5GPPP Architecture Working Group

View on 5G Architecture

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Abstract

The overall goal of the Architecture Working Group (WG) within the 5GPPP Initiative is to consolidate the main technology enablers and the bleeding-edge design trends in the context of the 5G Architecture. As a result, it provides a consolidated view of the architectural efforts developed in the projects part the 5GPPP initiative and other research efforts, including standardization. This effort serves not only to review the current state of the art, but also to identify promising trends towards the next generation of mobile and wireless communication networks, namely, 6G.

This is the fourth release of this white paper, whose beginning dates back in July 2016, when the first version was released. Since then, this effort continuously captured the technology trends as developed by the different phases of 5GPPP projects: the first phase (Phase I), that lied the foundation of the network slicing aware operation we are seeing in these days; the second one (Phase II) which provided the first proof of concepts; and the third one (Phase III) that has targeted the first large scale platforms. All these efforts were captured in the subsequent releases of the white paper (version 2 in January 2018 and version 3 in February 2020).

This current version 4 of the white paper hence is focusing on the output of the Phase III projects, thus, discussing the latest findings in terms of the integration of large infrastructure and vertical industries, aka verticals, the long-term evolution of the 5G technologies including and the service-specific features. The view consolidated in this white paper presents the current overview on the 5G Architecture as developed by European research efforts.

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1 Introduction

The 5G system (5GS) is now openly and widely available in major urban areas, and the coverage is planned to reach less populated areas in the next few years. So, the superior performance of 5G in terms of mobile broadband, unperceivable latency, and massive connectivity for the internet of things (IoT) will be soon available to the majority of European citizens. In parallel, 5G was also developed in relevant industrial scenarios, where new use cases enabled by 5G connectivity improved the productivity and the performance of the production chain, e.g., industrial IoT (IIoT).

Meanwhile, the standardization efforts proceed at full steam: the third release of 5G (Rel. 17) has progressed substantially, and new topics of interest are currently being discussed for the next one, which will mark the start of 5G Advanced. The overall architecture, which has been continuously improved since its first release to include new aspects such as the integration of vertical services for IIoT and enhanced ultra-reliable and low-latency communications (URLLC). Currently, trends are targeting the goal of network automation, with the exposure of analytics between network functions (NFs) to automatize as much as possible the operation, especially with the use of artificial intelligence (AI) and Machine Learning (ML) algorithms. Initially stemming from the core network (CN), this trend was captured by other domains, as well, such as the management and orchestration (MANO).

Also, the quest for improved performance has put into the spotlight the need for edge technologies besides the radio access network (RAN), with the goal of providing lower latencies for very specific services, such as the automotive applications. Finally, besides the pure performance point of view, the recent advances in 5G also targeted the easiness of integration between the vertical service providers and the network operators, through the usage of NetApps and a specific Service Layer for verticals. The goal of this white paper is hence to summarize the findings from the European research landscape, including the first large scale evaluation of the 5G technologies.

The white paper is organized as follows. The overall architecture description in Chapter 2 discusses the new stakeholders in the mobile network ecosystem and how the architectural work is taking into account their requirements in all the domains of the network. Then, we move to the new findings into the specific network domains, starting from Chapter 3, which details the RAN architecture and how the new technology is supporting very low latency services at the edge. Chapter 4 describes the CN architectural aspects, with the added support to new technologies such as multicast and precise positioning. We move to the discussion of the MANO aspects in Chapter 5, with a specific view on how to provide autonomous management of network slices over a softwarized network. Chapter 6 collectively discusses new technology enablers that cannot be bounded to one domain only, targeting specific infrastructure deployments at all levels, i.e., across network domains. In particular, the very important trend set by non-public networks (NPNs), aka private networks, is discussed here. Finally, Chapter 7 briefly discusses the different projects' efforts in bringing such new architectures into practice, describing how new use cases and solutions can be effectively provided by specific architectural instantiations.

2 Overall Architecture

The third version of the 5GPPP architecture whitepaper [2-1], focused on the underlying technology including service creation. To this extend it covered the 5G System (5GS) as a whole and discussed end-to-end (E2E) network slicing, service-based architecture, Software-Defined Networking (SDN), Network Functions Virtualisation (NFV), Management & orchestration, and E2E service operations & lifecycle management as the fundamental pillars to support the 5G Key Performance Indicators (KPIs). Given the new requirements coming from new stakeholders in the 5G ecosystem that will be described in Section 2.1, the recent advances in the softwarization of the mobile network ecosystem as well as the recent releases of the relevant standards for access, core, management and orchestration, we can draw architectural trends that are captured in this version of the white paper. A further trend that is newly introduced and that is quite intrinsic is the concept of Non-Public Networks (NPN). Sometimes called a private network, an NPN provides 5G network services to a clearly defined user organisation or group of organisations and is deployed on the organisation's defined premises, such as a campus or a factory.

Owing to this architectural representation of the third version of the 5GPPP architecture whitepaper [2-1], we integrated the trends that form novel architectural aspects and which became very influential in the implementation of phase III projects of the 5GPPP. The updated architecture is depicted in Figure 2-1 below, and comprises three main areas: the verticals, the network, and the infrastructure. These can be easily mapped to the stakeholders' ecosystem discussed in Section 2.1 below.

The **Service Domain for Verticals** includes all architectural innovations that help to include the business-related considerations to the offered services (among others, e-health, robotics, or enhanced video streaming services). Here, the key role is played by two innovations which have been considered in the recent 5GPPP projects, namely: the service layer and the concept of NetApps. The service layer, which is described in Section 2.5, provides a common interface towards the management and the operation of the network, enabling the interaction between the service intelligence and the underlying network. The concept of NetApps comprises all 5G network empowered applications that build a network service, through the usage of network slices. Slices are then used to provide such network services, and encompass different network functions (including core and access functions), possibly orchestrated over different clouds.

The different functions are operated in the **Network Domain**, arranged in different slices according to the KPIs that they have to provide. Within this domain, innovations come from four areas, namely: Access (Chapter 3), Core (Chapter 4), Management and Orchestration (Chapter 5) as well as cross-domain deployment aspects (Chapter 6). While each area presents specific innovations that are discussed in the related sections, one major challenge that is currently targeted by research effort is to achieve a flexible data exchange among them.

Innovations in the **Infrastructure** domain are captured in the context of specific fields such as the NPN or drone-based access. Finally, in Chapter 7, we present architecture instantiations and network architecture validation examples.

The architecture shall natively support the quest for network automation that is achieved through control loops and the usage of artificial intelligence algorithms (the interested reader is referred to the AI/ML Whitepaper [2-30] for more details). Specifically, we identified two main loops: the first loop enabled by the service layer that is leveraged by the service provider through the NetApps to steer the behaviour of the network and the second loop that happens within the network domain, with specific modules such as the network data analytics function (NWDAF) or the management data analytics function (MDAF) designed for this purpose.

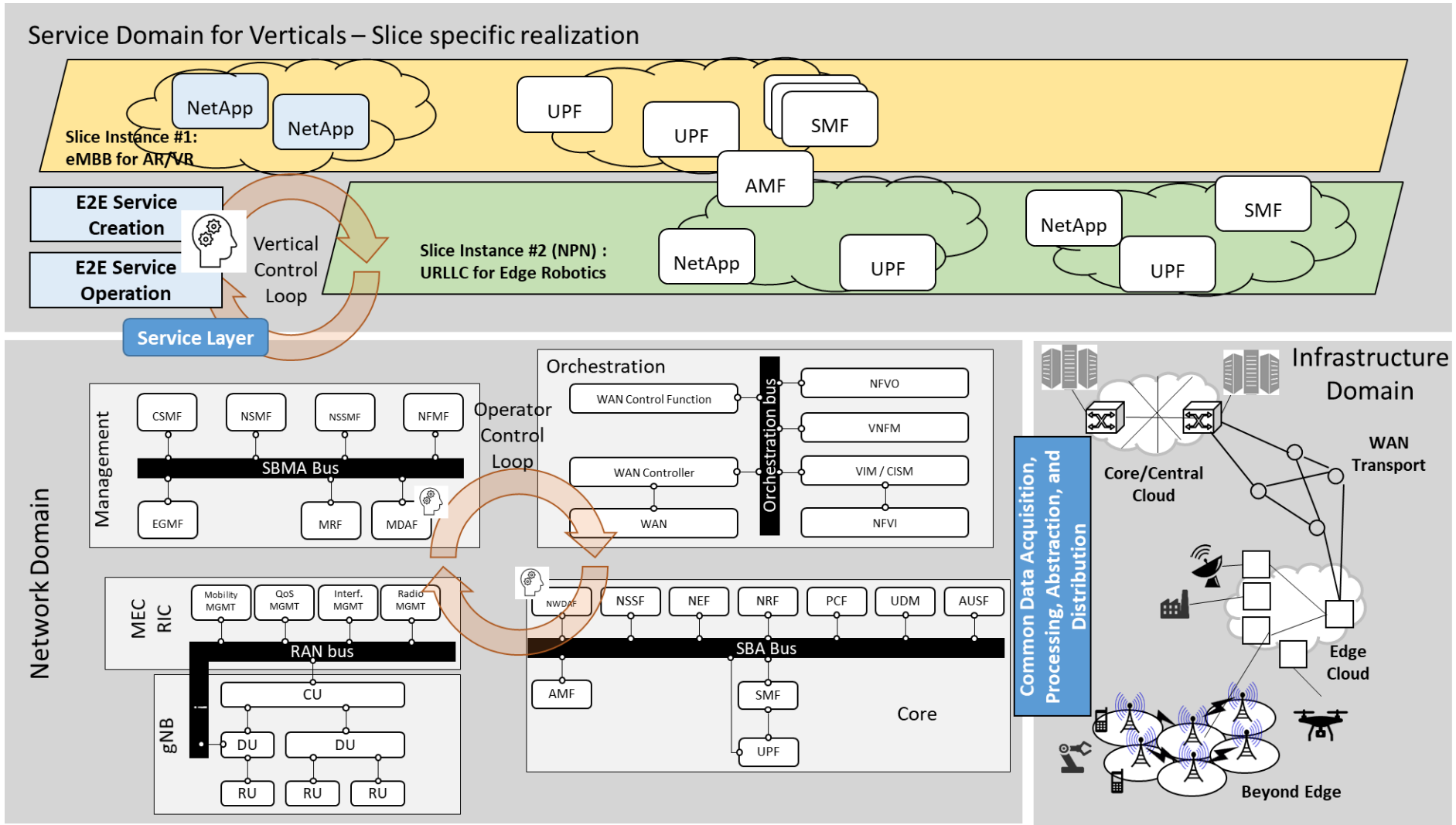

Figure 2-1: Updated Overall architecture

2.1 Stakeholders in the 5G ecosystem

Version 3.0 of the 5GPPP architecture whitepaper [2-1] described the basic stakeholder roles for provisioning 5G network services. Figure 2-2 refines this model based on the outcome of the 5GPPP Business Validation, Models, and Ecosystems Sub-Group of the Vision and Business Modelling work group [2-33]. The roles identified in Figure 2-2 can be shared between one or more stakeholders, which will assume the management of relevant interfaces at business and technical level.

