows, rail signaling, and other services. The IxProbe is connected between the onboard 5G gateway and the PoE switch, as the PoE switch needs to power the network camera and IxProbe is not PoE transparent.

If an onboard Ethernet switch uses M12 connectors, Ethernet cables with M12 and RJ45 connectors are needed for the network camera and IxProbe.

5.3 5G-EVE / 5G-VICTORI facility – Romania

The 5G Architecture of the FR/RO cluster is based on the ICT-17 5G-EVE cluster facilities located in France (Paris and Nice), extended to the Bucharest laboratory, deployed in two different flavours 5G NSA option 3x and 5G SA option 2. In all the flavours, the installed 5G software components are based on Open Source software packages, running on the Orange Romania (ORO) virtualised testbed environment, as described in the E2E reference architecture in Figure 5-16.

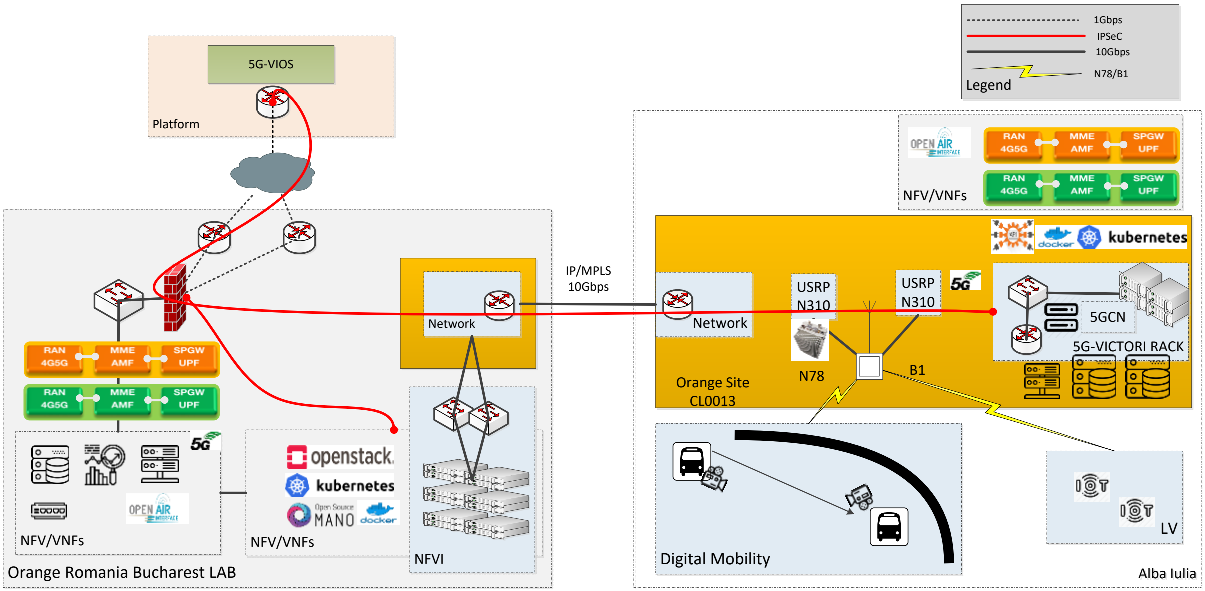
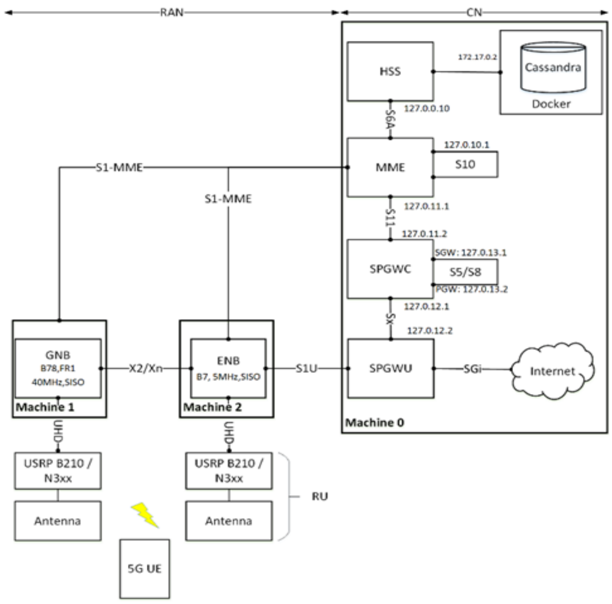


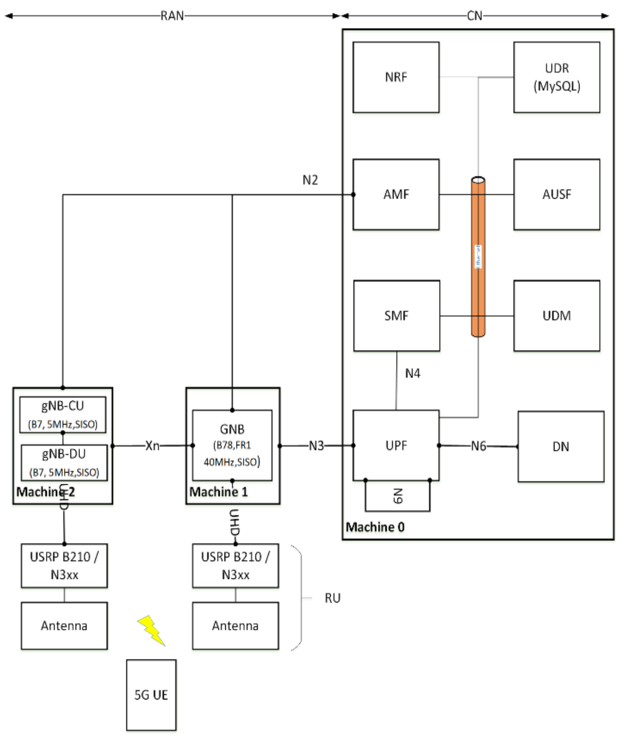
Figure 5-16 FR/RO E2E Reference Architecture

5.3.1 Detailed 5G architecture description

The 5G deployment in FR/RO cluster is based on the OpenAirInterface (OAI) 5G Stack implemented in the Orange facility, based on the integrated radio, CN software and hardware components for 5G NSA and SA systems (Figure 5-17).



5G NSA Architecture components



5G SA Architecture components

Figure 5-17 5G NSA/SA Architecture components

The 5G NSA Architecture is already implemented, and the focus of current activities is to demonstrate at AIM UC #1.2 “Digital Mobility Services” and UC #4.2 “Energy metering” using the 5G SA architecture implementation, option 2. This involves several steps, (1) the E-UTRAN New Radio – Dual Connectivity (EN-DC) Virtual Enhanced Packet Core (vEPC), Figure 5-18, implementation passing through (2) Enhanced Packet Core (EPC) CUPS and 4G-5G CN functioning, Figure 5-19, to (3) 5G SA deployment, Figure 5-20.

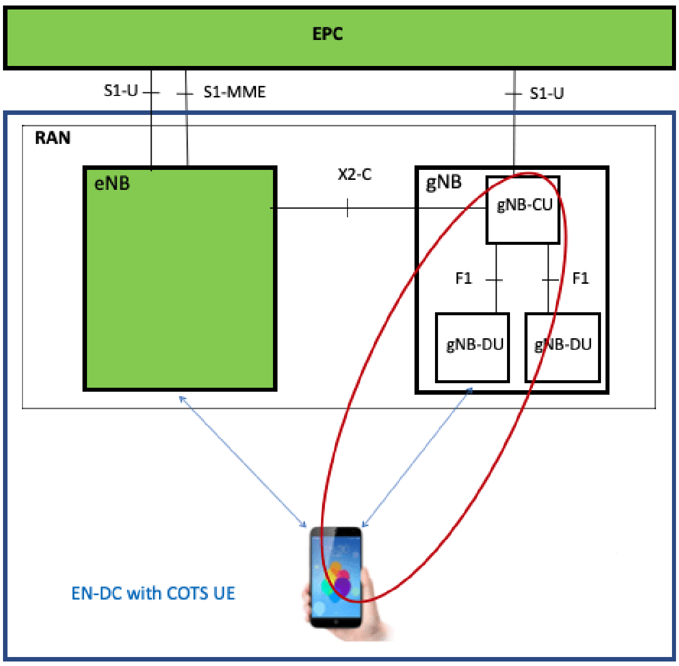


Figure 5-18 5G NSA Option3x

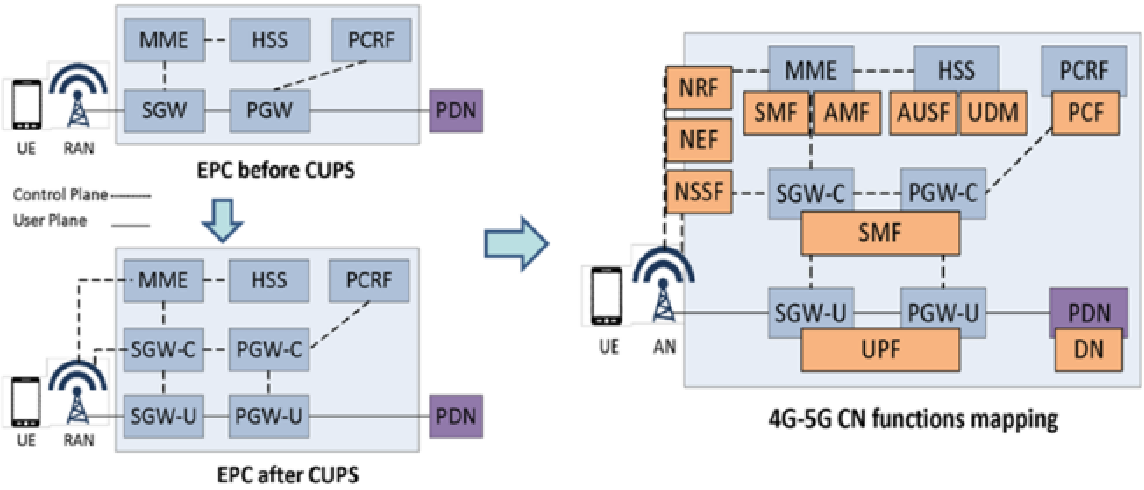


Figure 5-19 EPC CUPS 5G CN functions mapping

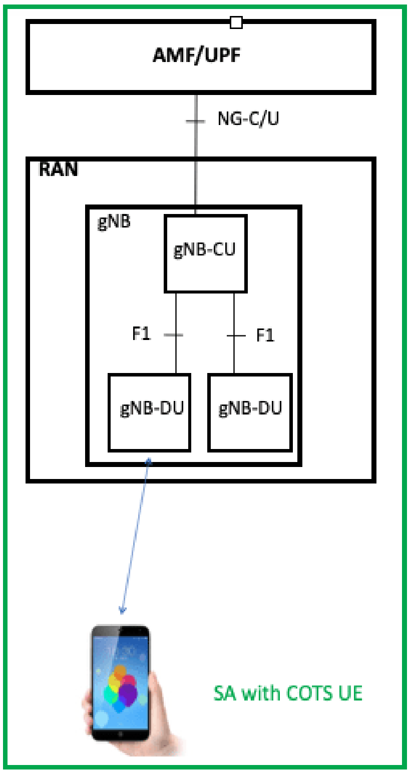


Figure 5-20 5G SA Option 2

The software components in both cases, 5G NSA or 5G SA are deployed based on a compute network infrastructure running K8s, within a configuration with a master node server and two slaves, for gNB-U/C and 5G CN UPF/AMF/UDM components, interconnected as described in Figure 5-21, allowing to E2E deploy 5G network and service slices.

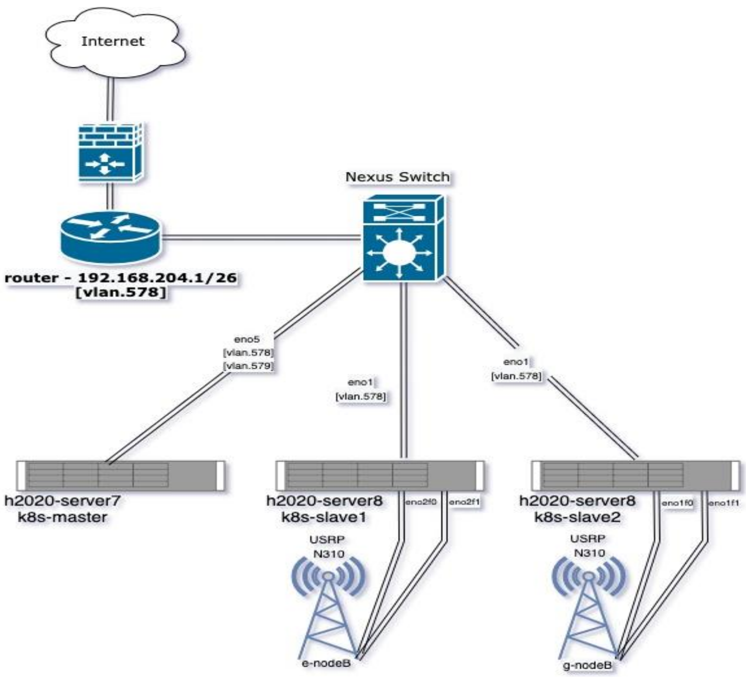


Figure 5-21 5G SA infrastructure component

5.3.1.1 Radio Access Network

OAI 5G RAN supports both the NSA and SA operation modes and enables connections and traffic flow with a 5G commercial UE.

In the NSA setting (see Figure 5-22 left), the gNB is supplemented by the LTE eNB that carries the CP of the 5G signalling, while the data bearer is set up on the gNB. An NSA capable 3GPP Rel-15 4G EPC is connected through the S1 interface to the eNB and the X2-C interface enables connection between the eNB and gNB for routing and managing the flow of IP traffic. The NSA mode is also referred to as the EN-DC mode and is shown in Figure 5-22.

In the SA mode (see Figure 5-22 right), the gNB is connected to the 5GCN through an NG interface. In both NSA and SA mode, a gNB could be deployed either monolithically or disaggregated consisting of a centralised unit and a distributed unit interconnected through the F1 application protocol (F1AP). The extended feature list of OAI gNB can be found at [22].

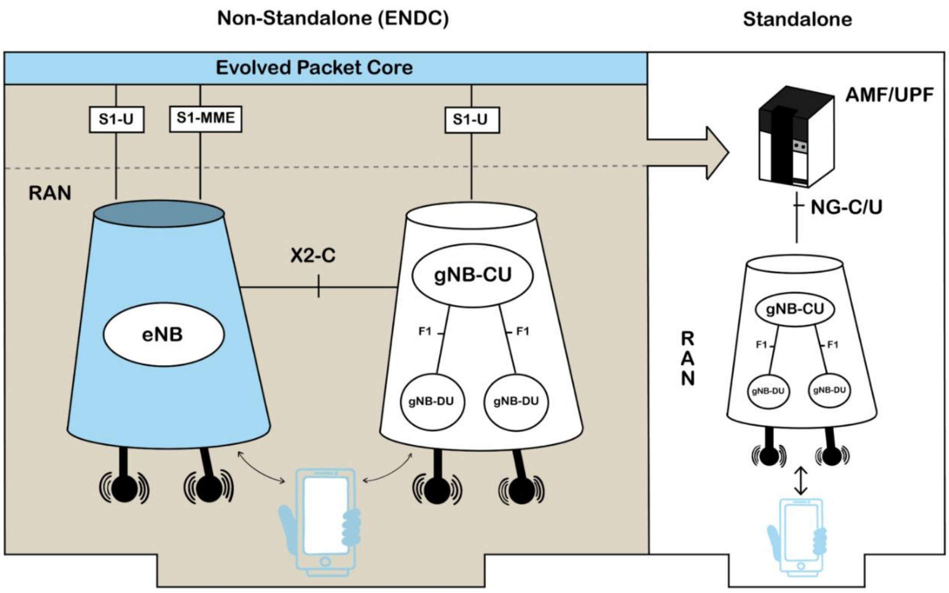


Figure 5-22 OAI RAN NSA and SA deployment options

For the disaggregated gNB, a CU/DU split can be used with the F1 interface between them (corresponding to split option 2 in 3GPP). This has been validated in the 5G SA mode with a COTs UE. The split mode allows for:

- Control plane exchanges between the CU and DU entities over F1-C (CP, Figure 5-22) according to F1AP protocol (TS 38.473, Rel.16 [23]), supporting UE E2E registration and PDU Session establishment,
- User plane traffic over F1-U (user plane, Figure 5-22) using gtp-u as per TS 29.281 [24].

5.3.1.2 Core Network (CN)

As for the 5GCN, the OAI stack provides the following components: AMF, SMF, NRF, NSSF, AUSF, UDM, UDR and UPF. The OAI 5GCN supports some basic procedures such as the registration, de-registration as well as the PDU session related procedures including session establishment, modification and release. For now, multiple UEs can be attached to OAI 5GCN and establish multiple PDU sessions at the same time. With NRF, OAI 5GCN can also support some additional features such as NF registration and discovery (e.g. to discover and select SMF, UPF), N2 handover, Paging, HTTP/2, FQDN support. For example, the AMF and SMF can discover and select an appropriate SMF and UPF respectively based on several parameters such as network slice information and DN name. Based on this feature, we can deploy multiple SMFs and multiple UPFs for network slicing scenarios. The extended feature list of OAI gNB can be found in [25].

Three different deployment options are available for the OAI 5GC:

- Option 1: relying only on the minimal NFs including AMF, SMF, NRF and UPF.
- Option 2: including UE authentication procedures to the option 1 by means of UDM, AUSF and UDR.
- Option 3: including network slicing feature to the option 1 or 2 by means of NSSF.

In terms of UPF, two different options are possible, but with different features:

- Option 1: reusing OAI SPGWU from 4G CN, which added several additional features to support 5G as a new GTP extension header to convey QFI information.
- Option 2: relying on VPP Travelping with DPDK support to achieve a better UP performance. For the moment, we can get up to 600 Mbps throughput in both UL and DL in a docker container deployment.

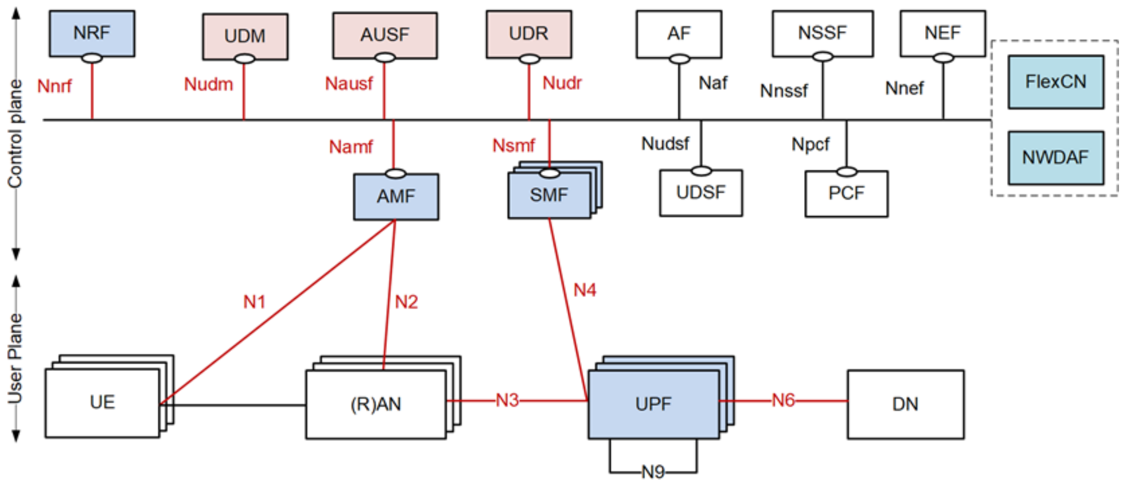


Figure 5-23 5G SA CP/UP network deployment interfaces for OAI

5.3.1.3 Mosaic5G (M5G) Stack

The Mosaic5G stack provides a set of extendable control and orchestration frameworks with extendable APIs on top of the OAI RAN and CN to enable fine-grained monitoring and programmability of the underlying network infrastructure. It further allows to leverage a customizable 4G/5G service delivery platform empowered by an ecosystem of intelligent network applications (xApps) and SDKs. Figure 5-24 shows the M5G stack and its relation to the OAI RAN and CN. The M5G stack provides the following platform:

- FlexRIC, a Flexible O-RAN compatible RAN intelligent controller (RIC), which currently supports fine-grained RAN stack monitoring and radio resource slicing.
- FlexCN, a flexible CN controller, which is currently able to support a fine-grained 5GC monitoring.
- Trirematics, an Intelligent RAN and CN service operator in a multi-x cloud-native environment.

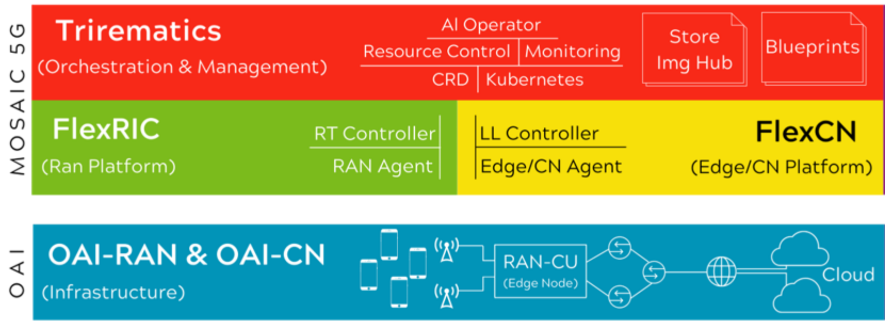


Figure 5-24 Mosaic5G stack and OAI-RAN and OAI-CN

5.3.1.4 OpenAirInterface Deployment scenarios:

Different options are available to deploy OAI-RAN and OAI-CN ranging from monolithic to fully disaggregated deployment as described above. A sample deployment is shown in Figure 5-25, with OAI-CN option 1 deployed in a docker environment (using docker compose) in a single machine, and a disaggregated OAI-RAN consisting of CU and DU running on a bare metal on a single machine connected to two NI USRP N310 SDRs. Such a deployment can be extended to support slicing by using OAI-CN option 3 deployment using NSSF function, and using M5G FlexRIC controller, an O-RAN compatible RIC, to support RAN radio resource slicing on the top of OAI-RAN. It has to be mentioned that with the RAN slicing, the requested bandwidth is released and the required radio resources are allocated to the slice ensuring the required QoS. With the OAI-CN slicing, the UPF may be dedicated to a particular slice.

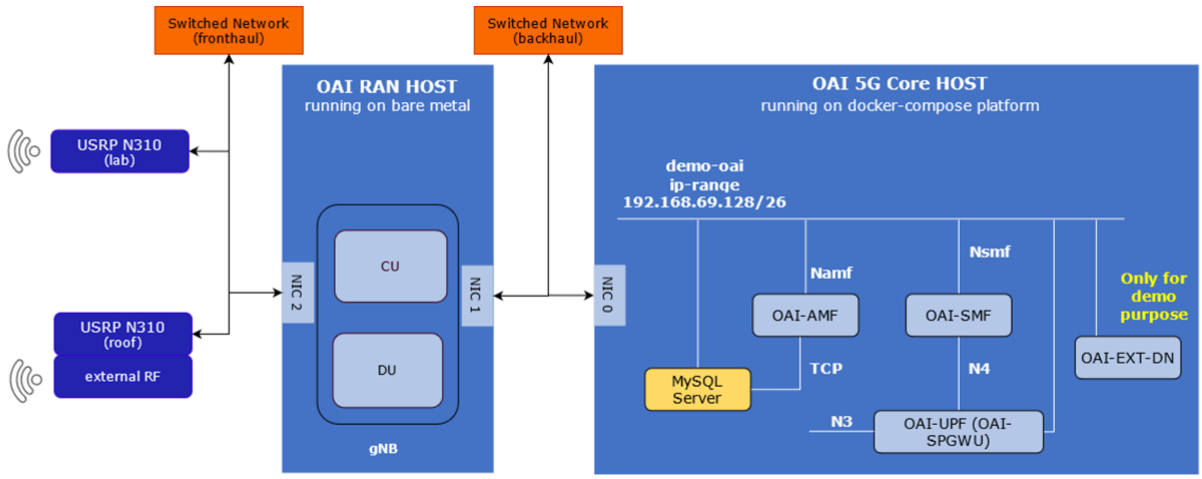


Figure 5-25 A typical deployment scenario using OAI

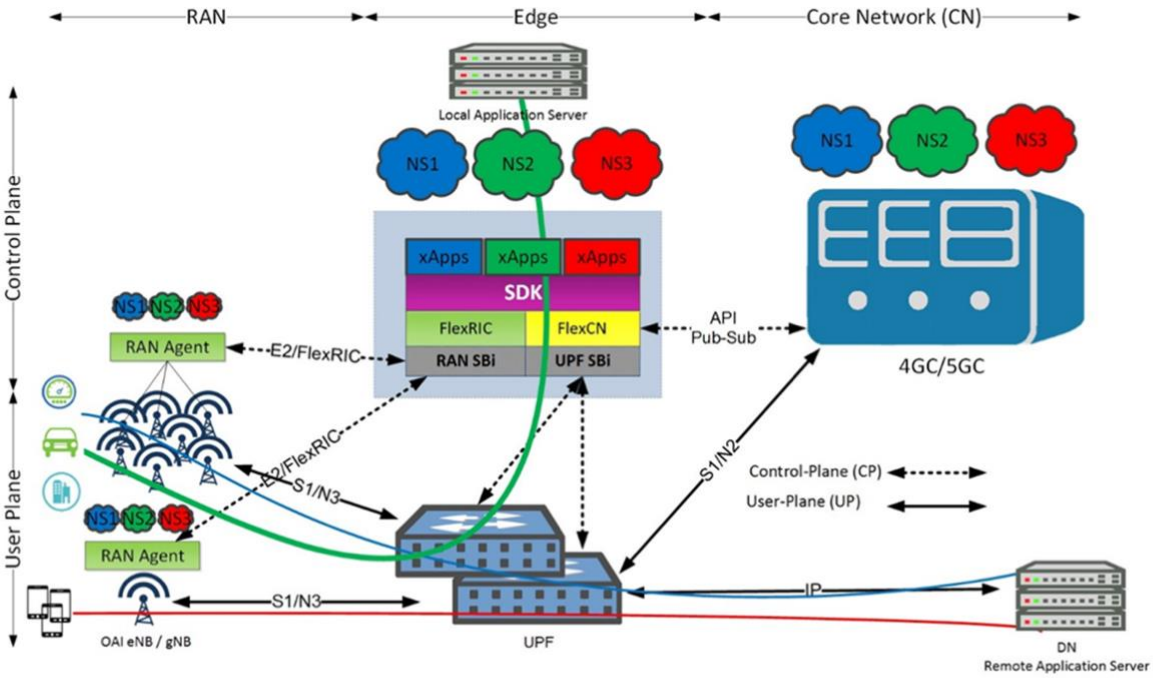


Figure 5-26 Flexible RAN and CN intelligent controllers

The 5G network is also based on the FLEXRIC feature, the O-RAN-compliant flexible RAN intelligent controller allowing to perform slicing in the RAN domain, as with RAN slicing, the requested bandwidth is released and the required radio resources are allocated to the slice ensuring the required QoS. The FLEXCN feature is the flexible CN intelligent controller allowing to perform slicing in the CN domain, both RAN and CN features being described in Figure 5-26.

5.3.2 Mapping of services over the 5G architecture

5G-VICTORI FR/RO UCs are mapped on the 5G Architecture described previously, based on the UC requirements described in detail in [26] and [27]. For a suitable UC mapping over the 5G SA architecture provided by the FR/RO, we enforce the UCs characteristics related to the infrastructure. The relevant mapping of the services is performed over 5G RAN, 5G Core, virtualised infrastructure and 5G MEC components. The IP/transport is not outlined, as the entire infrastructure is integrated in the same site in Alba Iulia through multiple 10 Gbps interfaces, ensuring the proper network QoS.