A principal role in 5G service provisioning is that of the Service Provider (SP), depicted as (1) in Figure 2-2, which directly interfaces the Service Customers and obtains and orchestrates resources from Network Operators (2), Virtualisation Infrastructure Service Providers (VISP) (3) and Data Centre Service Providers (DCSP) (4) (collectively referred to as Infrastructure Providers). The role of the SP comprises the roles of Communication Service Provider (CSP) (5), entailing the activities for offering traditional telecom services, Digital Service Provider (DSP) (6), entailing the activities for offering digital services such as enhanced mobile broadband and IoT to various vertical industries, and Network Slice as a Service (NSaaS) Provider (7) – as introduced in [2-2] – entailing the activities for offering a network slice along with the services that it may support and configure.

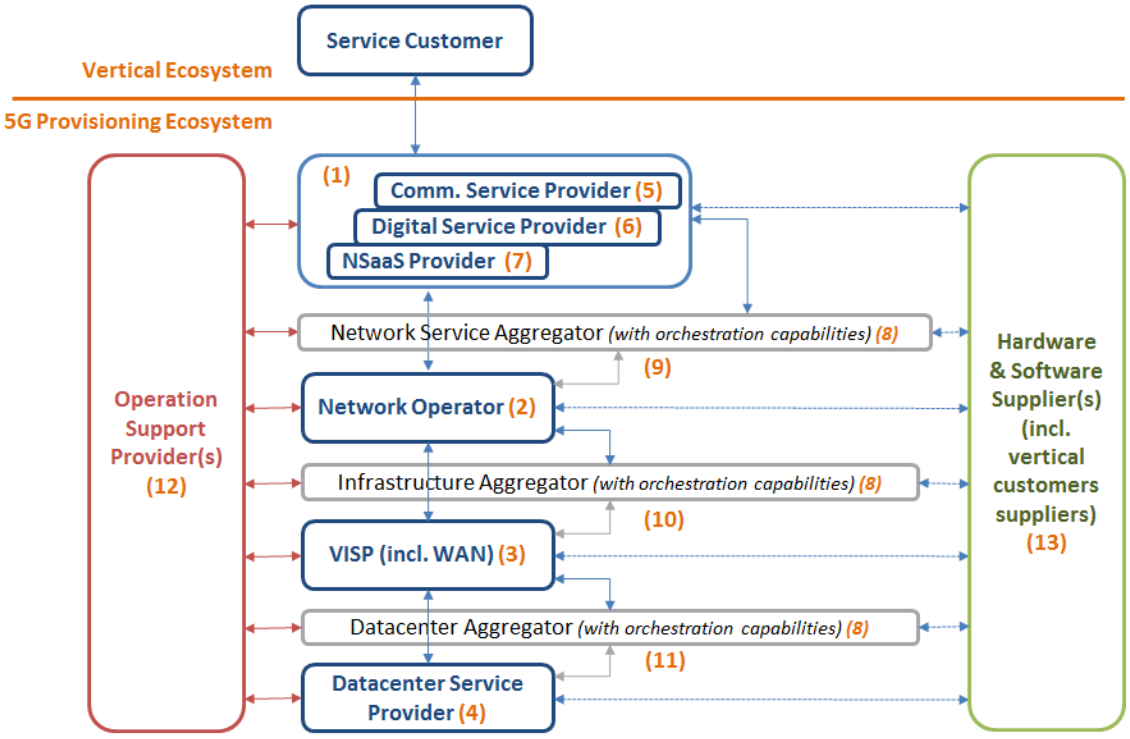

Figure 2-2: Roles in 5G provisioning systems

These roles include, among others, the business communication and business services provisioning activities towards their interfacing roles, and are technically related to BSS/OSS systems interfacing the virtual or actual infrastructure resources, operated and maintained by the actor performing the Network Operator role. The Network Operator role is now shifting towards operating a programmable network infrastructure, spanning from the radio and/or fixed access to the edge, transport and core network, and is extended to include the operation of virtual resources leased by other Infrastructure Providers through appropriate APIs. To this end, a clearly distinct new role that needs to be filled in 5G provisioning is that of VISP (3), which offers virtualised

network or cloud/edge computing resources available through APIs, and DCSP (4) which offers raw computing resources. In the IT world, these roles correspond to cloud and data centre providers, respectively.

Additional roles can be identified, such as the Service Aggregators at various layers, i.e., the Network Service Aggregator, the Infrastructure Aggregator and the Datacentre Aggregator (8), or the Spectrum Aggregator, having business relationships with several spectrum license owners in order to share spectrum more cost efficiently and in a flexible way. The role of Network Service Aggregator can undertake the activities of service provisioning across multiple network operators required, e.g., in cross border, or in multiple private and public network environments.

A high interaction is expected between pure IT and Systems' roles, namely the roles of HW and SW suppliers (13) and Operation Support Providers (12) and the roles of 5G resource provisioning, (1) to (11), as presented in Figure 2-2. Finally, and since 5G resource provisioning will be performed on a per vertical application and service deployment basis, the roles of Application Provider (AP) and System Provider to vertical customers (included in (12) and (13)) are considered part of the 5G ecosystem.

2.1.1 Impact of Non-Public Networks on the actor role model

The current 5G-PPP actor role model is focused on the provision of public services. However, the Non-Public-Network (NPN) ecosystem introduces significant changes considering the involvement of resources with multiple access technologies as an integral part of the E2E service delivery, as well as the interoperation of private and public network infrastructures for the deployment and operation of non-public services. To reflect these novelties, the original 5G-PPP actor role model is extended as illustrated in Figure 2-3.

The private and public roles are decoupled, to keep in-house management and orchestration separated from the provisioning activities executed on the PLMN. This decoupling ensures the private network can be operated independently of the PLMN, facilitating the realization of standalone NPN [2-34]. For PNI-NPN scenarios, the network service aggregator oversees providing the necessary means for the public-private network integration. At the same time additional roles are defined in the private administrative domain, which allow for dealing with the on-premise operational aspects. These new roles are:

- WAT service provider: it allows for indoor coverage using one or more wireless access technologies (WAT's), including 3GPP 5GNR and non-3GPP wireless technologies (e.g., Wi-Fi and Li-Fi).
- WAT aggregator: it allows federating different WAT's together, for an unified and consistent management of wireless resources when used in conjunction (e.g. for bandwidth aggregation, enhanced reliability, etc.).
- DSCP (on-premise edge): provides infrastructural services in local environments, leveraging the use of edge clusters. These clusters are built out of small-scale servers, sized for local execution and typically provisioned with hardware acceleration solutions. This constitutes a key difference with respect to the commodity servers in the data centers, thus establishing a clear demarcation point with respect traditional DSCP (core cloud, telco edge cloud).

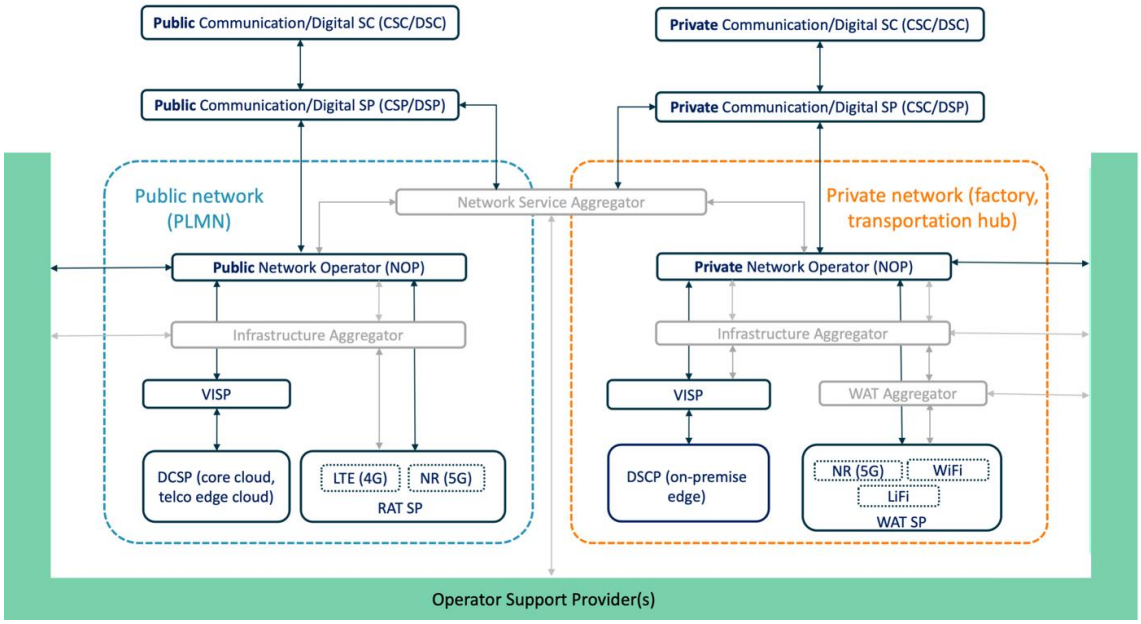

Figure 2-3: Extension of the 5G actor role model for NPN support

2.2 Verticals requirements on extended architecture

Table 2-1: Architectural solution for verticals requirements of extended architectures

Architectural solution	5G PPP Project	Additional Reference
Cluster/Vertical-specific architecture extensions	5G-VICTORI	[2-5][2-6]
Private networking for Industry 4.0/Smart Energy facilities	5G-VICTORI	[2-5][2-6]
E2E network architecture to support Digital Mobility services and the required KPIs	5G-VICTORI	[2-5][2-6]
Vertical-specific architecture extensions, considering vertical 3rd party AFs/VNFs, and edge deployments and orchestration/automation	5G-SOLUTIONS	[2-10]

As described in [2-6] , the 5G platforms play an important role in bringing together technology players, vendors, operators and verticals, orchestrating their interactions to target new business models and opportunities for both ICTs and vertical industries, enabling cross-vertical collaborations and synergies. It is obvious that in Europe there is a need of deploying 5G solutions for the vertical industries and the first step it is to develop future proof 5G architectures, large scale adapted for extensive trials for the 5G use cases applications.

5G vertical specific architecture extensions concept is requiring testbeds evolution for conducting not only large-scale trials but also advanced use cases (UC) that will be further proven in real commercial environment within a variety of 5G vertical's area as for example a mix of Transportation, Energy, Media and Factories of the Future as well as some specific UCs involving cross-vertical interaction [2-6]. From the definition and description of the different use-cases described in [2-5], relevant Key Performance Indicators (KPIs) are derived, as well as

requirements on the underlying network performance are identified, which in the definition of relevant architecture approaches and technology solution to be used.

The relevant use case described in [2-5] include *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, *Digitization of Power Plants*, Vertical: Smart Factory, and *CDN services in dense, static and mobile environments*, Vertical: Media

The architecture extension and roadmap of 5G clusters implementation [2-6] is captured through several activities, starting with (1) an initial high-level facility planning, (2) the network requiring capturing for use case dimensioning, (3) network needs coverage and mobility,(4) proper hardware and software identification, (5) infrastructure dimensioning(cloud, virtualization, automation), (6) architecture design and review and (7) 5G network and application onboarding, deploying and testing.