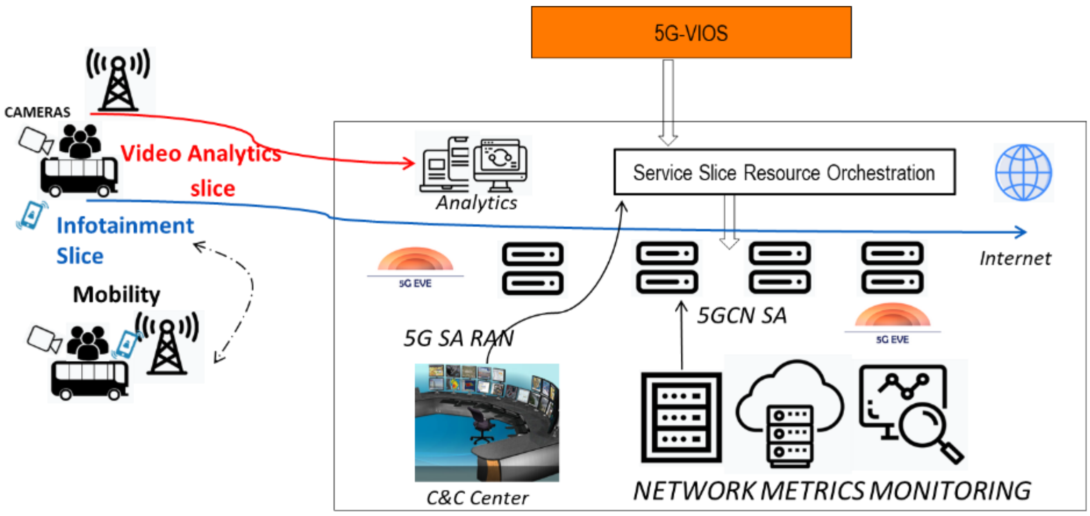


Figure 5-27 UC #1.2 Digital Mobility Services

5.3.2.1 UC #1.2: Digital Mobility Services Alba Iulia

UC #1.2 in Alba Iulia involves the following Apps:

- App1: Infotainment/ video services in dense, static and mobile environment.
- App2: AI recognition and identification of emergency situation.
- App3: Prioritised communication to command and control centre.

With respect of this UC, it is required that services should be provided in dense, static and mobile environment, with service communication priorities for the UC application. The communication services are split in two major network slices, the first eMBB slice (SST=1) for Infotainment, and the second ULLC slice (SST =2) for the prioritised communication to the C&C.

The service mapping, as described in Figure 5-27, consists of mapping into the 5G infrastructure of the communication requirements: App1 - bandwidth, 20 Mbps DL, low traffic prioritisation (for slice 1 - blue) and latency; App2 - E2E latency less that 10 ms, guaranteed bandwidth 10 Mbps UL and traffic prioritisation to the C&C based on the emergency trigger identified through App3 (slice 2 – red).

The E2E architecture of the 5G solution contains several components, as seen in Figure 5-28

- 5G UEs/Routers, providing to the passenger's access to the municipality services, devices that should connect to the 5G SA services deployed. The 5G router installed in the bus ensures 5G communication services, as previously described in the C&C. The devices installed in the bus are able to access suitable network defined slices (NSSAI based).
- 5G SA RAN and 5G Core, running as described in Figure 5-23, in the virtualised environment deployed in Alba Iulia, explicitly for the 5G services onboarding, in the Orange site, as shown in Figure 5-16.
- Edge Computing for App3 deployment, running in the same virtualised cluster (separated hosts), as the 5G functions, for video streaming analysis and data training.
- Back-end – hosts the captive portal which provides surveys, alerts, information, user authentication and hosts the streaming services offered to passengers.

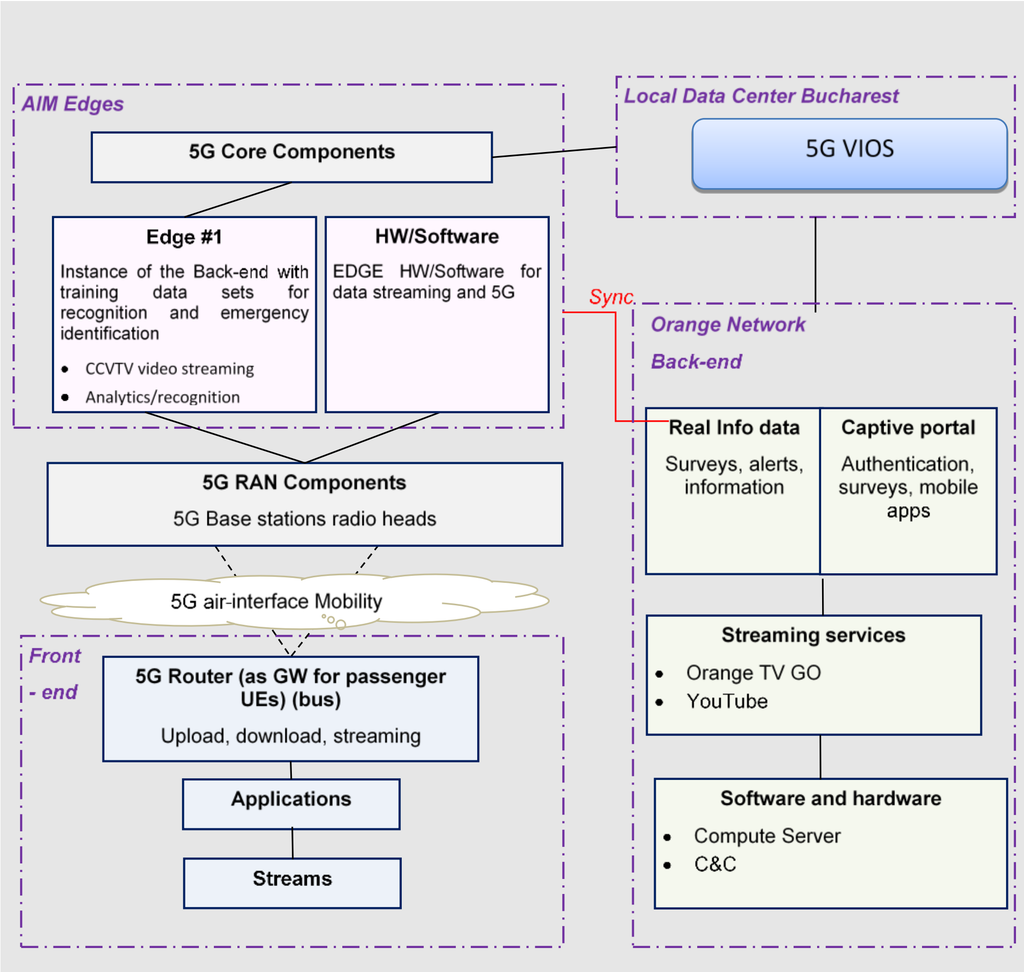


Figure 5-28 UC #1.2 mapping to the 5G SA infrastructure components

The **UC #1.2** main requirements in terms of communication services are related to several main key features of 5G. The **first** key feature is the possibility to ensure suitable communication services, based on each service characteristic, that is ensured through the slice implementation, as the UCs services are mapped to the slice. The **second** feature is related to the per slice resource allocation, as we have different needs between the services in terms of E2E communication, in case of the eMBB slice communication is performed through the PDN with the AIM infotainment services and the in case of the LLC slice communication is performed through the PDN to the EDGE App3 within the FR/RO cluster. The **third** key component is the 5G SA network that has to allocate resources, on demand, for the requested network slice user for emergency services. As the 5G SA deployment is using for this implementation a single 5G RAN and a single 5G virtualised core, the requirement is to allocate suitable resources for users in the specific slice, as described. Based on the service architecture shown in Figure 5-26, the controller allows slicing in the RAN domain. The requested bandwidth is dynamically allocated/released and the required radio resources are allocated to the LLC slice, ensuring the required QoS of the service. The flexible CN intelligent controller enables slicing in the CN domain and allocation of the resources for this slice. The **UC #1.2** services mapping to the 5G SA system elements are assured based on the KPIs indicators, as described in [26], highlighting some of them, as:

- UCs User Experience Data Rate, App1 and App2.
- Network Latency Round-Trip, App2.
- Service and slice instantiation, App1 and App2.

- Network Slicing and traffic prioritisation, App2.
- Analytics Service Reliability, App2.

The 5G deployment for the 5G RAN and Core (OAI) system is performed in a containerised environment (5G SA). The 5G service provisioning for the UC is automatically performed with regards to service slice creation and UEs association to a suitable slice, while agent application auto-associates UEs to slices based on NSSAI. 5G RAN video traffic prioritisation is performed through the Open RAN intelligent controller, triggered by an event that calls the APIs of the controller to perform resource prioritisation.

5.3.2.2 UC #4.2: Energy Metering

- App1: Real-time Low Voltage (LV) energy metering services for designated points of interests.
- App2: Energy Analytics for predictive and proactive maintenance for designated points of interest.

As described in [27], the UC is providing energy analytics for predictive and proactive maintenance for the AIM LV infrastructure, the metering data collection from endpoints, as depicted in Figure 5-29.

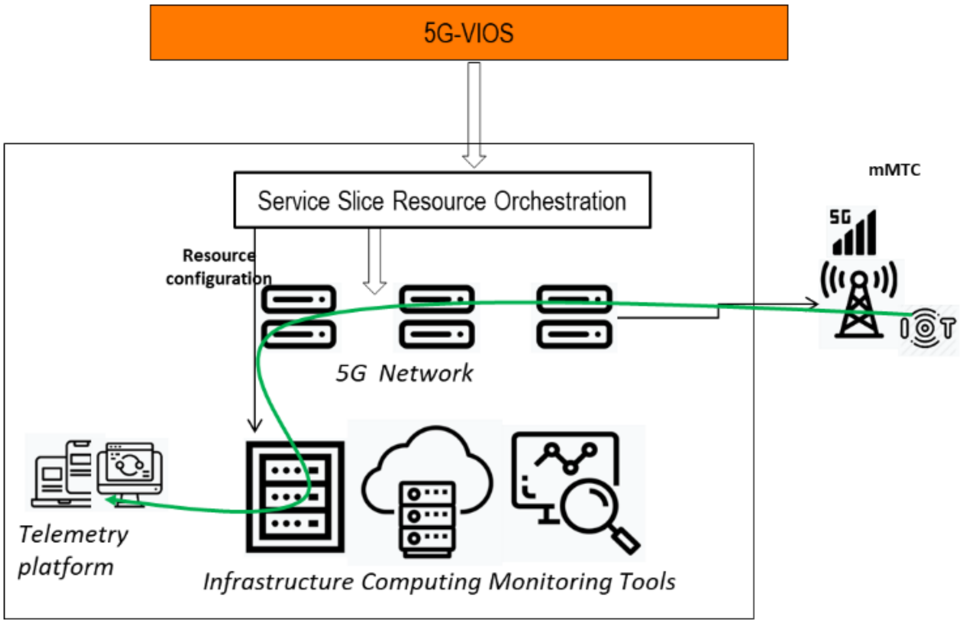


Figure 5-29 UC #4.2 LV energy metering

For the use case deployment in FR/RO infrastructure [28], a single network slice, like mMTC (SST=3) is instantiated to provide connectivity from the IoT devices through the 5G infrastructure to the telemetry platform hosted in Orange network, Bucharest DC. The 5G network infrastructure and related components are similar with the previous case, but mapped to the deployed scenario as depicted in Figure 5-30.

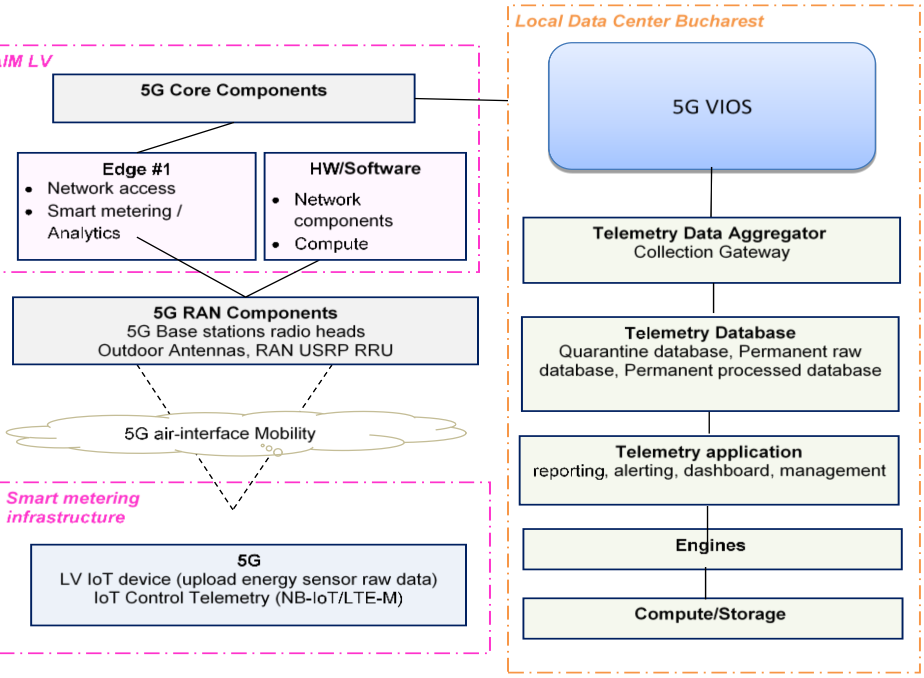


Figure 5-30 UC #4.2 mapping to the 5G SA infrastructure components

The UC #4.2, involving mMTC services is mapped to the 5G SA architecture (Figure 5-25), for the 5G RAN and Core elements, within a network slice. For this scenario, the network slice for the communication service deployed over the infrastructure is low bandwidth/capacity, aiming to cope with hundreds of devices within an area, as an IoT service. Due to the technology availability and the 5G SA IoT devices roadmap, the UCs will be mapped to the main 5G IoT infrastructure, on an eNB/gNB and 5G NSA vEPC implementation.

The 5G deployment for the 5G RAN and Core (OAI) is performed, as described, in a containerised environment (5G SA/NSA). The 5G service provisioning for the UC is automatically performed for the service including slice creation and UEs association to the IoT slice, as no prioritisation will be further implemented.

The UEs association to a suitable slice is provided by the 5G agent application that auto-associates UEs to slices based on NSSAI, or the International Mobile Subscriber Identity (IMSI) or selected PLMN.

The UC mapping to the 5G architecture is evaluating several requested KPIs, such as:

- 5G network deployment and instantiation.
- Service slices creation and UEs association to slices.
- Service slice performance (Bandwidth/slice and number of devices associated to the slice).

5.3.3 Interfaces

The relevant 5G SA interfaces are related to 3GPP interfaces [14], with the main components and N interfaces for the Authentication Server Function (AUSF), Access and Mobility Management Function (AMF), Session Management Function (SMF), Unified Data Management (UDM), Unified Data Repository (UDR), User Plane Function (UPF) and UEs. A specific proprietary interface is the E2/Flex SBI interface for 5G SA Core and RUN, as described in Figure 5-26 and mapped to the FR/RO 5G SA architecture, in Figure 5-31 and Figure 5-32.

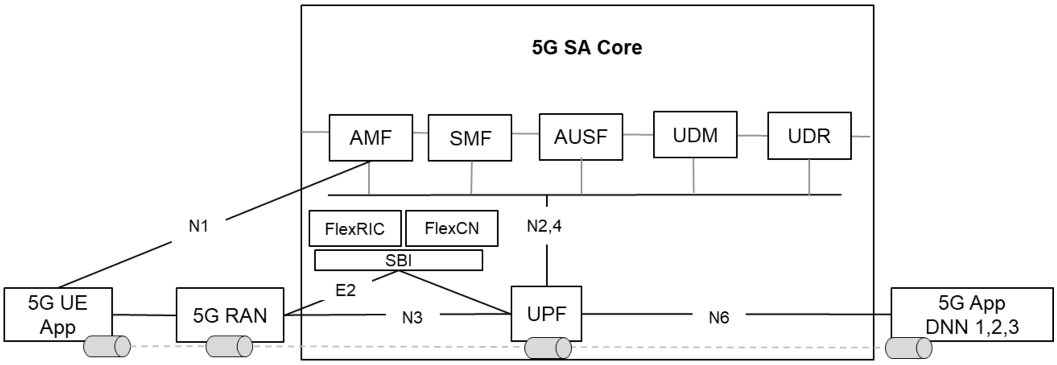


Figure 5-31 5G SA OAI 3GPP network interfaces

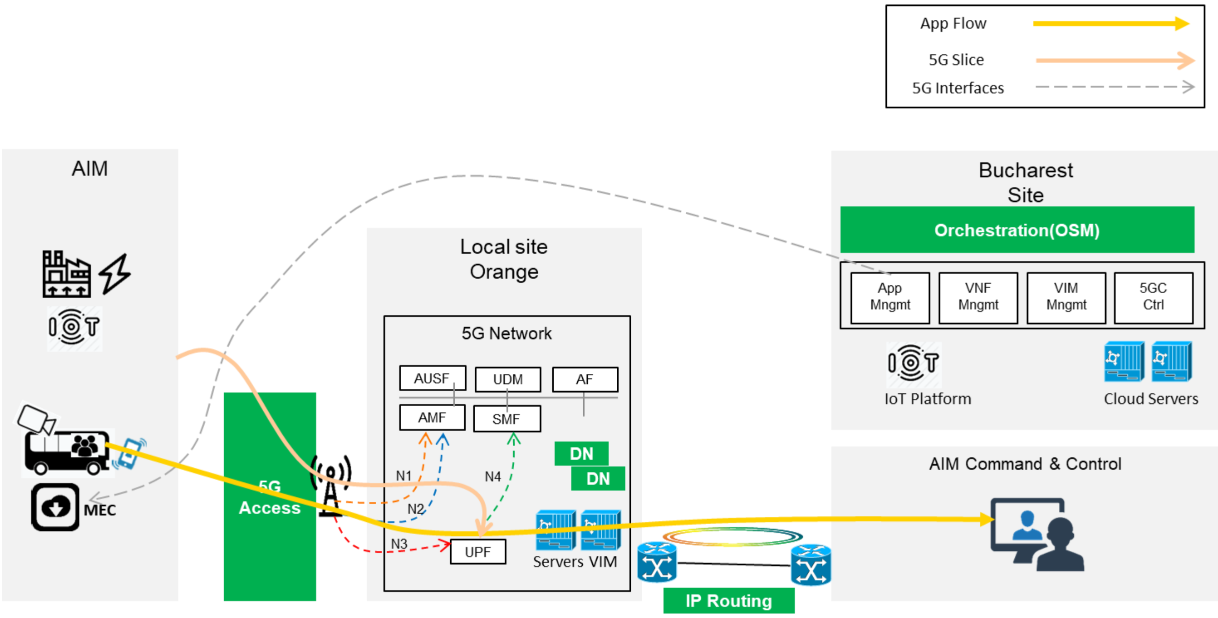


Figure 5-32 5G SA multi-slice OAI network deployment and interfaces

5.4 5G-UK / 5G-VICTORI facility – Bristol

5.4.1 Detailed 5G architecture description

The 5G-VICTORI Bristol Cluster extends the 5GUK Test Network, hosted/owned by the University of Bristol (**UNIVBRIS**), towards the implementation of the Digital Mobility related UCs. Basically, the 5GUK Test Network provides access to an urban dark fibre network, with configurable private cloud computing resources and wireless access, either at the edge or centralised at the High Performance Networks (HPN) Group, being part of the Smart Internet Lab workspace. Further details have been described in deliverables D2.1 [3] and D2.2 [1].

The high-level design of Bristol's 5GUK Test Network at the four key locations is shown in Figure 5-33. The 5GUK Test Network provides 5G, 4G LTE and Wi-Fi connectivity at three key locations: MShed, Millennium Square (MSq) and Smart Internet Lab.

For the needs of 5G-VICTORI Bristol Cluster, the 5GUK Test network coverage is extended towards the location of SS Great Britain Museum with an additional, Nomadic node that will be deployed on a boat. To meet the requirements of all demonstration, UCs discussed in deliverable D2.3 [2], additional compute resources will be installed at all edges as well as the Nomadic node. By doing so, the network can support seamless connectivity and mobility along the demonstration path for all users and for any UC, either on foot or inside the boat. Further details regarding the Nomadic node architecture are discussed in the next section.

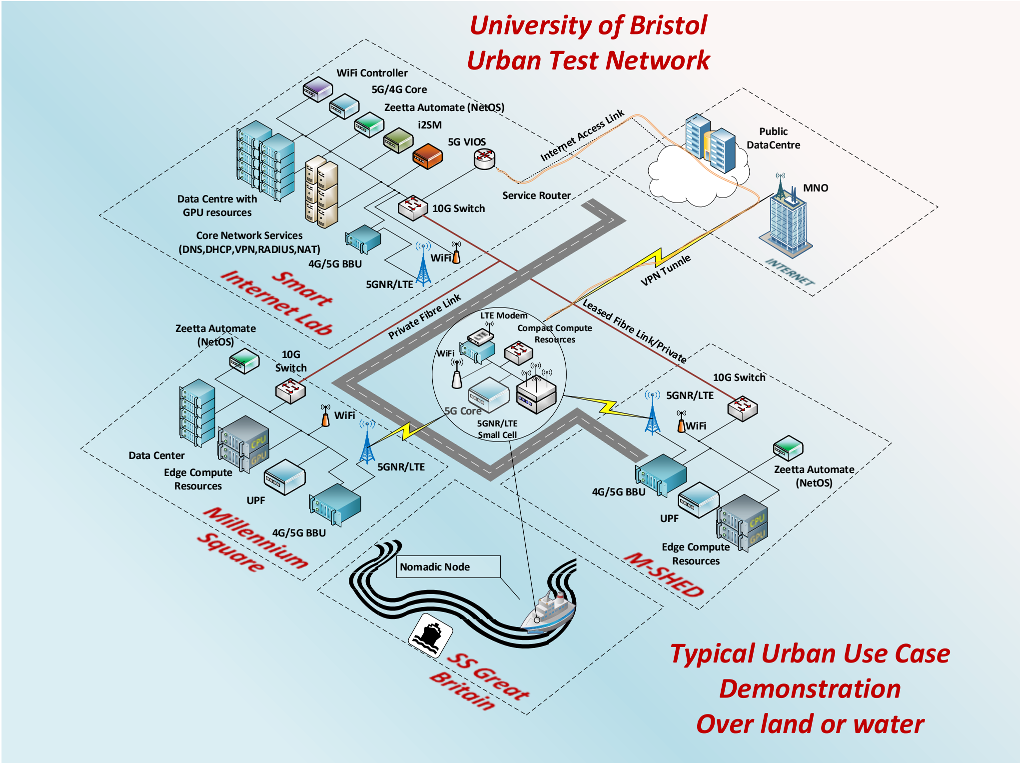


Figure 5-33 The high-level 5G-VICTORI Bristol Cluster: the key location (Smart Internet Lab), M-Shed, and MSq

To provide the required mobility services onboard the Nomadic node, the **DCAT**'s 5GNR and **i2CAT**'s Wi-Fi solutions are integrated with the 5GUK Test Network. The **Zeetta**'s slice management solution based on NetOS (i.e., Zeetta Automate), is instantiated at each network edge to configure the network slices on the 5GUK Test network Edge core switches and manage local layer-2 traffic [2]. 5G-VIOS Inter-Edge Connectivity Manager's SDN controller will call each instance of Zeetta Automate to create/modify/delete slices for each edge. Additional compute resources will be deployed within the Nomadic node on the boat.

A detailed description of the current network edges deployed at the 5G-VICTORI Bristol Cluster can be found in the following sub-sections.

5.4.1.1 The network edges deployed at Bristol Cluster

The Bristol Cluster has four edge nodes that have been deployed at HPN in the Smart Internet Lab, Msq, Mshed, and at a Nomadic node, which offer the MEC service provisioning through the available computing resources. Each deployed network edges will be described in the following sections.

5.4.1.1.1 Cloud network architecture at Smart Internet Lab

Figure 5-34 illustrates the cloud CN architecture in the Bristol Cluster. The Cloud network is based on OpenStack, with the controller node located at the Smart Internet Lab. The cloud architecture consists of multiple Access Zones (AZ) which isolate the network edges and differentiate their computational resources.

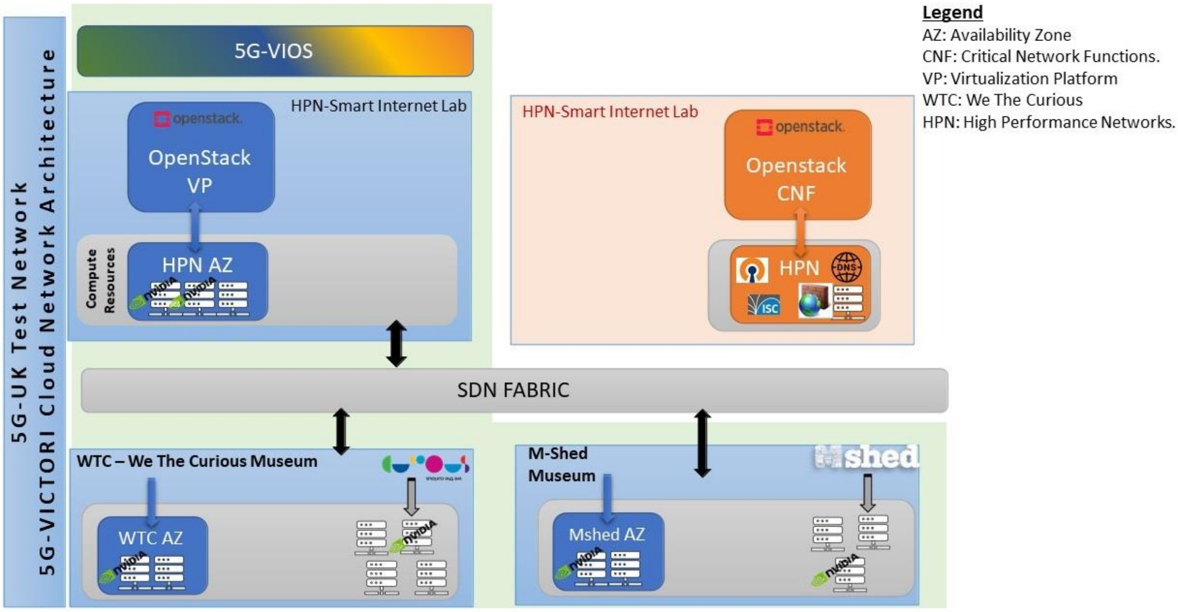


Figure 5-34 The Bristol cloud network architecture.

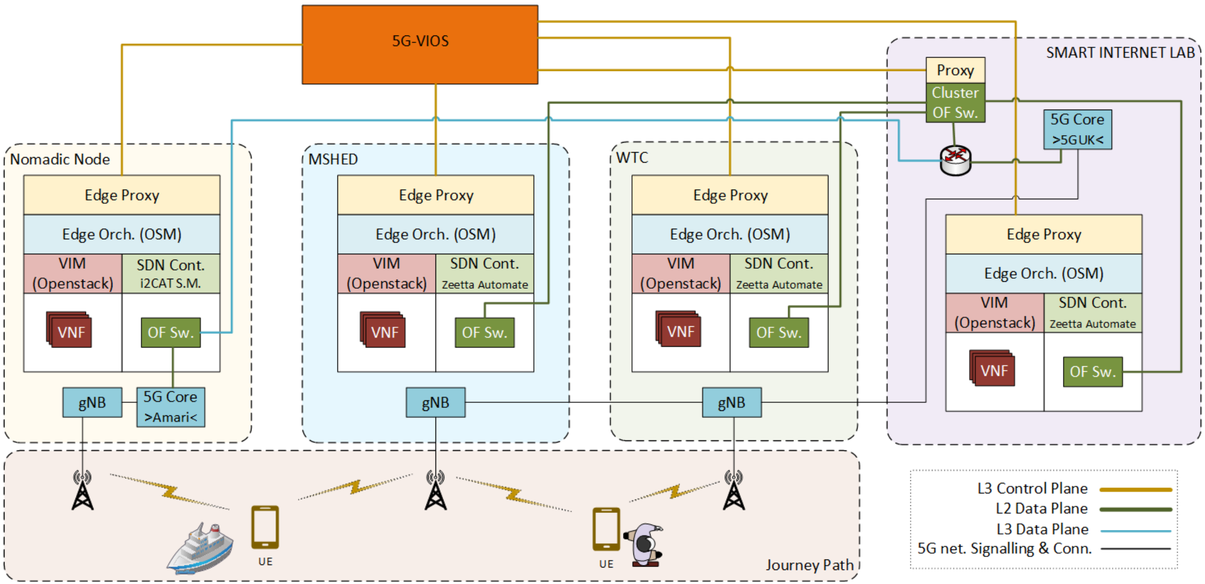


Figure 5-35 Bristol Cluster Edge nodes interoperability under 5G-VIOS orchestration

Figure 5-35 illustrates the Bristol Cluster edge nodes's interoperability with the 5GC and how they are deployed under the MANO of 5G-VIOS. It shows the functionality in terms of virtualisation, management, and orchestration. Basically, each edge node works under the OSM management. The independent instances of Zeetta Automate (NetOS) can be deployed at each edge node, and perform the required edge slicing. Similarly, the Nomadic node relies on i2CAT slice manager (i2SM) for slicing. On a logical level, i2SM is located within the Nomadic node. However, i2SM is instantiated on a VM hosted on a server in Smart Internet Lab. 5G-VIOS is responsible for the Management and Orchestration of the Bristol Cluster, which is instantiated on a server in Smart Internet Lab.