A list of network components and technologies supporting the cluster architecture evolution is identified and split through several domains [2-6], to support the vertical's use cases:

- Applications and use case experimentations, deploying and instantiation of various services, including MEC servers, various APIs to signal deployment on the edge, orchestrators for network slicing deployment and various KPIs monitoring.
- Physical 5G infrastructure, hardware/PNFs and compute resources
- Virtualized infrastructures, SDNs, VIM and platform monitoring tools
- Network slices and services resources orchestrators, inventories and services catalogues, multi-site orchestrators and inventories, mobility management and profiling, VNFs life cycle management
- Use case service design tools
- Monitoring and data analytics systems, data visualization, KPIs analysis and data analytics outputs exposure to dashboards for further visualization
- Evaluate applications KPIs focused on availability, reliability, mobility, broadband connectivity, latency, coverage, QoS experimentation, service optimization

5G is the Software Based Architecture model targeting to serve "X as a service" [2-6] concept, where X can be infrastructure, software or platform, the network slicing being applied in order to meet the customized specific combination of the services and network functions components. The 5G system can be flexibly extended and customized to serve the needs of the vertical industries, for overall RAN architecture, extended MEC hosting infrastructures and NFVI overlay, data plane network infrastructure and transport networks. The multi-domain management involves interaction between E2E services operations for all involved management domains [2-6], as the orchestration framework is designed for a holistic approach in the 5G ecosystem, relying on the separation of network services that support the developed applications and specific management infrastructure slices. The architecture extension involved also the DevOps, the integration of the development and operation of complex software systems and NFV orchestration. The DevOps approach affects the entire structure of the systems by introducing multiple stages at the deployment time, pre-deployment time and runtime.

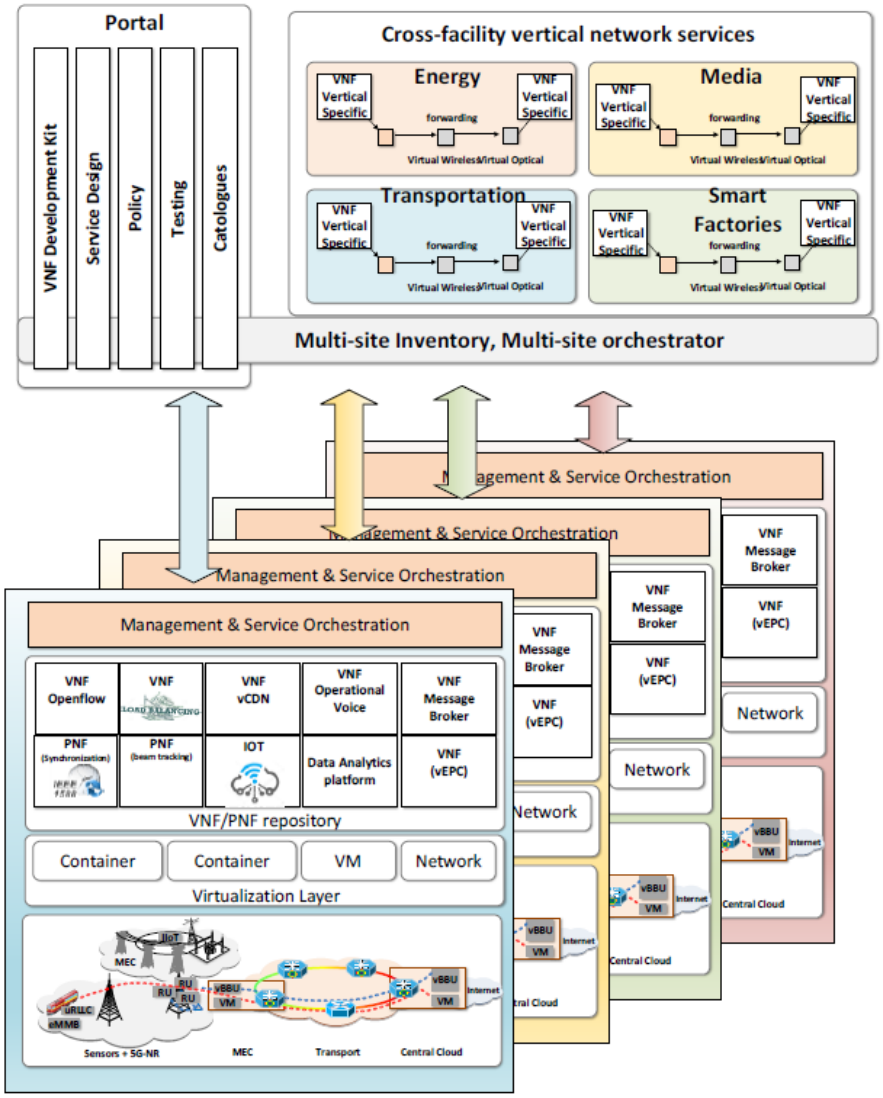

Figure 2-4: Reference architecture for common large scale field trials [2-5]

According to the overall 5G system architecture described in Figure 2-4, the relevant proposed architecture and extensions have to provide the vertical optimised common platform to address the requirements and business needs of the vertical industries. The E2E platform across multiple facility sites provides facility interworking, creating a common integrated infrastructure of networks and usable resources, the resources being able to be managed and accessed on demand by services and applications, enhancing the resource utilization efficiency and providing measurable benefits for the verticals in terms of cost, scalability, sustainability and management specification. Another important aspect is the service composition over infrastructures, achievable through the creation of repositories, comprising programable hardware and software components also as vertical specific NFs. Programable network functions are created for the vertical's industries communication needs, the common framework and construction elements being deployed to support the dynamic and on demand allocation of the demanding variety of resources for service provisioning, multi-site and multi-tenancy capable. This capability can be facilitated through the creation of infrastructure slices that can be independently provided to the entities, flexible service provisioning over cross-platforms slices relying on orchestration and NF service chaining over integrated programable infrastructures.

2.2.1 Requirements for private networking for verticals

A Non-Public Network (NPN) is the infrastructure that is used exclusively by devices authorised by the end user organisation. It is deployed in one or more specific locations of the customer, with devices assigned to the end user organisation only, with no limitation of the number that can be connected. The functionality of a private/non-public network extends beyond capacity and coverage into areas like security and integration with other industrial systems. The most common use case for a virtualised NPN mobile network industrial deployment scope is the deployment of 5G network slicing over the public mobile network. In this case the enterprise can obtain most of the advantages avoiding the cost or complexity involved in installing and operating on-site dedicated wireless infrastructure. One of the key business drivers which 5G NPN delivers for Smart Energy facilities, but also for Industry 4.0 overall is the high reliability, critical monitoring and control of applications supporting real-time decision making by combining smart technology including sensors, high interconnectivity, automation, machine learning and real-time processing.

The NPN requirements are very different from the conventional network requirements of public mobile networks. High reliability service with guaranteed SLA is required expressed through network performance attributes such as latency, reliability together with functional and operational requirements such as data traffic feeding, high-precision positioning, real-time monitoring. The traffic model for NPN use cases are different from the conventional consumer mobile network services requiring QoS flexibility such as uplink / downlink different bandwidth ratio. Strict data isolation should be provided within customer premises between services data related user plane / control plane communications but also between customers, if they share the same infrastructure. Here edge computing along with network slicing fulfils the strict data isolation or localisation use cases requirements. Security and privacy are one of the key requirements for an NPN requesting strong privacy and security framework to protect customer from various potential attacks. The most cost-effective way for customers to focus on their core business and offload the complexity of deploying and managing enterprise connectivity is to handover it toward mobile network operators. Therefore, the decoupling of operation and management is required.

The dedicated white paper on NPNs [2-34] provides a detailed analysis of several use cases and the motivation for the customer to deploy and NPN. The range of requirements is wide, whereas each requirement is typically not a single *killer* motivation for NPN. However, the combination of several requirements can be as is illustrated by spider diagrams like in the example in figure. In general, the NPN white paper identified the following areas that are the main source for requirements for NPN[1]:

- Coverage – The level and availability of coverage, including redundancy coverage
- Guaranteed QoS – Including Latency, Jitter and Throughput or a combination of them. The probability that the network is able to provide the required value at any time
- Customisation – Refers to the features needed by the enterprise to meet its business needs, including but not limited to time synchronization, localization accuracy, 5GLAN support, etc.
- Network Control –E2E control over network management, resources and services encompassing information, data, operations and communication technology

[1] It should be noted that the list of requirements for NPN and the spider diagram are a preliminary indication and will be updated after the consultation phase for this whitepaper and once the NPN paper – being prepared in parallel – is published.

- End User Data protection – Subscriber data protection level, i.e., type of encryption, storage location and level of redundancy
- Integration with Remote cloud – referring to Telco Cloud, Enterprise cloud, hyperscale cloud or a combination of these
- Traffic steering – means to steer and isolate traffic according to technical and business needs.

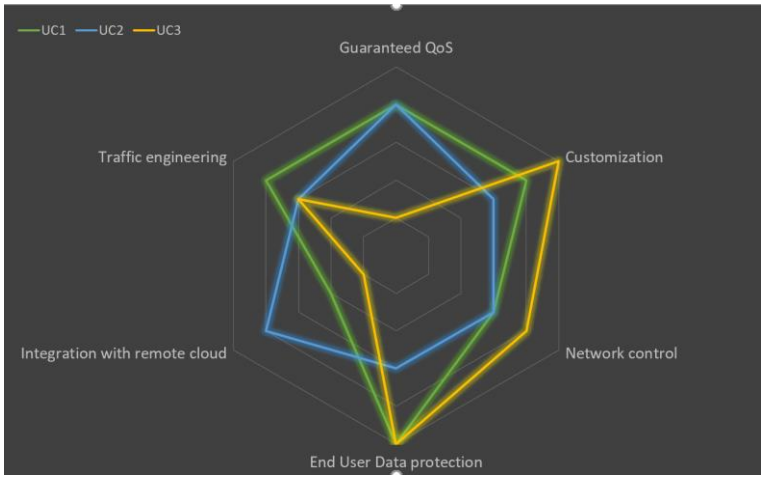

Figure 2-5: Example diagram with the vertices representing factors motivating NPNs

2.2.2 Requirements for digital mobility services and related KPIs

In general, digital mobility use cases address public safety and security in transportation and access for the travellers to various digital content (e.g., augmented reality, VR applications, very high broadband Internet).

The public safety and security refer to the capability of identifying different types of incidents that may occur (e.g., violence) by for example analysing in real time the images captured by the surveillance cameras leveraging edge computing capabilities [2-7]. After the incident is detected in the transportation systems, it is mandatory to inform the competent authorities. The specific messages are sent over a dedicated URLLC slice, in order to be sure that the messages can be transmitted over a link with guaranteed resources. Over the same 5G network, also an eMBB slice is enabled and may be used by travellers to access various digital content. Table 2-2 lists the main KPIs.