- **Core network (Open5GS)**

The Bristol cluster is utilising an instance of Open5GS implementing 3GPP deployments options 1 (4G SA) and 2 (5G SA). The core architecture is illustrated in Figure 5-36 [29]. To enable seamless mobility and low latency communication for the interactive class and AR/VR use-cases, the 5GUK Test Network took advantage of the disaggregated functionality in the 5G core to bring the User Plane (UP) closer to the edges.

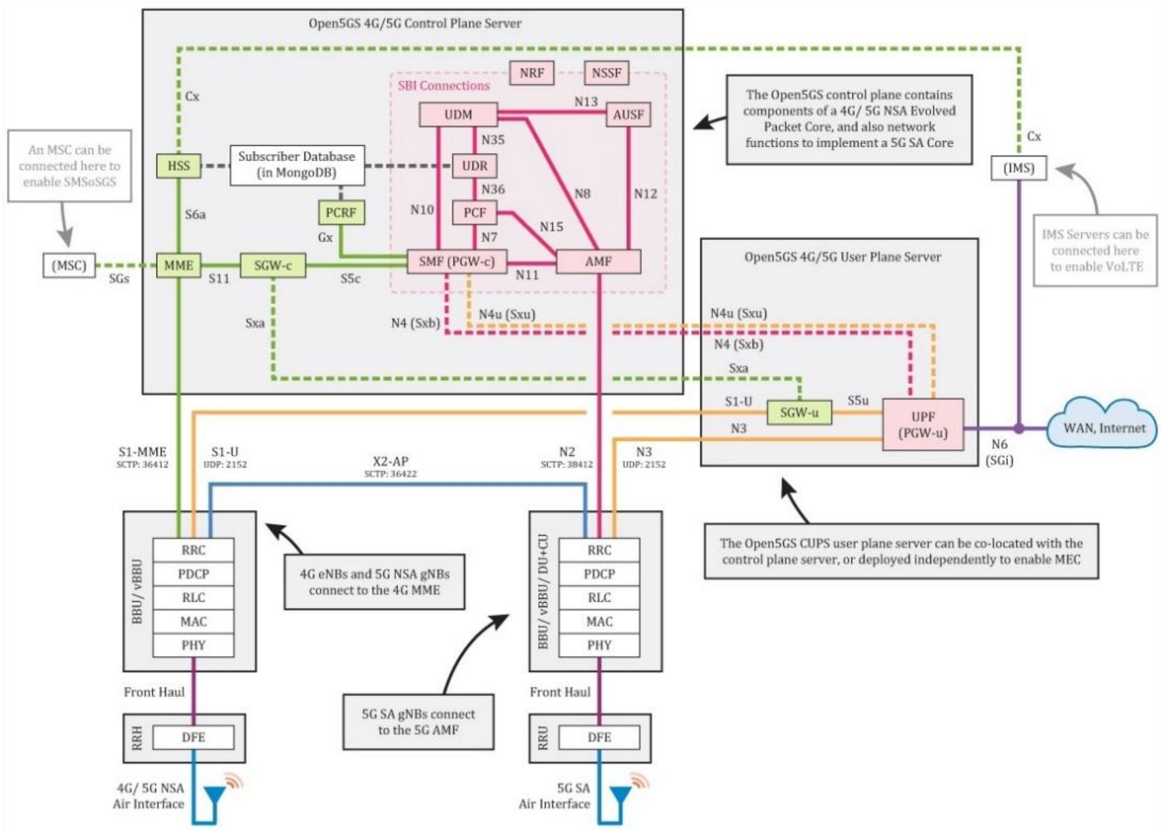


Figure 5-36 Open5GS architecture

Multiple UPF instances are instantiated, one at each edge, while the edges are also provided with enough computational power capable of running the required application services locally. By doing so, the NG link requirements are significantly relaxed, which in turn enables the deployment of a Nomadic Node at areas where the 5G coverage of the 5GUK Test Network is weak.

5.4.1.1.2 Millennium Square and WTC

The details of MSq and WTC have been discussed in deliverable D2.3 [2], where the outside areas of WTC and MSq will be included in the demonstration. The N78 need to be renewed for the demonstration in Oct. 2022. However there is no assurance regarding N78 availability through the regulator. Mitigation plan is to use N77 upper band, which is easier to obtain from the regulator.

- **Zeetta Automate instance**

Zeetta Automate per edge nodes are responsible for the layer 2 traffic by configuring network slices, they allocate devices and a VLAN for each slice. Zeetta Automate will expose its APIs to create / modify / delete slices. This will allow the Edge core switches per edge / domain to be added to a slice for a given VLAN. There will be only one instance of Zeetta Automate per edge.

Figure 5-37 illustrates the workflow for using Zeetta Automate which would be orchestrated by the Inter-Domain Connectivity Manager's ONOS controller [2]. This controller oversees delegating the provisioning of the network to the different edge controllers across the domains and at the same time takes care of the inter-connectivity between edges by configuring the Edge core switch ports on each edge. Each edge has its own proxy to communicate with the

ONOS controller. The API in ONOS to communicate with the island controllers needs to be adapted for the Zeetta Automate APIs.

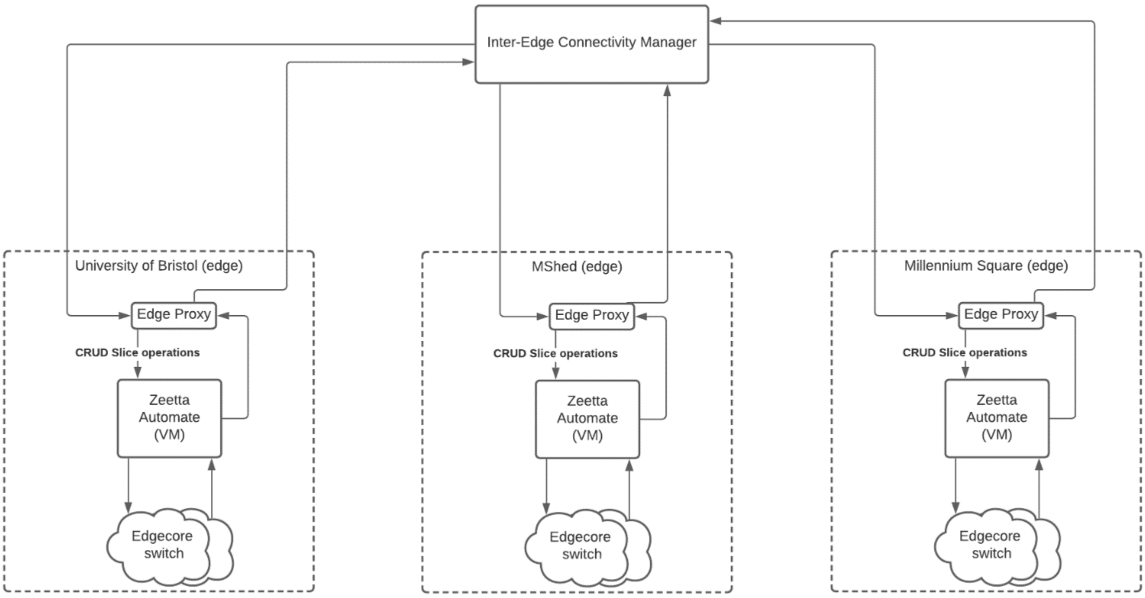


Figure 5-37 The slicing architecture with Zeetta Automate that will be applied to the edges.

5.4.1.1.3 MShed

As it is discussed in deliverable D2.3 [2] the MShed building is one of the key locations within the Bristol city centre hosting some of the University of Bristol 5GUK Test Network infrastructure. A MEC facility, three 4G LTE pico-cells and Wi-Fi APs are located inside the building (indoor area) while more Wi-Fi APs and 5G RAT are installed on the building's rooftop (ourdoor area). In the Mshed, the connectivity to the outdoor area is provided by Rukus T710 Wi-Fi APs located at the East and West rooftops, and two Nokia RUs (4G LTE and 5G M-MIMO) located at the East rooftop (i.e. Figure 4-3 in Deliverable D2.3 [2]). A fixed wireless (mmWave @26 GHz) mesh network is also installed on the East and West rooftops allowing gigabit connectivity between the MShed and MSq nodes. There is a good 4G LTE, 5G and Wi-Fi coverage outside the building.

In the indoor area of Mshed, the Server Room is the location that hosts the Core of the network at this site. Fibre link is installed to connect the Server Room with other locations within the MShed where the equipment is deployed. There is plenty of space and power plugs to accommodate upgrades and new equipment. Recent network upgrades in this server room include the installation of a new 10G Edgecore switch and a 5G-ready Nokia AirScale, both providing the required throughput (backhaul and edge) and edge services.

There are three exhibition halls each covered by their own LTE Licensed-Assisted Access (LAA) pico and Ruckus R720 Wi-Fi AP:

- Bristol-People
  Located on the first floor of the MShed building, the Bristol People houses one Ruckus Wi-Fi access point and one Nokia Pico cell. The Wi-Fi AP links 2x UTP connections. The LTE Pico cell links 2x UTP connections and 1x single mode fiber connection LC-LC terminated. The Server Room provides power from switches to both devices through PoE.
- Bristol-Places

Located on the ground floor of the MShed building is the Bristol Life Exhibition Room. Linking the two APs (one Ruckus Wi-Fi and one Nokia Pico cell) at this location is 4x UTP connections and 1x single mode fibre connection.

- Bristol-Life

  Located on the first floor inside the MShed building. The same access points (one Ruckus Wi-Fi and one Nokia Pico cell) in the two other Exhibition Rooms are also installed here, which requires the same connectivity (4x UTP connections and 1x single mode fiber connection).

5.4.1.1.4 Nomadic node

As it is mentioned in deliverable D2.3 [2], in 5G-VICTORI Bristol Cluster, the 5GUK Test network coverage is extended towards the location of SS Great Britain museum through designing an additional edge node, which is called Nomadic node, Figure 5-38. The Nomadic Node will be deployed on a boat. Also, the Nomadic Node includes additional compute resources to satisfy the applications specific to Bristol Cluster UCs. Therefore, a seamless connectivity and mobility along the demonstration path will be guaranteed for all users, either on foot or inside the boat.

DCAT's 5GNR and i2CAT's Wi-Fi solutions are integrated with the 5GUK Test Network so that the 5G Nomadic node can provide the required mobility services onboard. It supports seamless 5G connectivity at the surrounding area of SS Great Britain, and at locations where the 5GUK Test Network's coverage is not sufficient for the requirements of the UCs.

Initial lab testing was successful integrating the Amarisoft Callbox (DCAT's 5G solution) to the 5GUK Test Network. The 5GUK team performed E2E connectivity tests via both, wired (Ethernet to switch) and wireless (5G CPE to 5G NR) backhaul connectivity. The test results are depicted in Table 5-1 and Table 5-2. Despite the successful connection tests, throughput and latency performance was not satisfactory, with the tested setup suffering stability issues, slow down/up links (DL/UL) speeds and high packet RTT. Since then, the 5GUK Test Network has been upgraded and significant improvements have been made with respect to throughput and latency. Additionally, the Amarisoft Callbox software will be upgraded from 5G NSA (4G Core) to 5G SA (5GC), with further performance improvements being expected.

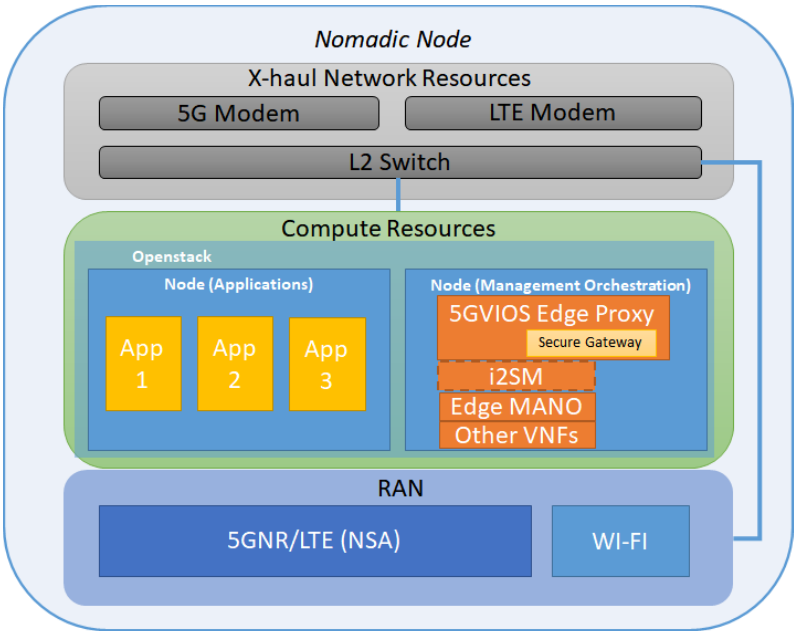


Figure 5-38 Nomadic node high-level architecture [2]

Table 5-1 Amarisoft Callbox integration test results with wired backhaul

Test	Average	Max	Min
TCP DL (Mbps)	213	254	151
TCP UL (Mbps)	11.4	97.5	0
Ping (ms)	29	88	16

Table 5-2 Amarisoft Callbox integration test results with wireless backhaul

Test	Average	Max	Min
TCP DL (Mbps)	159	203	101
TCP UL (Mbps)	15.1	53.9	0
Ping (ms)	82	147	38

- **i2CAT Slice Manager (i2CAtSM)**

Network slicing ensures that the different performance requirements for each application specific to Bristol Cluster UCs are satisfied. Each network slice addresses the KPIs' requirements of each mentioned application and includes multiple RATs. The details of each network slice has been discussed in sections 4.2.3, 4.3.3, and 4.4.3 of deliverable D2.3 [2], respectively.

In the Nomadic Node, the Slice Manager (i2SM) will provide the functionalities of the RAN and CN NSSMFs, managing the RAN and Core resources at this edge to create the demanded slices. The i2SM also implements part of the Operation and Maintenance (OAM) functionalities of O-RAN's Service Management and Orchestration (SMO) layer, being able to remotely configure the RAN nodes (i.e., Amarisoft and Wi-Fi) via a NETCONF-based interface which adapts ORAN's O1 interface. The i2SM also provides a telemetry subsystem based on Prometheus, where the RAN nodes expose their RAN telemetry using custom Prometheus exporters.