Table 2-2: Network KPIs for digital mobility [2-7]

Description	**Slice**	**KPIs**
Network availability	URLLC & eMBB	99.9%
Network reliability	URLLC & eMBB	99.9%
Network slice capabilities/management	URLLC & eMBB	Yes
E2E latency for digital content (in ms)	eMBB	<30 ms
E2E latency for public safety service (in ms)	URLLC	<5 ms
Mobility – high user mobility	URLLC & eMBB	<50 km/h

High bandwidth required for data intensive public safety applications and HD video streaming	URLLC & eMBB	>20 Mbps
Edge computing capabilities	URLLC & eMBB	99%
Jitter – Time critical communications should be stable and reliable. Timing variation must be minimal	URLLC	<1 ms
Packet loss - Reliability and high availability of the services in extreme conditions is essential for emergency systems. Therefore, packet loss should be made as small as possible	URLLC	0.01%

A number of future digital mobility use cases are demonstrated at the 5GUK Test Network facility in Bristol, UK [2-11]. Digital Mobility-Bristol facility has strict network performance requirements in terms of latency and throughput [2-7]. Both metrics are multi-dimensional and can have different requirements or measurement procedures at different network locations and/or levels.

Throughput KPIs mostly involve the physical capabilities of the network which depend on the RAN and infrastructure technologies and design. Specifically, as described in [2-7], digital mobility Use-Case-Bristol facility identified the main throughput KPIs as:

- Backend-to-Edge throughput
- Throughput between edges
- Edge-to-User throughput

Latency KPIs not only involve the physical capabilities of the network but also other attributes related to the computational power at the backend and edges, as well as the complexity and efficiency of the corresponding mobility services (software/protocols/etc). Consequently, KPIs related to latency are more difficult to investigate, measure and/or improve. The main categories of latency KPIs for digital mobility UC-Bristol facility are:

- Backend-to-Edge latency
- Latency between edges
- Edge-to-User latency
- End-to-end latency
- Edge services provisioning time (in the case of mobility of the users): Edge services/VMs instantiation time during handovers
- Service mobility latency: Time required between the application signals the mobility of the user until services re-establishing at the new edge

High throughput and low infrastructure latency between edges along with powerful edge computing capabilities can significantly reduce latency for digital mobility and ensure seamless connectivity and service provision to users. Computational resources capable of hosting the required VMs to support future mobile services must be available not only in the backend but also closer to the users.

The project [2-9] makes use of the built-in capabilities of the developed UC application stakeholders on Android phones and VM servers/services at the backend and the edges to measure the corresponding latency/throughput KPIs. Meanwhile, the end-to-end, backend-to-edge and edge-to-user latencies and throughput are measured using the 5GUK Measurement and Monitoring tool. Seamless digital mobility is highly dependent on orchestration performance, service mobility performance and inter-edge network performance. As described in [2-7], ways

are investigated for improving the digital mobility performance, aiming at a better end-user experience within the context of digital mobility.

2.2.3 Requirements considering vertical 3rd party AFs/VNFs, edge deployment and orchestration

This section addresses requirements for vertical-specific application integration and architecture extensions, considering vertical 3rd party virtualized network application functions, edge cloud deployments and orchestration/automation. With the promises of advanced 5G services towards verticals it is important to capture and accommodate the needs of the different verticals, whether addressing capabilities that should be commonly applicable across many verticals or the requirements are targeting specific needs of a given vertical. The requirements are considered in the context of the fundamental and baseline service offering, that of the logical network service offering toward Vertical Enterprise Customers (VEC) as well as specialized connectivity services on-demand offered to Online Application service Providers (OAP). Around such a Logical Network as a Service (LNaaS) offering, there are multiple topics to consider for proper service life-cycle management and support. Further elaboration on the service modelling concepts and exposure capabilities are considered in Section 2.5.4 below.

The LNaaS offering must go beyond today's virtual private network (VPN) service offerings and SD-WAN solutions that are foreseen in the near term. The logical network (LN) concept must enable and support a variety of 5G NPN configurations, including various ways of integrating with the public network, including the so-called public-network-integrated NPN (PNI-NPN). A VEC specific LN can be interconnected to other partner LNs as well as reaching end-points addressable on the public Internet or other future specialized public services networks. Hence, there is a need for supporting a verity of topologies and underlaying network technologies. An example of this need is the support of requesting Specialized Connectivity Service on-demand (SCS), from the LN of the VAC and any of its point of interconnection with other LNs or public network, to any other end-points in these reachable networks. Application on-boarding, deployment (including setup of connectivity properties into advanced network conditions and topologies) and application service activation must provide:

- Service SLA, management of robustness levels and abstracted resilience mechanisms (e.g., related to high availability cloud properties).
- Support for self-service portals.
- Service monitoring
- Support for sandbox and trials
- Support for testing as a service
- Support for migration from sandbox, to acceptance testing and eventually commercial operations

2.3 Architecture extensions

Table 2-3: Architecture extension

Architectural solution	5G PPP Project	Additional Reference
Architectural extension on baseline to release 16	5G-VICTORI	[2-5]
Telco-oriented cloud native orchestration of 5GC and vertical applications	FUDGE-5G	[2-21]

2.3.1 Architecture extensions introduced by 3GPP Release 16

3GPP Release 16 [2-3] improves the 5G system mainly through radio enhancements, enabling several vertical industries: autonomous driving V2X, railways, maritime, automated factories, healthcare, public safety, electrical power distribution, satellite industrial domain, logistics and many more. Figure 2-6 illustrates how the versatility and reliability of the 5GS has been further improved to industry-grade, with enhancements to URLLC, network slicing, edge computing, cellular IoT, positioning services, LAN-type services, time sensitive networking for industrial IoT, non-public networks and integrated access and backhaul. The use of 5G as an underlying communication network (i.e., to be used transparently by applications external to the network) has been enhanced, mostly under the work on *Northbound APIs*. Besides all these industrial aspects, other enhancements cover the coexistence of 5G with non-3GPP systems, entertainment (e.g., streaming and media distribution) and network optimizations (e.g., user identity).

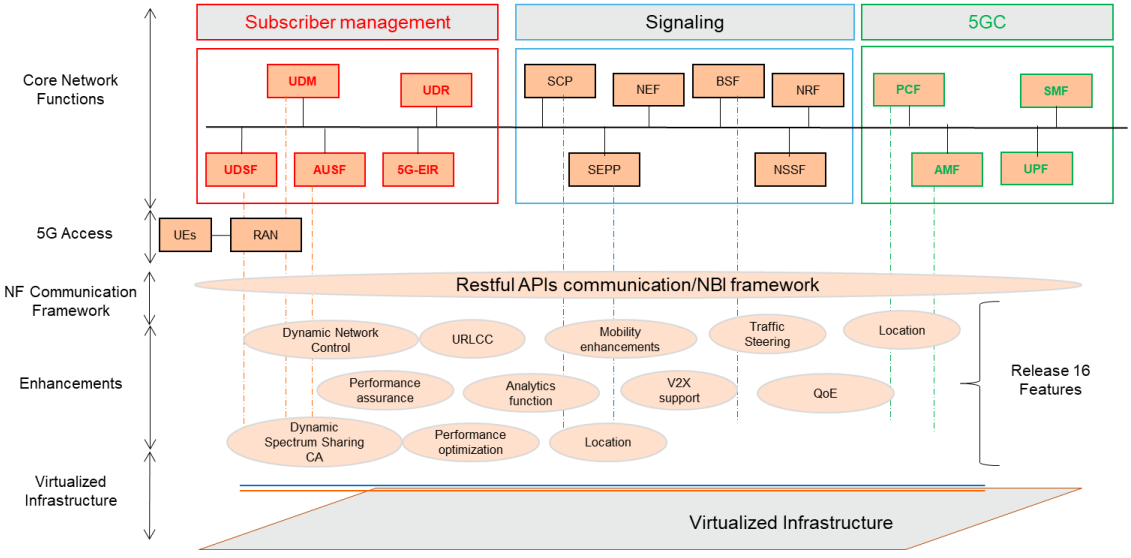

Figure 2-6: Release 16 5G features and enhancements supporting verticals

Several 3GPP-Release 16 feature enhancements are highlighted, extending the 5G use case families beyond Release 15, as for example features for:

- Dynamic network control
- 5G RAN and Core enhancements to support URLLC, redundant transmission paths to avoid services failures, N3/N9 interfaces
- QoS monitoring and Packet Delay Budget control at 5G RAN and Core level, enhancements for session continuity, physical layer enhancements for URLCC

- 5G NR enhancements for IoT, PDPC packet multiplication for increased reliability, CA, multi-connectivity for PDU sessions, efficient gNB scheduling, logical uplink resources prioritization at UE level
- NR mobility enhancement's, inter-band CA and for 2/3 bands DL and x UL (x=1,2), 256 QAM FR2 support, NR-NR dual connectivity and NR CA, dynamic spectrum sharing and power saving
- NR in un-licensed spectrum and non-3GPP system coexistence
- Advanced V2X support, V2X services architecture, mobile communication system for railways in high-speed scenarios, mission critical services for public warning, as described in Figure 2-7.

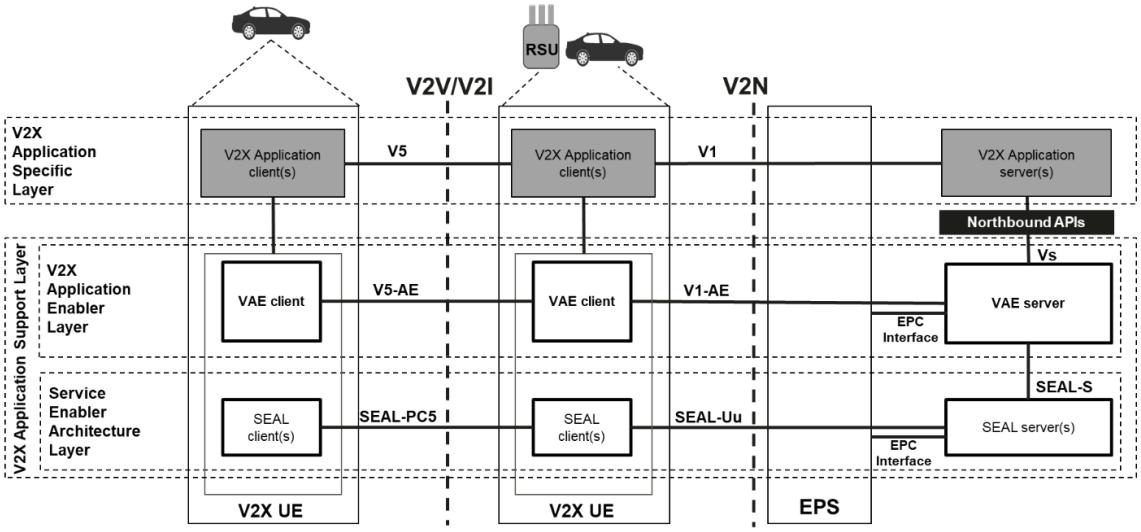

Figure 2-7: Application layer support for V2X services [2-3]

Other 3GPP Release 16 features are related to enhancements for APIs, architectures enabled for mission critical, accuracy and other enhancements, such as:

- Enhancements for Northbound APIs for SCEF, NEF, 3GPP Northbound APIs optimization, 3GPP Common API framework,
- Architecture enabled for vertical mission critical services, traffic steering in 5G system architecture
- High accuracy 5G location and positioning services, relevant for many 5G verticals, 5GC and NR enhancements
- Performance measurements, assurance and KPIs for 5G network slicing as delay, loss, drop, latency, radio resource utilization, throughputs, sessions management and UE measurements reports
- Performance assurance for network slicing, thresholds monitoring services, E2E packet delay, packet loss, latency, radio resource utilization, throughputs, sessions management and UE measurements reports
- Network architecture to support data analytics services, data collection from 5G NF and AF, analytics exposure provided to consumers through analytics IDs (e.g., Network Performance, Service Experience, UE mobility, User Data Congestion)
- QoE management and management collection
- Flexible and efficient Service Based Architecture, enhancements supporting indirect communication of NF services (intermediate Service Communication Proxy, NF producer indicates NF consumer), as described in Figure 2-8.

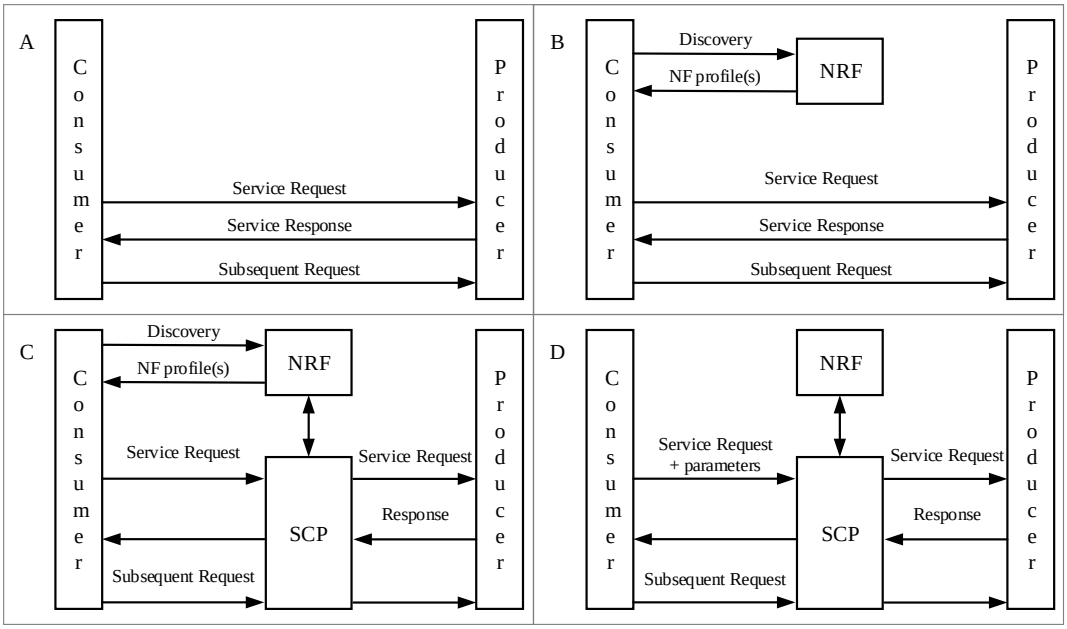

Figure 2-8 : NF/NF services interactions [2-3]

2.3.2 Telco-oriented cloud native orchestration of 5GC and vertical applications

A holistic approach is taken for the 5G system architecture by putting the Service-based Architecture principles at the heart of the system architecture which is illustrated in the figure below as a high-level component overview. As can be seen in Figure 2-9, a three-layered system is defined separating the infrastructure from enterprise services (service layer) by a dedicated platform layer that implements unified service routing, orchestration and lifecycle management, monitoring and service slicing for enterprise services.

The infrastructure layer is concerned with components and technologies that are assumed to be available in an operator's infrastructure and exposed through standardised and open APIs. Within the infrastructure layer a unified access domain is assumed, in the likes of 802.3 as the common denominator as the frame format. If a switching fabric is available in the operator's network, it is assumed to be fully programmable via Software-defined Networking (SDN) procedures, e.g., OpenFlow. The 5G platform in [2-21] is fully softwarised, hence all its components can be virtualised and provisioned as Virtual Network Functions (VNFs). Therefore, the platform can either be provisioned on native Commercial off the Shelf (COTS) systems without any virtualisation or via an infrastructure orchestrator following the ETSI MANO reference model.

The platform layer is composed of the three functional blocks routing, service orchestration and monitoring. The routing block comprises the two functions service routing and resource scheduling. While service routing is concerned about the ability to perform fast and adaptive service routing among Cloud Native Network Functions (CNFs), resource scheduling is performing decisions on which CNF service instance to be chosen from a pool of one or more available instances across a set of locations. These decisions can implement various optimization criteria in order to meet specific quality of service aspects, such as distributing load equally over a set of CNF instances, limiting the delay of service invocations or similar. The service orchestration block provides location-aware cloud native orchestration for CNFs and an additional vertical application orchestrator for – as the name implies – vertical applications, also utilising the SFV orchestrator. The third block inside the platform layer is concerned with monitoring which is composed of a cross layer and vertical application monitoring as well as an

analytic functionality. The fourth and last block to the very left in the platform layer is the ability to slice resources across a range of domains independently from the service layer, but based on input from enterprise services.

The service layer is divided into the two areas of enterprise services, i.e., 5GC and vertical applications. While the 5GC lists innovations around 5G Multicast (MC), 5G Time Sensitive Networking (TSN), 5G Local Area Network (LAN) and interconnected NPNs, the vertical applications cover four exemplary use cases demonstrating the concepts, in the context of the verticals: media, industry 4.0, public protection and disaster relief (PPDR), and virtual office.

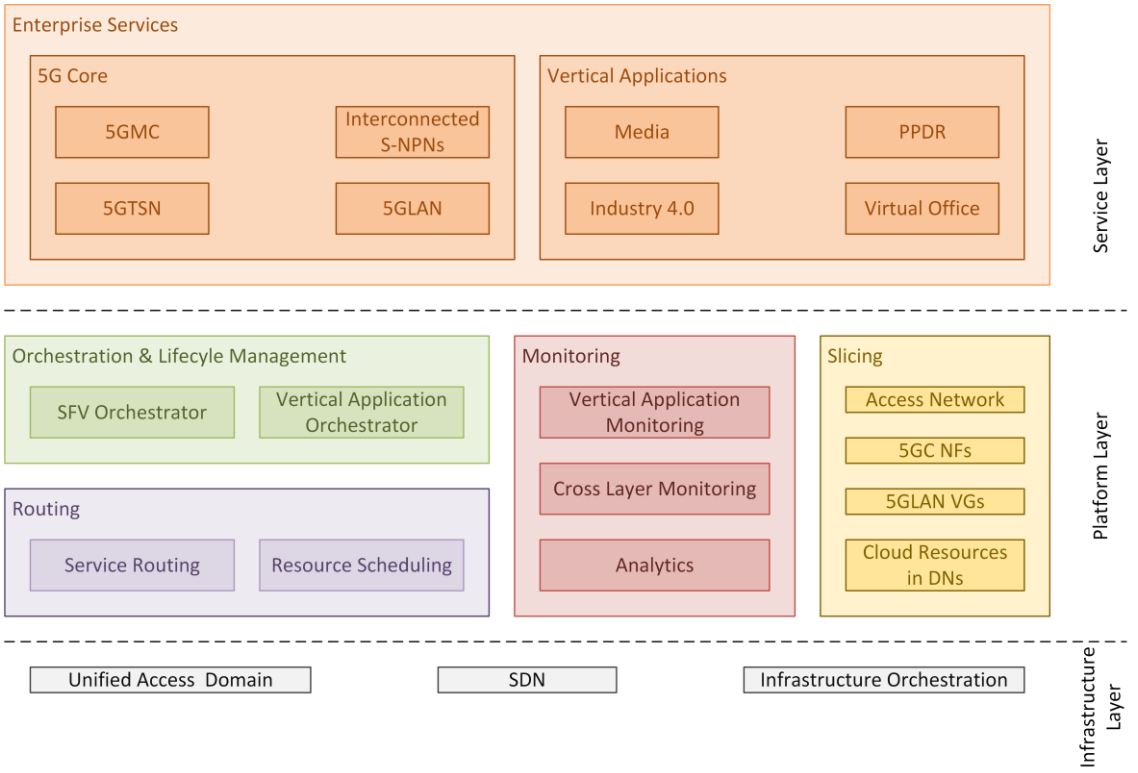

Figure 2-9: High level system component overview of a fully disintegrated private network architecture [2-21]

2.4 Security Architecture

Table 2-4: Architectural solution for security architecture

Architectural solution	5G PPP Project	Additional Reference
Overall security architecture	Inspire-5GPlus	[2-4]
High Level Architecture for Security in B5G/6G networks	Inspire-5GPlus	[2-4]

2.4.1 Overall security architecture

Appropriate consideration and implementation of trust and security will be essential for the success of beyond 5G systems. It is assumed that the complexity of the 6G architecture will be higher than in 5G that has already introduced disruptive concepts and technologies for which the

resulting risks are still not fully known, e.g., softwarisation, virtualisation, and cloudification, even though they have positively impacted the flexibility and adaptive capabilities of networks. Nevertheless, security management, often being conservative and requiring a significant level of situation awareness, is still sensitive to the increased complexity of novel concepts.

The integration of disruptive technologies requires on the one hand to ensure these technologies are securely used, i.e., not jeopardising the overall system security, but on the other hand taking benefit of the advantages of these innovative technologies and applying them for implementing security functions in the network, and for reaching consistency with systems properties. In order to reach the required scalability and dynamism levels of security, security services should be as much as possible following the "as a service" model, softwarised, and based on virtualised technologies. Management and control of security should remain aligned to these innovative paradigms making of smart orchestration, chaining, and AI the enablers of concomitant deployment of security to provide an intelligent distribution of security functions across the systems. This intelligence is essential for a protect-detect-react loop that ensures a compliance with security policies and SSLAs, optimizes detection of known attacks or anomalies, and dynamically deploys the required mitigation. Deception and Moving Target Defence (MTD) are examples of promising techniques to influence the way security is delivered and operated.

The smart control of 6G networks needs to be driven through Artificial Intelligence capabilities which at the same time are a source for new attack vectors, but applying these technologies in the security domain enable more intelligent security solutions. AI relies on data quality, either for users' data or system data. Data protection becomes a major concern so that data-centric security technologies such as homomorphic encryption or Multi-Party Computation will become mandatory. Two further main elements will impact the attack surface of future networks: The first one is linked to the IoT raising issues related to security distribution, and the second one is linked to the software life cycle. Moreover, the security architecture may be subject to entirely new paradigms taking benefits of the fundamentals of the physics, as e.g., quantum infrastructures.

The main aspect for enabling security will be too deeply root protection and resilience in the architecture, so that attacks become harder to carry out and easier to manage. This requires that trust anchors are put in place and resilient configuration patterns are deployed, so that service networks can resist attacks. This requires a disruption of traditional approaches where security concerns are often expressed late to even go beyond the" by-design" paradigm with solutions

2.4.2 High level architecture for security in B5G/6G networks

In beyond 5G and 6G, a fully automated network and service management and operation will need to be included from the initial design phase. However, a major challenge and risk of introducing full automation is that small isolated errors or cybersecurity attacks, which are expected to become an unprecedented challenge in beyond 5G and 6G, might propagate and replicate rapidly and bear the risk of endangering the entire critical ecosystem. What is needed is a *fully automated – zero-touch – end-to-end smart network and service security management framework* that empowers not only *protection* but addresses also *trustworthiness* and *liability* in managing virtualized network infrastructures across multiple domains.