As was described in D2.3 [2], cellular and Wi-Fi users in the Nomadic Node will share a common data plane and IP pool, being able to reach the same application instances deployed at the edge and the core. Traffic forwarding between the wireless nodes and the Vertical applications on the Nomadic node will be performed at layer 2, using VLAN tags to differentiate the data traffic from/to different slices.

Finally, regarding the 5G Core slicing, all the slices will share a common Control Plane (i.e., AMF, UDM, UDR) using a common PLMN, but slice-specific SMF and UPF according to their S-NSSAI identifiers . Also, we foresee two different alternatives regarding the placement of the CP and UPs: isolated Nomadic node (i.e., the whole core CP is deployed at the edge) or integrated Nomadic node (i.e., only the UPF is deployed at the edge), which is selected according to the gNB of the UE. These two options are depicted in Figure 5-39 and Figure 5-40, respectively.

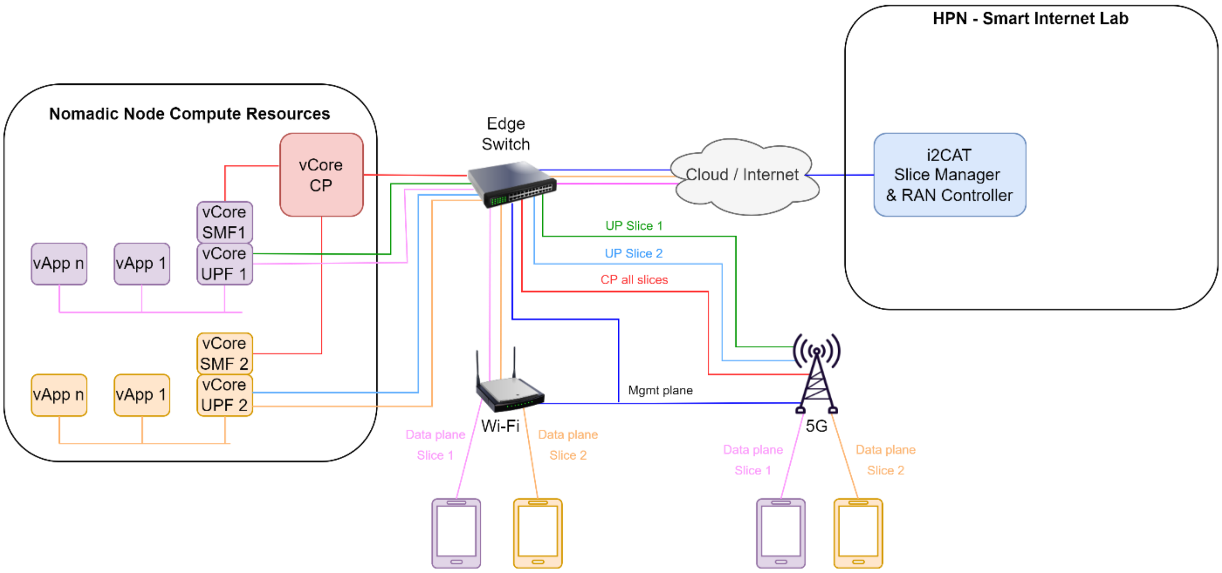


Figure 5-39 Nomadic Node architecture – Isolated 5G Core option

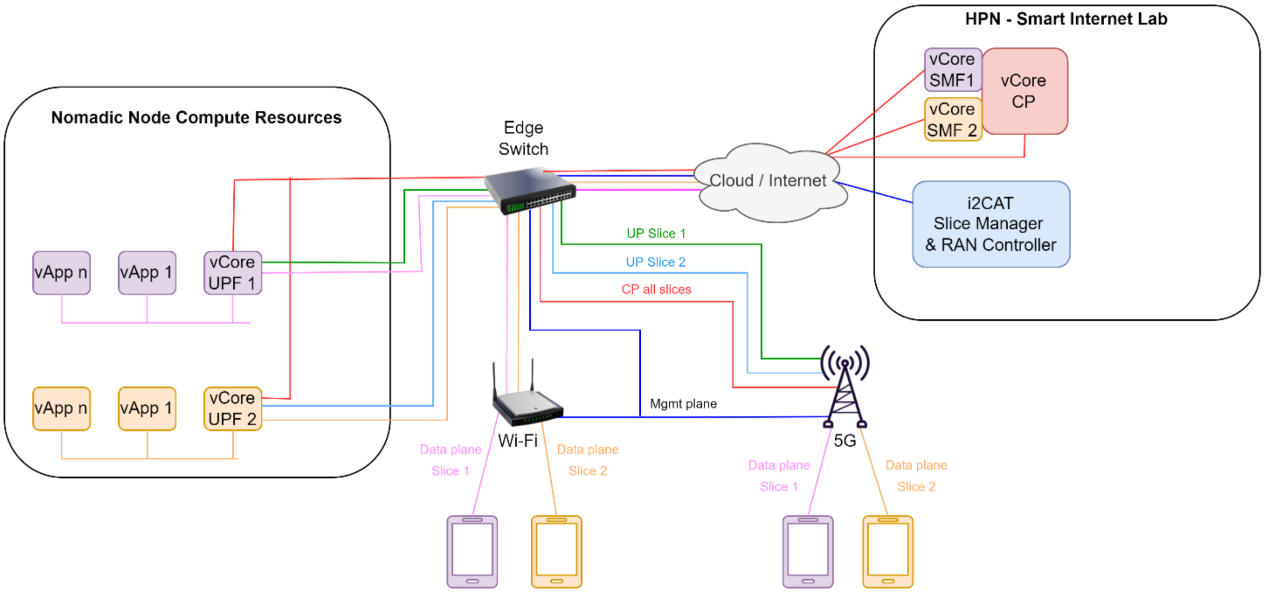


Figure 5-40 Nomadic Node architecture – Integrated 5G Core option

5.4.2 Mapping of services over the 5G architecture

In the Bristol Cluster the physical connectivity between HPN (i.e., Smart Internet Lab) and WTC (i.e., MSq), and between HPN and MShed are provided. Nomadic Node backhaul connectivity is being provided though 4G/5G. Also, the UEs' connectivity interfaces are being provided.

The HPN, MShed and WTC nodes are interconnected using dark fibre, achieving multi-gigabit throughput performance with very low latency. The Nomadic Node communicates with the rest of the network via a wireless link. An in-house built CPE device with multi-access technology will be used to provide the required backhaul connectivity to the Nomadic Node using Multipath TCP (MPTCP) to aggregate traffic using all available network interfaces (i.e., 5G, 4G and Wi-Fi).

Different services over the 5G network in Bristol Custer are presented. As it can be seen in Figure 5-40, the service associated to applications (i.e. App1, App2, and App3) are providing at edges at HPN, MShed, WTC, and Nomadic node. They are under the orchestration and management of 5G-VIOS where the edge Proxy provides interfaces between each of the location.

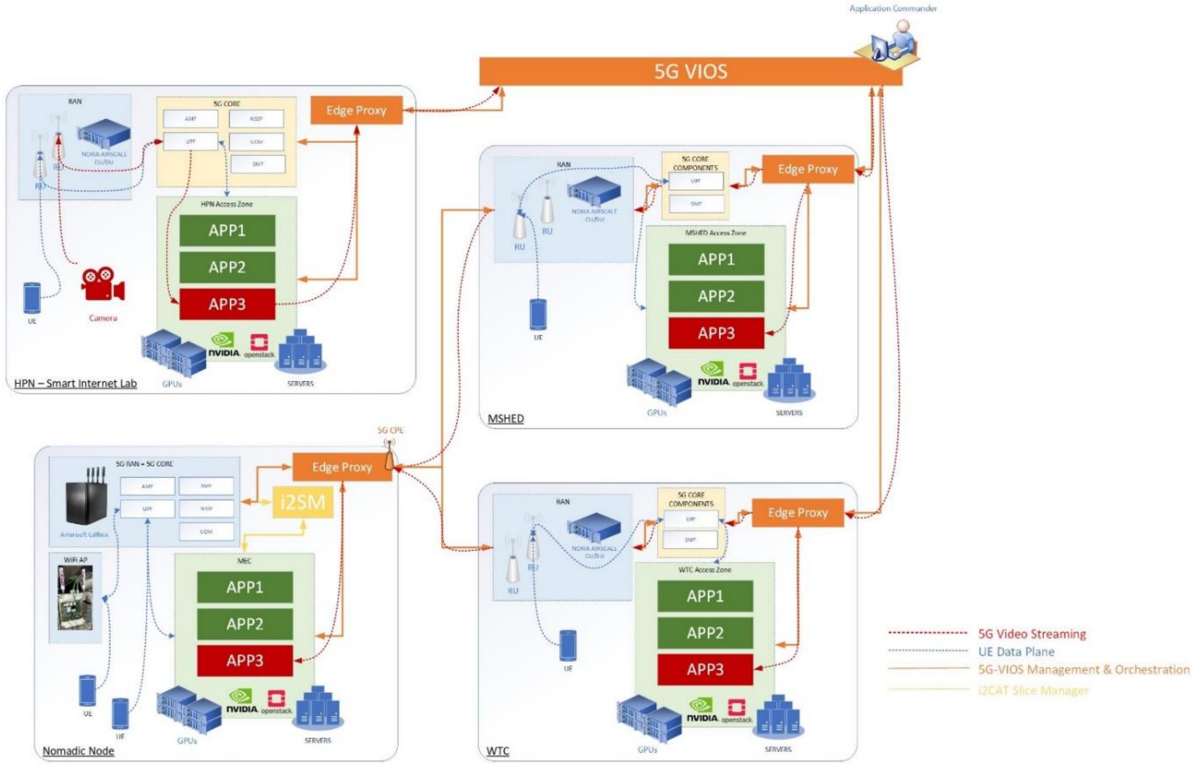


Figure 5-41 Services over 5G-UK Bristol Custer.

5.4.3 Interfaces

- **Physical Interfaces**: According to Figure 5-41, three physical interfaces are deployed Bristol Cluster.

Table 5-3 Physical Interfaces across sites

Interface Name	Component's connectivity	Description
M-shed-HPN	Edge core 10G Switch	10G Switches are already deployed at M-shed and HPN at smart Internet Lab to provide physical link connectivity between the core cloud and edge node at M-Shed.
WTC-HPN	Edge core 10G Switch	10G Switches are already deployed at WTC to provide physical link connectivity between the core cloud at HPN in smart Internet Lab and edge node at WTC.
Nomadic Node Backhaul	4G/5G connectivity	To provide Nomadic Node connection to HPN at Smart Internet Lab.

- **Logical interfaces** have been deployed between the 5G-VIOS and edges and Nomadic nodes. Figure 5-41 illustrates the logical interface between 5G-VIOS and edge nodes including Nomadic node, where the Table 5-4 includes their details. As Assume the Edge Proxy is part of the 5G-VIOS. The 5G-VIOS 'core' connects to the Edge Proxy through the interfaces which are included in Table 5-5. Meanwhile, we assume there is a routable address from 5G-VIOS to the Edge Proxy.

Table 5-4 Logical Interfaces between 5G-VIOS and Edges at Bristol Cluster

Interface Name	Description
VIOS-Nomadic	Provides connectivity between 5G-VIOS and the Nomadic node.
VIOS-MShed	Provides connectivity between 5G-VIOS and the edge node at MShed.
VIOS-WTC	Provides connectivity between 5G-VIOS and the edge node at WTC.
VIOS-HPN	Provides connectivity between 5G-VIOS and the HPN at Smart Internet Lab.

Table 5-5 Logical Interfaces between 5G-VIOS Edge Proxy and Bristol Cluster edge facility components

Interface Name	Description
OSM NBI	Connect the local orchestrator (OSM) with edge proxy
Zetta-NBI	Connect Zetta NetOS with edge proxy
5GC-NRF	Connect 5GC NRF with edge proxy
5GC-NEF	Connect 5GC NEF with edge proxy
I2CAT-API	Connect i2CAT slice manager with edge proxy
Profiling-API	Connect the edge profiling with the edge proxy
Monitoring-API	Connect the edge monitoring with the edge proxy

5.5 Cross-facility services

5G-VICTORI will offer the necessary tools in order to provide services across the different facilities involved in the project. In the context of the project, two inter-cluster scenarios are considered based on the Vertical application deployment options discussed in Section 5. These inter-cluster scenarios will be evaluated in deliverable D4.3 at the end of the project.

- **Patras-Bristol**

The Patras – Bristol UC focuses on the provisioning of a 360° VR Multi-camera Live stream that will be concurrently delivered to students located at the University of Patras and at the University of Bristol. The training class will be hosted at the University of Bristol where 360' cameras connected through Ethernet will be used at the University of Bristol to record lectures. Students located both at Bristol and Patras facilities will be able watch the stream through 5G-capable VR-headsets. To implement this UC, the Vertical application (AS) is hosted in DNs located at both facilities while the AF is hosted in 5G-VIOS. The central cloud is used to provide the necessary resources for the creation of the content (360° cameras and video recording) while the edge compute nodes provide caching functionalities. The corresponding diagram is shown in Figure 5-42. The AF provides the application logic and offers functionalities related to user authentication, software key licensing and optimal content placement,

Users placed at the different facilities get access to the cached content through their local 5G networks. Central cloud and MEC nodes are interconnected over a controlled IP network. The relevant connectivity is established through 5G-VIOS.