The security architecture in 6G should be split into several security management domains (SMDs), for robustness, but also to support the separation of security management concerns, e.g., for the Radio Access Network (RAN), Edge or Core Network. The principal design and functional components of SMDs should be the same in all domains. Each SMD is responsible for intelligent security automation of resources and services within its scope, and comprises a set of functional modules, e.g., a Security Data Collector, a Security Analytics Engine, Decision Engine, Security orchestration, Trust Management as well as Policy and SSLA Management. The various security

management services provided by these modules are exposed within the same domain but also cross-domain through an *integration fabric*. A special SMD – the end-to-end SMD – will be needed to manage security of E2E services (e.g., E2E network slice) that span multiple domains. The decoupling of the E2E security management domain from the other domains allows escaping from monolithic systems, reducing the overall system's complexity, and enabling the independent evolution of security management at both domain and cross-domain levels.

The functional modules need to operate in an *intelligent closed-loop* way to enable *AI-driven software defined security (SD-SEC)* orchestration and management in compliance with the expected Security Service Level Agreement (SSLA) and regulatory requirements. By adopting service-based and SD-SEC models, this framework allows to build up sustainable security measures that can adapt to dynamic changes in threats landscape and security requirements in next-generation mobile networks.

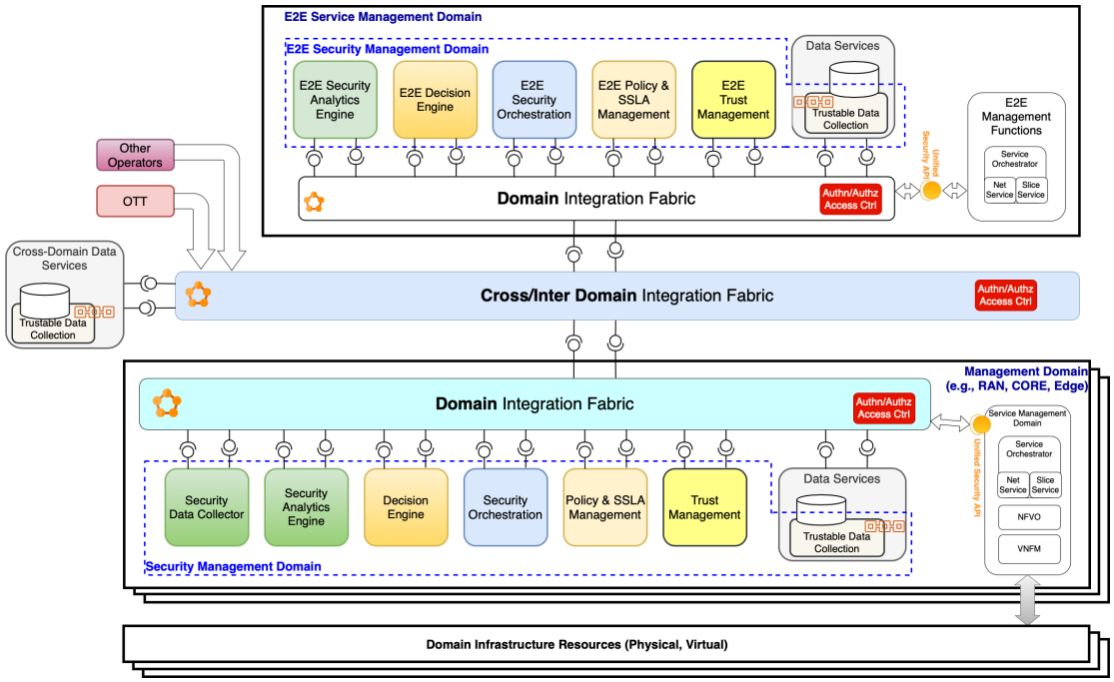

Figure 2-10: Security Framework High-Level Architecture

See [2-4] for a detailed discussion on intelligent security architecture for 5G and beyond networks.

2.5 Service layer evolution

Table 2-5: Architecture service layer evolution

Architectural solution	5G PPP Project	Additional Reference
Service Layer for verticals	5G-TOURS	[2-36]
5G-as-a-Service: Integrating and customizing the 5GaaS API for a specific service	5G-HEART	[2-35]
Vertical industry service migration/deployment to 5G NSA/SA MEC	5G-HEART	[2-35]

Service Layer for verticals	5G-SOLUTIONS	[2-10]
Unified Service-based Architecture placing service registration, routing, orchestration and resource control at the platform level with 5GC and vertical applications as 5G services on top of platform	FUDGE-5G	[2-21]

2.5.1 Service Layer for verticals

In order to meet the needs of the vertical customers, the 5G architecture has to include a service layer that provides them with a suitable northbound interface which has to be aligned with the incipient efforts on Exposure Governance Management Function (EGMF) [2-12] at 3GPP. Yet, its scope may go much beyond that of the standard.

This service layer [2-13] has to perform the following operation, as needed by verticals, considering tailored requirements for the network slice lifecycle management:

- *Instantiation*: When a tenant needs a network slice, it has to issue a request to the infrastructure indicating information such as: (i) the geographical area that needs to be covered by the network slice, (ii) the Key Performance Indicators (KPIs) such as the capacity, maximum latency or reliability, that needs to be supported, (iii) the user equipment that belong to the slice, etc.
- *Orchestration of application-layer virtualized functions*: Sometimes the tenant needs to run some of its application layer functions within the network infrastructure employing e.g., MEC technology. Hence the service layer has to support this feature, indicating e.g., the capacity of the underlying infrastructure.
- *Monitoring and runtime management*: Once the slice has been instantiated, the service layer shall provide monitoring capabilities for SLA assurance purposes. In this way the tenant can monitor the service provided by the network slice and see if the obtained performance matches the requested one. Based on this information, the service layer shall support re-shaping of the slice. For instance, if the slice's load increases, a larger slice may be requested.
- *Operate the network slice*: The tenant needs to be able to perform some configurations on a running network slice, such as adding new users to the slice, increasing its coverage, changing the requirements or the load, re-orchestrating application-layer virtualized functions, etc.

Given the openness of the 5G ecosystem, it is likely that many of the tenants employing a network slice are players which may not have the skills and expertise to manage mobile network services. As the ultimate goal is to allow such players to be part of the network slicing market without imposing a steep learning curve (i.e., employing a sort of Network Slice as a Service platform), it is very important that such service layer can manage most of the low-level burden. Additionally, this service layer may have two possible implementations, as a programmatic API or a web interface that can be used to perform the aforementioned operations manually. This approach could be coupled with intent-based approaches, where the policies coming from vertical tenants are specified with 'business intent', declaring high-level service policies rather than specifying detailed networking configuration. Alternatively, verticals may use other solutions such as GSMA NEST [2-14] templates.

The service layer is of particular importance in the context of NPN: empowering the vertical with the ability of performing the aforementioned operation in a more trustworthy environment such as the one envisioned by NPNs will effectively enable the user to network to service continuum,

ideally joining the service intelligence with the network one. The service layer can thus be customized according to the specific use case envisioned by the vertical, as discussed in Section 2.6.

2.5.2 Integrating and customizing 5G-as-a-Service APIs

5G-as-a-Service (5GaaS) is an API on top of the network orchestrator which allows 3rd party clients with IT skills to request specific services tuned to their needs, as illustrated in Figure 2-11. 5GaaS makes templates available for the clients which can be customized to specify different requirements in terms of QoS, duration, location, supplementary services, etc. In the future, these templates can be provided by the clients themselves. 5GaaS uses the filled in template to decide how to satisfy those requirements, which might require creating a new slice, deploying some specific service, etc. Furthermore, 5GaaS is a multi-operator service, which is independent of the orchestrator implementation used by the user. 5GaaS uses an operator-specific infrastructure controller to adapt to the orchestrator in use.

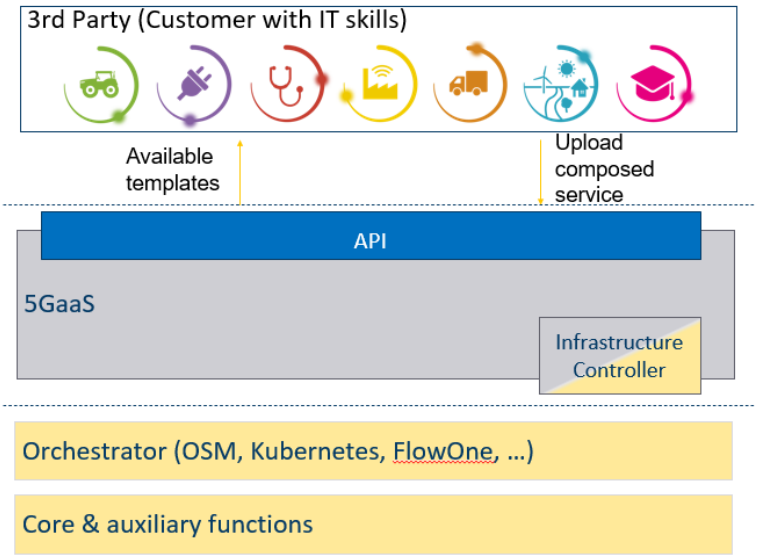

Figure 2-11: 5G as a Service diagram, where yellow is operator specific

5GaaS has been expanded to support a new type of service suitable for live streaming data. This type of service allows the client to select the number of 5G cameras (UEs) covering the event, the desired latency constraints, the location and the duration of the event. This service deploys a full 5G NSA core network and 2 separate service functions, a video aggregation function and a network authentication and authorization function. On top of that it can deploy emulated UEs and an emulated gNB for testing purposes. This setup was tested on a platform based on OpenStack [2-15] and Open-Source MANO (OSM) [2-16].

On top of that, 5GaaS has been expanded with another infrastructure controller which provides support for Kubernetes [2-17] based orchestration layers, effectively decoupling 5GaaS from the operator's network implementation.

2.5.3 Vertical industry service migration and deployment to 5G NSA/SA edge

In order to better cater to the specific needs of sensor-bases road safety and Industrial IoT use cases, an edge cloud environment has been configured to provide processing and communication resources for the re-location of vertical industry services. By collecting the key service components related to the analysis of the sensor data from the user/sensor devices and backend

server to the network edge, data fusion between the real-time and already post-processed historical sensor data can be performed in a centralised manner for a restricted operational environment such as a section of road or production facility/site. By moving away from the traditional distributed processing at the user devices or centralised processing at the remote cloud, and providing a hybrid approach at the network edge, more accurate monitoring and safety services can be provided with adequately low end-to-end latencies for a variety of scenarios requiring a combination of mMTC and URLLC capabilities from the utilised communication platform.

The initial implementation of the edge cloud environment has been made by configuring and deploying an MQTT broker and local database to serve a selected trial site. All user/sensor devices in the area publish their raw data to the broker. The broker is responsible for collecting the sensor data and passing it to a common local database for analysis with the historical data received from the remote service cloud through a dedicated API. Possible warnings and alarms triggered by the analysed data are pushed forward directly to other users/sensor or monitoring systems subscribed to receive such messages from the MQTT broker. In order to facilitate the deployment of alternative distribution methods for the messages triggered by the analysed sensor data as well as the extension of the service capabilities, a VM template for the deployment of additional service components has been defined for the edge cloud.

2.5.4 Service layer information, data models, and exposure mechanisms

The key service concept for vertical enterprise customers is Network as a Service, typically this is a Logical NaaS. In general, the NaaS can be based on public network infrastructure or a combination of public and private network infrastructure. The NaaS must also reflect various ways and means of interconnection with other networks, and may also be related to other NaaS instances. The Logical Network as a Service, Service information model (and data models for implementation) is at the core of service layer exposure, as perceived by the enterprise customer (e.g. industry SME and their industry partners). An evolutionary approach must be supported, in order to abstract the topology, referencing underlaying abstracted network entities and elements as relevant to the service offered. Also, the service layer is based on the exposing of wireless and fixed connectivity, as well as computing resources for dynamic application function deployment and supporting of the interconnection to (other) public and/or private networks, cloud networks or other partner networks (partner of the enterprise customer). Several service layer capabilities for verticals are taken into consideration, as service layer features:

- Resilience and robustness support
- Exposure via suitable, standardized, and customizable (B2B) APIs, supporting Customer User interface and Vertical Application solution providers
- Vertical private network operations (managed service providers)
- Enables and supports customer self-management of the overall NaaS and underlaying service entities and corresponding elements
- Customer device / UE management and configuration
- Managed connectivity to/from and between various end-points or destination regions
    - Managed quality path level (traffic aggregates), to/from tunnel end-points, or to destination regions
    - Connectivity on-demand (connectivity session level, matching application sessions), including Specialized Connectivity Service on-demand (SCS).
- Management of service availability and robustness properties
- Enabling and supporting Service Assurance, QoS and QoE models and management

- Monitoring and assessment of service performance
- Telemetry and analytics
- Enabling and supporting Experimentation, Testing and Validation
- Expression of experiments and test cases referencing entities and elements exposed by the service model
- Towards EaaS and support of NPN acceptance testing
- NaaS Service Information and Data model's development and standardization

The harmonization and synthesis across multiple candidate input models are needed, based on the standardized information data models from ETSI NFV [2-18], IETF [2-19] and TM Forum [2-20] information and data models.

2.5.5 SBA-enabled unified platform hosting 5GC and vertical applications

The newly introduced Service-Based Architecture (SBA) vision in 3GPP Release 15 is put under trial in [2-21]. SBA is at the centre of its system architecture by placing service routing and resource scheduling, service orchestration and lifecycle management, monitoring and service slicing at platform level. This paradigm shift, based on SBA principles, allows to treat any 5GC and vertical application as enterprise services and imposing a unified service provisioning, routing, monitoring and slicing on them. This evolution of the SBA vision for a (beyond) 5G system enables an increased flexibility, availability and reliability by taking the advances of public clouds and adopt them for the telco world. Allowing to treat 5GCs and vertical application as enterprise services with an underlying platform layer that offers the communication and orchestration functionality necessary, not only enables a true realisation of services using a 12-factor app methodology (aka microservice software engineering paradigm) but pushes complexity and control realms from the service layer into the platform layer for a unified approach across services. This fosters multi-vendor deployments where each enterprise service, which is placed as part of an overall service chain, only requires to implement the functionality of what the service must offer without the need to also handle the complexity of which other enterprise service/instance should receive a request.

2.6 Vertical specific architecture extensions

Table 2-6: Architecture Vertical specific architecture extensions

Architectural solution	5G PPP Project	Additional Reference
Private networking for Industry 4.0/Smart Energy facilities	5G-VICTORI	[2-5]
Extended layered network architectures for high-speed rail transportation facilities	5G-VICTORI	[2-7]
Slices for rail specific service delivery in transportation environments	5G-VICTORI	[2-9]
E2E network architecture to support Digital Mobility services and the required KPIs (focus on architecture extension here)	5G-VICTORI	[2-8]

Architecture for professional content production: live audio, multiple cameras and immersive video	5G-RECORDS	[2-25]
Intent-based E2E network slice deployment for verticals	5GROWTH	[2-28]
Intent-based E2E network slice deployment for verticals	5G-COMPLETE	[2-29]
NetApp Principles and Implementation Aspects	EVOLVED-5G	[2-37]

2.6.1 Architecture extensions for private networking for verticals

At the highest level, NPNs can be divided into two categories, isolated, standalone networks and NPNs deployed in conjunction with a public network.

The first category comprises a single configuration, while the second implies multiple configurations, each differing in terms of the degree of interaction and infrastructure sharing with the public network. In the isolated scenario NPN is deployed as an independent, standalone network all network functions being located inside the logical perimeter of the defined premises separated from the public network, the only communication path between the NPN and the public network is via a firewall identified as demarcation point.

In the shared scenario configuration both the public network traffic and the NPN traffic are treated as if they were parts of completely different networks. This is achieved through 5G virtualisation of network functions in a cloud environment through multiple network slices, delivering different network characteristics for different users or applications. Low latency network communications capabilities for near real-time control applications in manufacturing applications, high bandwidth suitable for conveying image data in AI/ Edge applications or low bandwidth for industrial measurement applications such as Smart Energy. This implies different architecture that can be delivered only through a virtualised network which optimises performance to the specifics of industrial use cases. Smart Energy facilities is part of critical infrastructure which requires enhanced security requirements such as authorisation, authentication and access control features. Data encryption and integrity protection mechanisms are mandatory to protect the data transmitted and enhance data security of the enterprise. Network slicing and edge computing offer major advantages by providing virtual network capability to create logically separated virtual networks over the public network without reliance on additional encryption protocols such as PP2P, IPSEC or L2TP. Distinct slices can be defined for different types of devices, sub-networks or users to create distinct security perimeters. Through NFV, traditional security functions like firewalls, access authentication, SSL are virtualized and operated within the slice to meet the security requirements. Use of Edge Computing along with network slicing offers the capability to localise and isolate data traffic allowing information to be kept entirely within the premises and the control plane for enhanced protection of manufacturer networks from external attacks.

An overview of enabling technologies for implementing an NPN is provided in the related 5GPPP white paper on NPN [2-34]. These include network slicing for PNI-NPN integration, which enables flexibility of choice for the deployment type, the SBA as a means to natively integrate enterprise application functions and to use network exposure functions via well-defined APIs, such as for advance analytics. Support of flexible access control and authentication through new SIM technology variants is an important element to ensure service continuity across borders of and NPN and the PLMN. 5GLAN, support for time sensitive networking and non-3GPPP access, are technology enablers that are necessary for a smooth migration from legacy and other deployed technologies to 5G NPN. Furthermore, support for positioning and localisation, support for hybrid

cloud constellations and support for various flavours of interconnection services between decentralised NPNs of the same administrative domain are essential enablers responding to business requirements and supporting the decision process for migration. Finally, the flexibility to construct a small-scale NPN via integrated solutions like "5G network in a box" may provide economic incentives for wide deployment of NPN solutions.

2.6.2 Extended layered network architectures for high-speed rail transportation facilities

In modern railway transportation facilities, there is a demand for a broad range of novel on-board services addressing various end-users, in particular applications for passengers, critical services and emergency services to stakeholders engaged in train operation, as well as complementary services related to optimization of train operation. These services are collectively denoted as FRMCS services. A prototype network and associated deployment to facilitate train operations and services considering the FRMCS service definition is developed in [2-9]. The project evaluates the performance of FRMCS service over the Patras 5G facility – a testing infrastructure, deployed at operational railway environment. In particular, it tests and demonstrates representative *Business*, *Performance* and *Critical* services.

The architecture proposed should ensure that services are provided while the train moves through Patras city centre, through heterogenous technologies, establishing high capacity low latency connections at high speed mobility. High capacity is needed for the former services, in order to provide high quality of service to passengers, whereas for the latter low latency/ ultra-reliable connections are needed in order to transmit data obtained from various sources in real-time to the train operations, driver and control centre. However, FRMCS service requirements, pose stringent requirements for access network coverage. Applying common network planning principles that ensures high-capacity coverage implies identifying the characteristics of the area under study. These may vary from remote, isolated areas, with challenging terrain for radio coverage (e.g., mountainous, with many curves, tunnels, etc.) to metropolitan areas (e.g., with high buildings, with many curves, tunnels etc.), along the railway tracks. Considering the access network capacity, at least 300Mbps-1Gbps are required at train level, and in cases that this is not possible, data rates of 1-1.5 Gbps are required at places where the train remains for some time, e.g., at platforms, at train depots, etc. Furthermore, high speed mobility invokes impairments and fast fading effects that cannot be pre-evaluated. Apparently, there is no single solution to address such environment. At the same time in order to adhere to technology neutrality requirements, solutions comprising various technologies, and aggregating backhaul traffic from multiple technologies access network nodes at transport network segments are being considered.

To address the above-mentioned requirements, the deployed solution in [2-9] is based on a joint flexible backhaul/fronthaul (FH/BH) network realized over heterogeneous wireless technologies, to support dedicated disaggregated virtualized access nodes on top of high-speed moving trains. A layered network architecture that integrates existing core network functionalities with extensions is proposed that provides the flexibility required in this high speed, variable and service-oriented environment. The integration takes place at four levels, with the fourth layer laying at the Control Centre (edge) Data Centre.

At lower level lies a train on-board network. This consists of several compute and network elements, all interconnected by fibre network. The proposed on-board network comprises a 10 Gbps Ethernet LAN with SDN-capable switches, connecting Sub-6 and mmWave antenna modules to be installed on the roof of the train, and software-based 5G-NR and Wi-Fi APs to be placed inside the train. The train-internal wireless part of the on-board segment comprises of SW-based solutions for 5G NR and Wi-Fi, provided over an aggregation environment augmenting the

overall capacity of the network, and controlled through a single Centralized Unit (CU). The CU can be instantiated as a VNF on an (edge) data centre and manage multiple heterogeneous Distributed Units (DUs) that integrate the radio-level characteristics of the base stations. At this point, a compute node is also necessary to deal with the handover management, while it can also act as a potential CU of the disaggregated 5G-NR cell. Moreover, cameras are interconnected and application related equipment realizing the critical service to be transported from the train to the Control Centre located in the cloud.