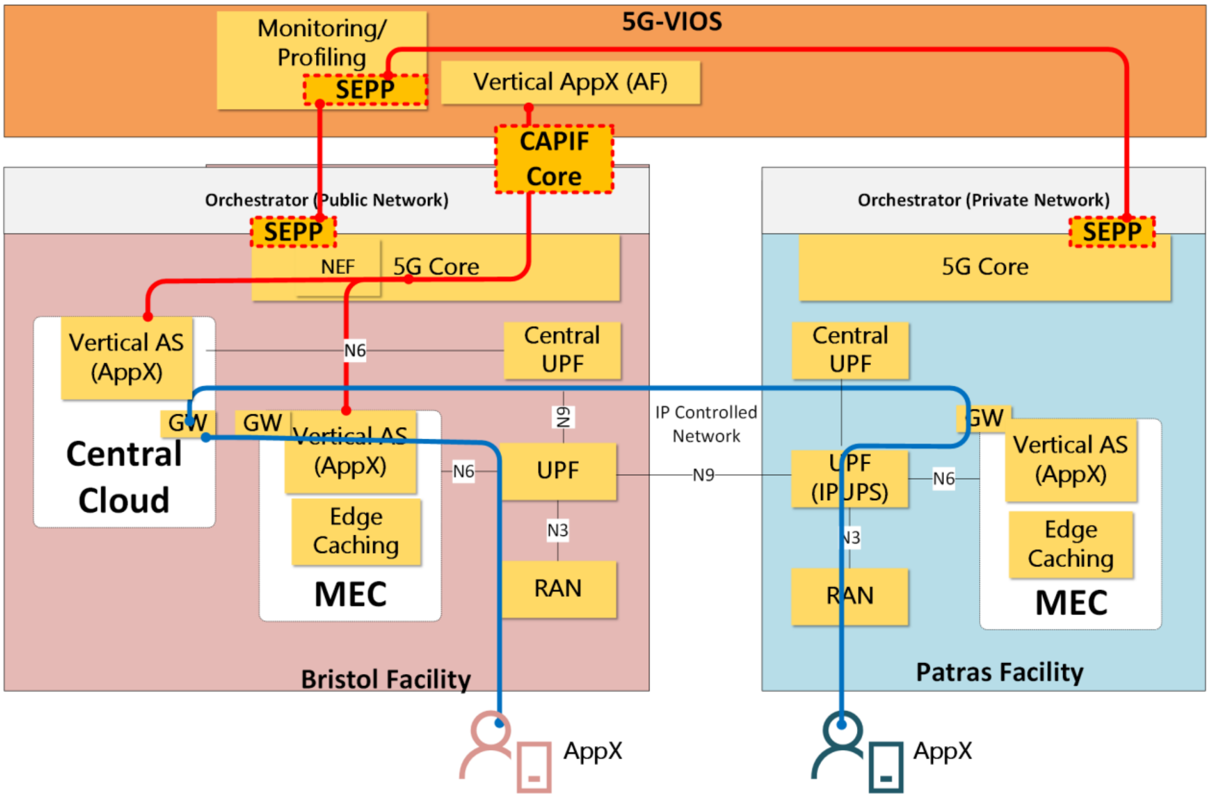


Figure 5-42 5G-VICTORI used to provide a Vertical app hosted in a single location

Specifically, the data traffic related to the MEC of AppX is offloaded through the local UPFs of the two facilities towards the central cloud of Bristol facility. The AS of 360VR service operating in Patras is connected directly via a controlled IP network to the AS of the central cloud facility in Bristol. The controlled IP network is established by means of local 'pairing' links between operators' premises. The local 'pairing' links are terminated by GWs that can play the role of border GWs to DNs and can have some functionality (e.g. NAT GW functionality) supporting inter-domain connectivity over the controlled IP network [16]. In Bristol, connectivity between the local AS and the central cloud is provided through the local orchestrator.

- **Berlin-Bristol**

This scenario follows the deployment option 1 of Section 4.3. Specifically, we assume that the user is initially located in Berlin. The Berlin facility (Figure 5-43) has a MEC platform (DN) hosting the Vertical application provided by UHA. The control of the UHA application (AS functionality) is hosted in 5G-VIOS. The remaining functionalities of the 5G-VIOS are not depicted for simplicity purposes. Network metrics and statistics are exposed by each facility to the monitoring and network analytics modules of 5G-VIOS through SEPP. The CAPIF core functionalities (publish of service APIs, discovery of service APIs and charging of service APIs invocations, etc. [10]) are provided by 5G-VIOS and through this interface the AF of UHA application can be reached. Based on the collected measurements and the QoE of the Vertical application the AF assists in traffic routing, steering and MEC selection process. Specifically, when the user is located at Berlin facility, it contacts the SMF of the Berlin facility to steer traffic to the local MEC. However, as the user moves to the Bristol facility analytics modules hosted in 5G-VIOS take actions (notifies the public SMF) in order to migrate the UHA application to the server of the Bristol facility.

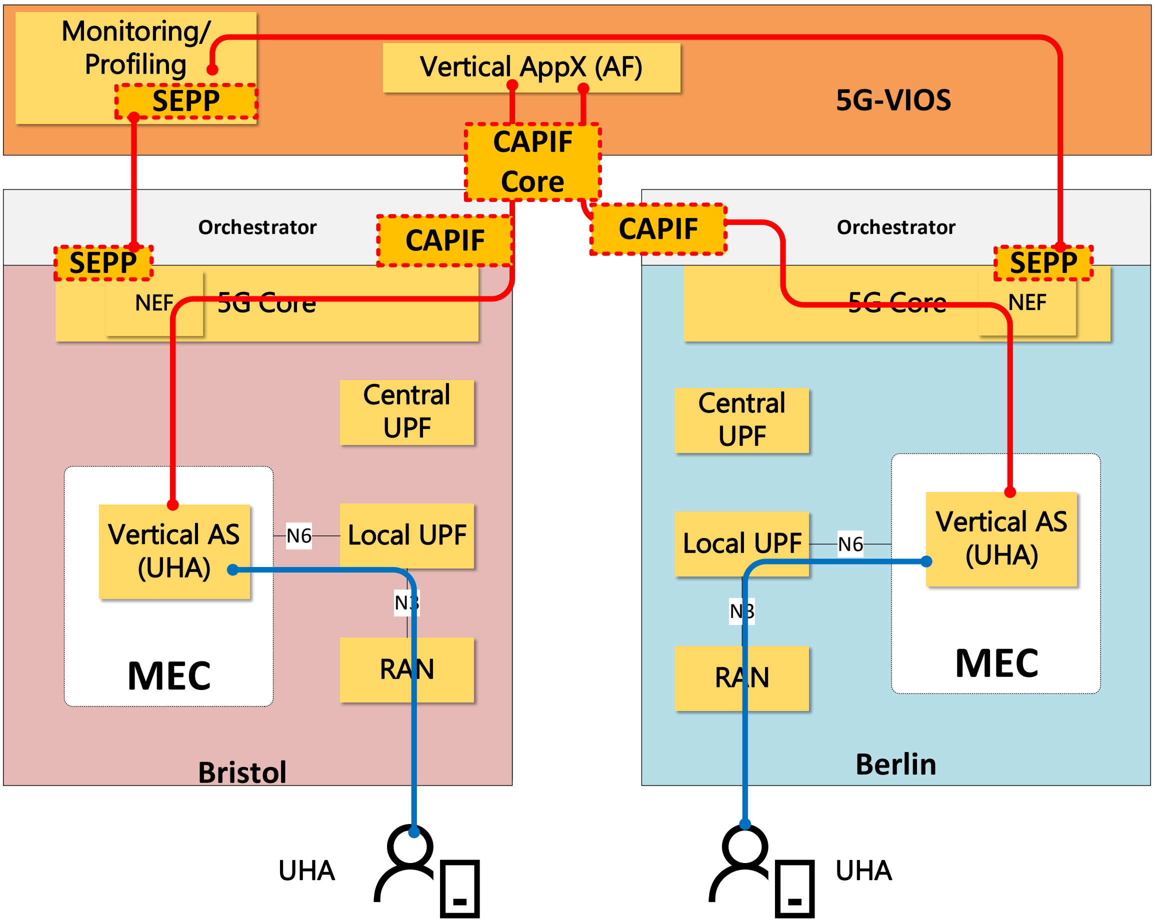


Figure 5-43 5G-VICTORI used to provide a Vertical apps.

6 Conclusions

In support of the overall 5G vision aiming to offer services to a variety of Vertical industries, and to support new business models and opportunities, 5G-VICTORI has proposed a novel architectural approach to facilitate a 5G platform with increased functionality and flexibility. The proposed approach aims to transform traditionally closed, static and inelastic network infrastructures into open, scalable and elastic ecosystems that can support a large variety of dynamically varying applications and services.

5G-VICTORI adopting a flexible 5G architecture and a variety of advanced 5G technologies comprising and integrating together commercially available solutions, open source platforms and innovative technologies developed in the framework of the project addresses large-scale trials for advanced UC verification in commercially relevant 5G environments. These large scale trials will be executed in operational environments in a number of 5G platforms across Europe and for a number of verticals, while some specific use cases (UCs) will be involving cross-Vertical interaction. The project exploits extensively the existing ICT-17 5G Testbed Infrastructures interconnecting main sites of the 5G-VINNI, 5GENESIS, 5G-EVE and the 5G UK testbed in a Pan-European Network Infrastructure. Intensive 5G-VICTORI activities have focused on extending and upgrading these existing infrastructures to enable integration of the verticals' commercially relevant, operational environments. This activity has been key towards the demonstration of the large variety of 5G-VICTORI Vertical and cross-Vertical UCs focusing on **Transportation**, **Energy**, **Media** and **Factories of the Future**.

This document summarises the requirements that the 5G-VICTORI infrastructure aims to support focusing on the "Business level use cases and requirements" as well as the 5G-VIOS architectural requirements. Detailed service-, technology- and deployment- specific requirements have been already provided and discussed in detail in deliverable D2.1.

In addition, this deliverable report provides an overall description of the 5G-VICTORI functional architecture focusing on the functionalities, features and characteristics that the 5G-VICTORI platform is designed to offer. Following this a detailed description of the overall project 5G E2E reference architecture used for the instantiation and integration of the various verticals and corresponding infrastructures at the different facility locations is provided. The proposed and adopted flexible network architecture has been inspired by standardised 5G architectural approaches (ETSI, 3GPP, IEEE and O-RAN) adding to these innovative features. A key innovation relates with the concept of the functions repository to enable service provisioning in support of Vertical UC requirements. This functions repository allows verticals to define and implement their own functions as well as access and deploy other functions developed by other verticals available in the same repository. Another architectural innovation is the introduction of a thin inter-domain orchestration layer that resides on top of the orchestration solutions of the individual facility referred to as 5G-VIOS. This orchestration layer enables dynamic inter-site connectivity, inter-domain orchestration and on-boarding of inter-domain services as well as E2E slice monitoring and management for the deployed E2E services. These capabilities enable a common platform over which a variety of Vertical industries are able to provide, independently and in isolation, their service offerings deploying resources and functions available through the common 5G-VICTORI infrastructure and function repository.

This document also provides the details of the various project architectural deployment options at the different facility locations i.e. the specific 5G architectures adopted at each of the 5G-VICTORI facility infrastructures (5G-VINNI, 5GENESIS, 5G-EVE and the 5G UK testbed). This information includes description of the specific architectural structures, platforms and technologies deployed per facility, provides insight on how the Vertical services that will be demonstrated per facility as part of the planned UCs are mapped over the available 5G infrastructures and some discussion on the required interfaces.

The deployment option of the **Patras** facility involves deployment of a RAN based on the Amarisoft SA 5G solution and a CN. The 5GCN comprises a set of NFs available through the Open5GCore developments performed by the Berlin cluster deployed at the central cloud facility of the Patras5G, which enables connection of mobile users and wireless devices (UEs). The 5GCN comprises all necessary functions that manage all mobile voice, data and internet connections. Various wired/wireless technologies are deployed in the transport network and depending on the UC, edge cloud capabilities are also provided. The detailed 5G architecture has been designed to address the needs of the UCs planned to be demonstrated in Patras. The services that will be demonstrated have been mapped over the Patras5G infrastructure, and include: low latency services with flexible 5G architecture (Smart Factory), eMBB services under high speed mobility and CDN services at the station for Media services.

The deployment option of **Berlin** includes four 5G nodes comprising the UEs, the RAN, the 5GCN and the DN. The UEs are commercially available smartphones or CPE devices capable of connecting with the 5G SA network over 5G NR utilising a band in the 3.7-3.8 GHz range allowed in Germany. The RAN consists of commercially available gNodeBs utilising the 5G SA architecture. The base 5GCN deployment comprises the following NFs: NRF, AMF, SMF, AUSF, UDM and UPF. The interfaces required to support the demonstration activities are also discussed. The services that will be demonstrated and have been mapped over the Berlin 5G infrastructure include: Rail Signaling and CCTV services over 5GCN, and CCTV via the 5GCN.

The 5G deployment in the **FR/RO** cluster is based on the OAI 5G Stack implemented in the Orange facility, based on the integrated radio, CN software and hardware components for 5G NSA and SA systems. The 5GCN of the OAI stack provides the following components: AMF, SMF, NRF, NSSF, AUSF, UDM, UDR and UPF and supports some basic procedures such as the registration, de-registration as well as the PDU session related procedures including session establishment, modification and release. At the moment, multiple UEs can be attached to the OAI 5GCN and establish multiple PDU sessions at the same time. The 5G NSA Architecture is already implemented. The services that will be demonstrated and have been mapped over the FR/ORO 5G infrastructure include: Digital Mobility Services and Energy metering.

The **5G UK** testbed involves four interconnected key locations. The deployed 5G architecture involves a 5G NR solution and for the 5GCN the Bristol cluster is utilising an instance of Open5GS implementing 3GPP deployments options 1 (4G SA) and 2 (5G SA). The Bristol Cluster has four edge nodes, and Nomadic node locations which offer MEC service provisioning through available computing resources. In addition, the Cloud network is based on OpenStack, with the controller node located in Smart Internet Lab. The cloud architecture consists of multiple Access Zones (AZ) which isolate the network edges and differentiate their computational resources. The services that will be demonstrated and have been mapped over the 5G UK testbed infrastructure include: seamless mobility and low latency communication for interactive class and AR/VR UCs.

Finally, 5G-VICTORI offers the necessary tools to provide services across the different facilities involved in the project. In the context of the project, two inter-cluster scenarios are considered based on the Vertical application deployment options. These include (a) a cross-facility UC between Patras and Bristol that focuses on the provisioning of a 360° VR Multi-camera live stream that will be concurrently delivered to students located at UoP and at UNIVBRIS, and (b) a cross-facility UC between Berlin and Bristol that focuses on the provisioning of an AR service available in the Berlin cluster that will be delivered to end-users in Bristol.

7 Bibliography

[1] 5G-VICTORI, “D2.2 Preliminary individual site facility planning”.

[2] 5G-VICTORI, “D2.3 Final individual site facility planning”.

[3] 5G-VICTORI, “D2.1 5G VICTORI Use case and requirements definition and reference architecture for vertical services,” 2020.

[4] ETSI, “ETSI TS 128 530 V16.2.0 (2020-08). 5G;. Management and orchestration;. Concepts, use cases and requirements. (3GPP TS 28.530 version 16.2.0 Release 16).,” 2020.

[5] 5GPPP, “5G PPP 5G Architecture WG White Paper Rev.3.0,” https://5g-ppp.eu/5g-ppp-5g-architecture-wg-white-paper-rev-3-0-for-public-consultation/.

[6] ETSI, “ 3GPP TS 28.535 version 16.5.0 Release 16 ; Management and orchestration; Management services for communication service assurance; Requirements”.

[7] ETSI, “ETSI 22.261 Service requirements for the 5G system (2022)”.

[8] ETSI, “ETSI TS 28 550 Management and orchestration; Performance assurance (16.8.0) 2021”.

[9] 5G-VICTORI, “D2.6 5G-VICTORI Infrastructure Operating System – Final Design Specification (2021)”.

[10] ETSI, “ETSI TS 123 222 V16.9.0 (2020-10). LTE;. 5G;. Common API Framework for 3GPP Northbound APIs. (3GPP TS 23.222 version 16.9.0 Release 16).”.

[11] “O-RAN ALLIANCE,” [Online]. Available: https://www.o-ran.org/.

[12] “Network Exposure Function,” [Online]. Available: https://www.nokia.com/networks/products/network-exposure-function/.

[13] ETSI, “3GPP TS 33.535; Authentication and Key Management for Applications (AKMA) based on 3GPP credentials in the 5G System (5GS). (3GPP TS 33.535 version 16.2.0 Release 16”.

[14] ETSI, “ETSI 33.501; Security architecture and procedures for 5G System (17.5.4) 2022”.

[15] ETSI, “5G; Common API Framework for 3GPP Northbound APIs; 3GPP TS 29.222 version 15.3.0 Release 15”.

[16] MEC, “5GAA A-200150; MEC for Automotive in Multi-Operator Scenarios; 2021”.

[17] 5G Patras, [Online]. Available: http://wiki.patras5g.eu/.

[18] “Open5GCore | Fundamental 5G Core Network Functionality,” [Online]. Available: https://www.open5gcore.org/open5gcore/fundamental-core-functionality.

[19] Larsen, “L. M. P. Larsen, A. Checko and H. L. Christiansen, "A Survey of the Functional Splits Proposed for 5G Mobile Crosshaul Networks," in IEEE Communications Surveys & Tutorials, vol. 21, no. 1, pp. 146-172, Firstquarter 2019, doi: 10.1109/COMST.2018.2868805.”.

[20] “5G-PICTURE,” [Online]. Available: https://www.5g-picture-project.eu.

[21] Karamichailidis, “P. Karamichailidis et al. “Session Management across Heterogeneous Wireless Technologies in a Rail Transport Environment”, proc. of IEEE 5G for CAM 2021, IEEE 5G Virtual Summit”.

[22] OAI, [Online]. Available: https://gitlab.eurecom.fr/oai/openairinterface5g/-/wikis/OpenAirFeatures .

[23] ETSI, “ETSI TS 138 473 V16.3.1 (2020-11). 5G;. NG-RAN;. F1 Application Protocol (F1AP). (3GPP TS 38.473 version 16.3.1 Release”.

[24] ETSI, “ Universal Mobile Telecommunications System (UMTS); LTE; 5G; General Packet Radio System (GPRS) Tunnelling Protocol User Plane (GTPv1-U) (3GPP TS 29.281 version 17.2.0 Release 17)”.

[25] EURECOM, [Online]. Available: https://gitlab.eurecom.fr/oai/cn5g/oai-cn5g-amf/-/blob/master/docs/FEATURE_SET.md .

[26] 5G-VICTORI deliverable, “D3.3 "Preliminary Use case specification for Media Services",” 2021.

[27] 5G-VICTORI deliverable, “D3.5 "Preliminary Use case specification for Energy and Factories of the Future Services",” 2021.

[28] 5G-VICTORI, “D2.5 5G-VICTORI Infrastructure Operating System – Initial Design Specification”.

[29] “Open5GS | Open source project of 5GC and EPC,” https://open5gs.org/.

[30] S. Dräxler, H. Karl, H. Razzaghi Kouchaksaraei, A. Machwe, C. Dent-Young , K. Katsalis and K. Samdanis, “5G OS: Control and Orchestration of Services on Multi-Domain Heterogeneous 5G Infrastructures,” in *European Conference on Networks and Communications (EUCNC2018)*, 2018.

[31] ETSI, “ETSI TS 122 104 V16.5.0 (2020-09). 5G;. Service requirements for cyber-physical control applications in vertical domains”.

[32] “Open5GCore | Network Slicing Support,” [Online]. Available: https://www.open5gcore.org/.

[33] ETSI, “TS 22.280: "Mission Critical Services Common Requirements (MCCoRe); Stage 1".”.

[34] ETSI, “3GPP TS 23.379: "Functional architecture and information flows to support Mission Critical Push To Talk (MCPTT); Stage 2".”.

[35] ETSI, “3GPP TS 23.281: "Functional architecture and information flows to support Mission Critical Video (MCVideo); Stage 2".”.

[36] ETSI, “3GPP TS 23.282: "Functional architecture and information flows to support Mission Critical Data (MCData); Stage 2".”.

[37] ETSI, “TS 23.503 – Stage 2 Policy Control and Charging for 5G System”.

[38] ETSI, “TS 23.502 – Stage 2 Procedures and flows for 5G System”.

[39] open5gs, [Online]. Available: https://open5gs.org/open5gs/docs/guide/01-quickstart/.

[40] 5G-XHaul Project, “Deliverable D3.2”.

8 Acronyms

8.1 H2020 specific

Acronym	Description
5G-EVE	5G European Validation platform for Extensive trials, https://www.5g-eve.eu
5G-VICTORI	Vertical demos over common large scale field trials for rail, energy and media industries, https://www.5g-victori-project.eu
5G-VINNI	5G Verticals Innovation Infrastructure, https://www.5g-vinni.eu
5GENESIS	5G End-to-end Network, Experimentation, System Integration, and Showcasing, https://5genesis.eu
5GUK	The 5GUK Test Network, http://www.bristol.ac.uk/engineering/research/smart/5guk/
5G-PICTURE	5G Programmable Infrastructure Converging disaggregated neTwork and compUte Resources, https://www.5g-picture-project.eu/
H2020	Financial instrument implementing the Innovation Union, a Europe 2020 initiative aimed at securing Europe's global competitiveness.
ICT-17	H2020 5G-PPP 5G trial platforms, e.g. 5GENESIS, 5G-EVE and 5G-VINNI

8.2 5G and Open5GCore Specific Interfaces

Acronym	Description
5GMM	5G Mobility Management
Cx	Open5GCore interface for Diameter protocol IMS user authentication
F1	Inter-connection of a gNB-CU and a gNB-DU supplied by different manufacturers
N1	Non-Access Stratum signaling (UE - CN)
N2	Access Stratum signaling (RAN - CN)
N3	RAN - UPF data plane
N32	Forwarding interface between the SEPPs
N33	Interface between AF and NEF
N4	UPF - SMF signaling (PFCP protocol)
N5	Interface between PCF and an Application Function (AF)
N6	UPF (IP anchor) – Data Network
N9	UPF – UPF (interconnects UPF instances)
O1	Interface between management entities in SMO Framework and O-RAN managed elements
Rx	Open5GCore interface Diameter protocol translator between Rx and N5
S1	Connects the eNB to the EPC

8.3 General

Acronym	Description
3GPP	3rd Generation Partnership Project, https://www.3gpp.org
4G	4th Generation mobile network technology
5G	5th Generation 3GPP defined cellular network
5G-IA	5G Infrastructure Association

5G-PPP	5G Public-Private Partnership
5GC	5G Core
5GCN	5G Core network
5GS	5G System
5GN	5G Network
5G-VIOS	5G-VICTORI Operation System
AF	Application Function
AI	Artificial Intelligence
AMF	Access and Mobility Function
API	Application Programming Interface
AP	Access Point
AR	Augmented Reality
AS	Application Server
AUSF	Authentication Server Function
AZ	Availability Zone
BBU	Baseband Unit
BH	Backhaul
BSS	Business Support System
CAPIF	Common API Framework
CCTV	Closed Circuit Television
CDN	Content Delivery Network
CN	Core Network
CNF	Containerized Network Function
CP	Control Plane
CPE	Customer Premises Equipment
CSP	Communication Service Provider
CU	Central Unit
CUPS	Control-/User Plane Separation
DB	Database
DN	Data Network, aka Server Network
DCSP	Datacentre Service Provider
DDoS	Distributed Denial of Service
DHCP	Dynamic Host Configuration Protocol
DL	DownLink
DMVPN	Dynamic Multipoint Virtual Private Network (VPN)
DN	Data Network
DPDK	Data Plane Development Kit (DPDK)
DSP	Digital Service Provider
DU	Distributed Unit
E2E	End-to-End
eMBB	enhanced Mobile BroadBand
EMS	Energy Management System
eNB	Evolved Node B

EN-DC	E-UTRAN New Radio – Dual Connectivity
EPC	Enhanced Packet Core
ETSI	European Telecommunications Standards Institute
E-ULTRAN	Evolved-UMTS Terrestrial Radio Access Network
F1AP	F1 application protocol
FlexCN	Flexible CN controller
FlexRIC	Flexible O-RAN compatible RAN Intelligent Controller
FQDN	Fully Qualified Domain Name
gNB	gNodeB is the 5G radio base station
GTP	General Packet Radio Service (GPRS) Tunneling Protocol
GTP-U	GPRS Tunneling Protocol - User plane
GUI	Graphical User Interface
GW	Gateway
H.264	Video codec, Advanced Video Codec (AVC)
H.265	Video codec, High Efficiency Video Coding (HEVC)
HTTP	Hypertext Transfer Protocol
HTTP2	Hypertext Transfer Protocol 2
HV	High Voltage
HW	Hardware
ICT	Information and communications technology,
ICM	Inter-edge Connectivity Manager
IEEE	Institute of Electrical and Electronics Engineers, https://www.ieee.org
IMS	IP Multimedia Subsystem
IMSI	International Mobile Subscriber Identity
IoT	Internet of Things
IP	Internet Protocol
IPUPS	Inter-PLMN UP Security
IPv4	Internet Protocol version 4
JPEG	Joint Photographic Experts Group
JSON	JavaScript Object Notation
K8s	Kubernetes
KPI	Key Performance Indicators
L2	Data Link Layer
L3	Signalling network functions Layer
LAA	Licensed-Assisted Access
LCM	Life-Cycle Management
LLC	Low Latency Communications
LTE	Long Term Evolution Standard
LV	Live Voltage
M12	Round connector with a 12-millimeters locking thread
M5G	Mosaic 5G
MAC	Medium Access Control
MANO	Management and Orchestration

MEC	Mobile Edge Compute
MGMT	Management Interface
mIoT	massive Internet of Things
ML	Machine Learning
M-MIMO	Massive Multiple Input- Multiple Output
mMTC	massive Machine-Type Communications
MPTCP	Multipath Transmission Control Protocol (TCp)
MQTT	MQ (messaging and queuing) Telemetry Transport
N77	3.7 GHz 5G band, or C-band 5G
N78	3.5 GHz 5G band, or C-band 5G
NAS	Non-access stratum
NAT	Network Address Translation
NB-IoT	NarrowBand-Internet of Things
NBI	NorthBound Interface
NEF	Network Exposure Function
NETCONF	network Configuration Protocol
NF	Network Function
NFV	Network Function Virtualization
NFVO	Network Function Virtualization Operator
NG	Next Generation
NGAP	Next Generation Application Protocol
NOP	Network Operator
NR	New Radio
NRF	Network Repository Function
NS	Network Slice
NSA	Non-Standalone
NSaaS	Network Slice as a Service
NSMF	Network Slice Management Function
NSSAI	Network Slice Selection Assistance Information
NSSF	Network Slice Selection Function
NSSMF	Network Slice Subnet Management Function
NWDAF	NetWork Data Analytics Function
OAI	OpenAirInterface, https://www.openairinterface.org
OAI-CN	OpenAirInterface-Core Network
OAI-RAN	OpenAirInterface-Radio Access Network
OAM	Operations, Administration and Maintenance
OEM	Original Equipment Manufacturer
ONOS	Open Network Operating System, https://opennetworking.org/onos/
Open5GCore	The Fraunhofer FOKUS Open5GCore toolkit, https://www.open5gcore.org
Open5GS	Open Source Project for 5GC and EPC, https://open5gs.org/
O-RAN	Open Radio Access Network
OSM	Open Source MANO
OSS	Operations Support System

P4	Programming Protocol-Independent Packet Processors Language
PCF	Policy Control Function
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PDU	Protocol Data Unit
PFCP	Packet Forwarding Control Protocol (TS 29.244)
PHY	Physical Layer
PLMN	Public Land Mobile Network
PM	Performance Measurement
PoE	Power over Ethernet
PTP	Precision Time Protocol (IEEE 1588v2)
QAM	Quadrature Amplitude Modulation
QFI	Quality of Service Flow Identifier
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
REST	Representational State Transfer
RFSP	RAT/Frequency Selection Priority
RJ45	Registered Jack-45
RLC	Radio Link Control
RMS	Railway Management System
RRU/RU	Remote Radio Unit
RTT	Round Trip Time
SA	Stand-Alone (=5G supporting signaling)
SBA	Service Based Architecture
SBI	Service Based Interfaces
SBR	Service Broker
SC	Service Customer
SDF	Service Data Flow
SDK	Service Development Kit
SDN	Software Defined Networking
SDR	Software-Defined Radio
SEPP	Security Edge Protection Proxy
SLA	Service Level Agreement
SM	Service Management
SMF	Session Management Function
SMO	Service Management and Orchestration
S-NSSAI	Single Network Slice Selection Assistance Information
SP	Service Provider
SPGWU	User Plane of the Packet Data Network Gateway
SST	Slice/Service Type
SW	Software

TCP	Transmission Control Protocol
TDD	Time Division Duplex
UC	Use Case
UDM	Unified Data Management
UDP	User Datagram Protocol
UDR	Unified Data Repository
UE	User Equipment
UL	UpLink
UP	User Plane
UPF	User Plane Function
uRLLC	ultra-Reliable Low Latency Communications
UTP	Unshielded Twisted Pair
vEPC	Virtual Enhanced Packet Core
VIM	Virtualized Infrastructure Manager
VISP	Virtualisation Infrastructure Service Provider
VLAN	Virtualized Local Access Network
VM	Virtual Machine (for example running on VMware)
VoD	Video on Demand
VPN	Virtual Private Network
VNF	Virtual Network Function
VR	Virtual Reality
vRAN	virtualized Radio Access Network
Wi-Fi	Wireless Fidelity
WTC	We The Curious
X2-C	X2 control-plane is between eNodeBs for transmitting signaling
xApp	Intelligent Network Applications