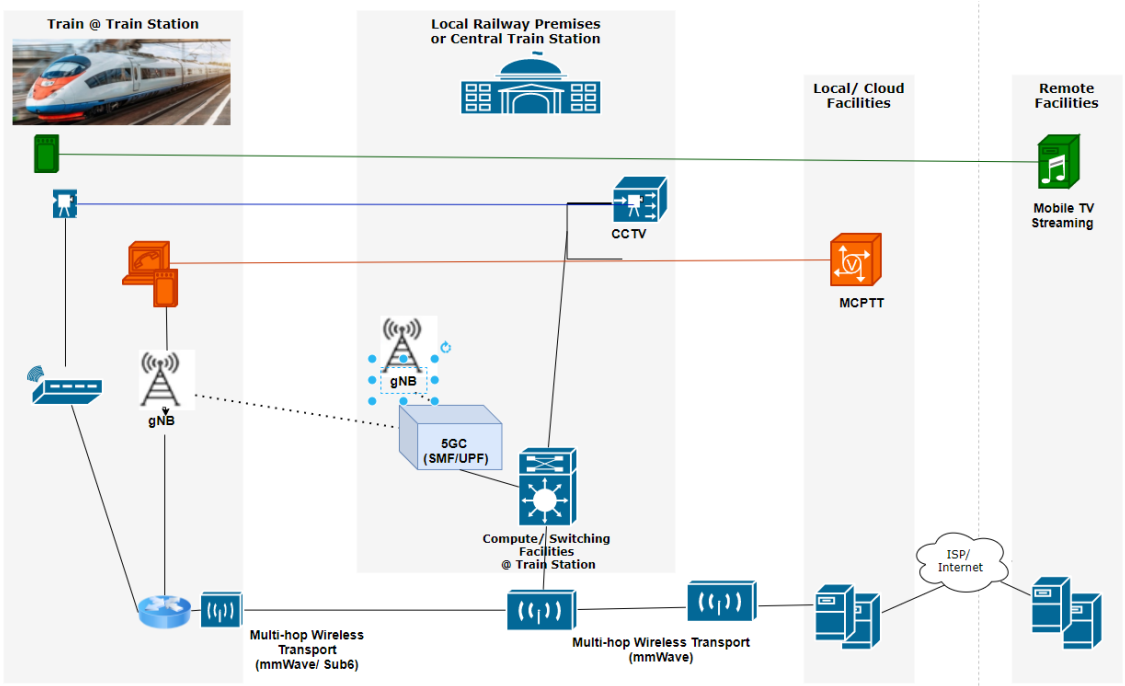

Figure 2-12: 5G architecture for testing FMRCS railway services [2-9]

At the second level various technology are used, for the track-to-train connections, a heterogeneous wireless network is deployed operating in the Sub-6 GHz frequency band and mmWave units featuring beam tracking capabilities. At the third level, the interconnection of the track side APs to the core network is achieved through multiple Point-to-Point mmWave, that provide up to 10 Gbps capacity, as shown in the map of figure but also through fibre links. Finally, a full 5G Base station unit with MEC capabilities is assumed to be located at train stations and is connected through mmWave BH to the Control Centre.

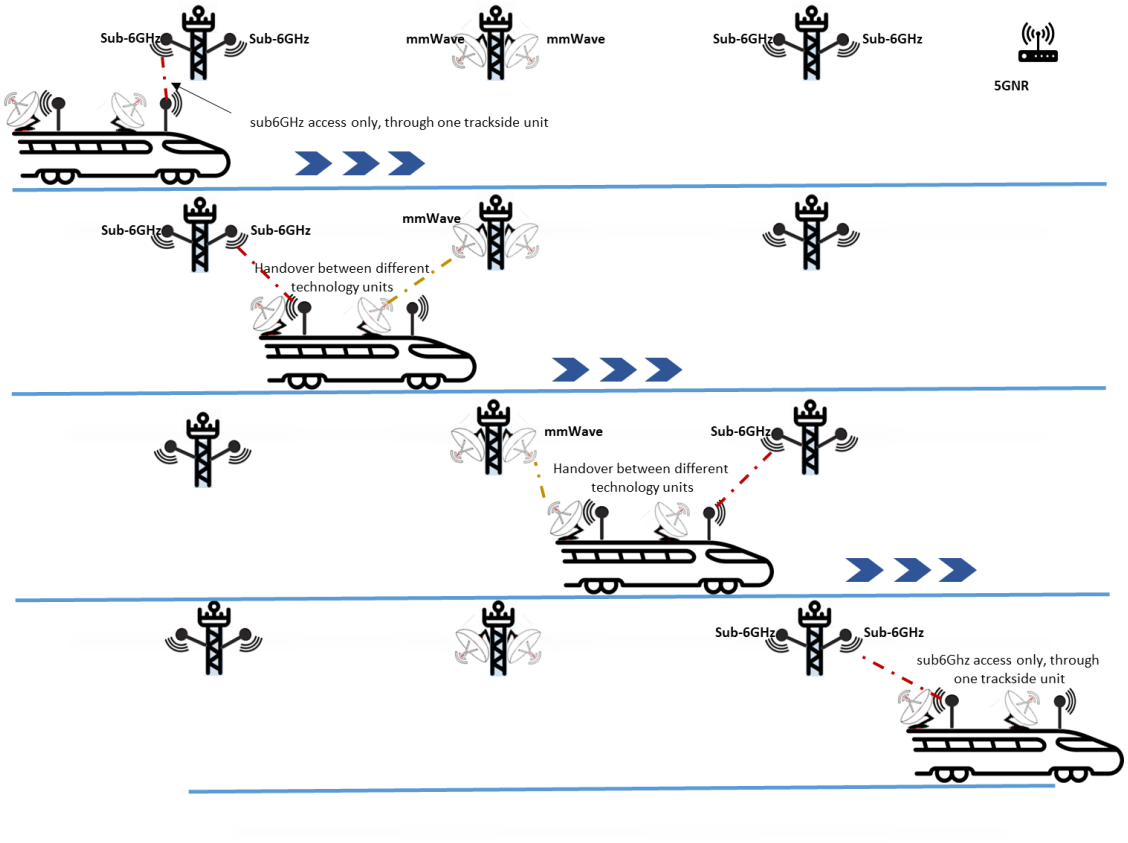

Figure 2-13: 5G mmWave track-to-train connections

2.6.3 Network slices for service delivery in rail transportation environments

The existing telecommunications infrastructure deployed at the railway environment includes several versatile telecommunication technologies and different public and private network deployments to serve the demand for versatile services from various end-users. These practices, are pushing existing networks deployed in the railway environment to their limits, make it difficult to guarantee total coverage for all services along the extensive railway tracks, and are also leading to sub-optimal utilization of resources and slow service deployment. The standard succussing GSM-R, Future Railway Mobile Communication System (FRMCS) [2-22] addresses the current network inefficiencies and meets the requirements of the aforementioned services. It is considered as key enabler for rail transport digitalization and reflects the technology neutrality and network services' logic of 3GPPP 4G/5G standards, tailored to the specific services' requirements and deployment challenges of the railway environment

In particular, *Business services* refer to communication and broadband connectivity services provided to passengers present at railway facilities, i.e., at the train stations/ platforms, on-board. These services include infotainment, digital mobility, travel information services etc. The *Performance services* category includes non-critical services related to train operation, including infrastructure monitoring and maintenance services. Usually, these services are deployed and consumed inside the railway facilities environment, so the service deployment will consider this aspect, like for example CCTV services for supervision of the rail tracks quality and provision of maintenance when needed will be used as example. *Critical services* are related to train operation/ movement, railway automation and operation control systems, trackside maintenance, emergency and safety services, etc., and involve information exchange between various users/ stakeholders, e.g. railway infrastructure operators, train operators, railway staff, railway first responders, etc.

Usually, these services are deployed and consumed inside the railway facilities environment, so also in this case the service deployment will take this aspect into consideration. Examples of these are Mission-Critical Push-to-Talk (MCPTT) and Mission Critical Data (e.g. between the controller(s) at the train/ operations centre and the driver/ on-board staff etc.)

The on-board hosted services correspond to three different slices, which are instantiated concurrently for providing the required network substrate to the hosted services. The three services correspond to three different slices; 1) an eMBB slice, for providing on-board users with high-speed Internet connectivity and video streaming services, 2) an eMBB and URLLC slice, for providing a low-latency and high-bandwidth connection for the track-monitoring service to the cloud, and 3) a URLLC slice for providing low-latency communications for a MCPTT service needed for the operation control of the railway system.

Regarding the first slice instantiation, it spans the entire network from the Data Centre to the train on-board, across several of the deployed components. It focuses on providing seamless connection as the train crosses the different track-side stanchions, facilitated by a mobility management solution, and focuses on providing high-speed network connectivity to the cloud. The components across which the eMBB slice is instantiated comprise all backhaul and fronthaul elements and mobility management modules and functions.

Regarding the second slice instantiation, it relies on high-speed and low-latency communications for transmitting the track video footage in real time to the rail Operation Control Centre (OCC). As the OCC is instantiated in the data centre, the slice spans the entire network as well (on-board, track-to-train, track-to-cloud) and adopts characteristics of both eMBB and URLLC. The components comprising the slice for the second service comprise all technology elements together with application specific modules.

Finally, for the MCPTT service running on-board, the network is requested to provide a URLLC slice. The MCPTT service that is used does not have stringent requirements in terms of throughput, but relies on low-latency connections that ensure the smooth operation of the system. As MCPTT relies on a server instantiation for managing the connections among terminals, the server is instantiated in the data centre. Therefore, the URLLC slice will span the entire network from the cloud to on-board train.

2.6.4 E2E network architecture extension for digital mobility services related KPIs

5GUK Test Network [2-11] has integrated multi-vendor, multi-architectural and multi-RAT designs in order to enhance current telecommunications services for a number of futuristic digital mobility use case demonstrations incorporating three different applications: APP1, APP2 and APP3. These applications have been defined according to the requirements set by the Digital Mobility UC-Bristol [2-5], as follows:

- APP1 provides immersive media and VR services to travellers arriving at MShed. A synchronous 360° tour guide at specific geolocations is given to a group of users with 5G connectivity. In order to support user mobility, the facility at Bristol provides seamless connectivity to users when they are moving from one location to another, even during a boat trip. Edge synchronization and streaming server services need to follow user mobility and move to different edges accordingly. By doing so, a seamless virtual tour guide is realised along the demonstration route in the city of Bristol.
- APP2 implements a remote training class taking place at the University of Bristol. Users with access to the 5GUK test network or the network at University of Patras can stream the 360° VR camera feed in real-time and at any location covered by the 5GUK test

network or any of the two networks. This demonstration uses a service slice creation that spans across the corresponding edges connected via an Infrastructure Operating System (5G-VIOS) [2-23].

- APP3 takes advantage of low-latency, high-throughput 5G connectivity to provide real-time AR services. An AR journey takes place along the demonstration route (footpath and river) and includes a visit to SS Great Britain location before ending at Millennium Square (Msquare). Network services such as synchronisation, spatial data renderer/ visualiser, journey planner, and video streaming services are deployed and run at edge and backend servers. Collection of user information including GPS location data is required to predict user mobility and reduce the latency between the handover of edge services. Furthermore, the developed Android application provides passengers with location-specific guidance and multi-modal transport journey planning beyond the starting location using AI techniques. Backend GPU clusters deploying high-end GPUs provide the required AR and AI processing at each of the edges.

Figure 2-14 provides the design of the E2E network architecture to support the demonstration of the digital mobility use case within the 5GUK Test network architecture. An integrated instance of Zeetta Automate (NetOS) is running at each stationary network edge and configures network slices on the required transport network switches. 5G-VIOS instructs Zeetta Automate to create/modify/delete network slices within their assigned edge nodes, whereas the Inter-Edge Connectivity Manager within the 5G-VIOS is responsible for the inter edged slice management.

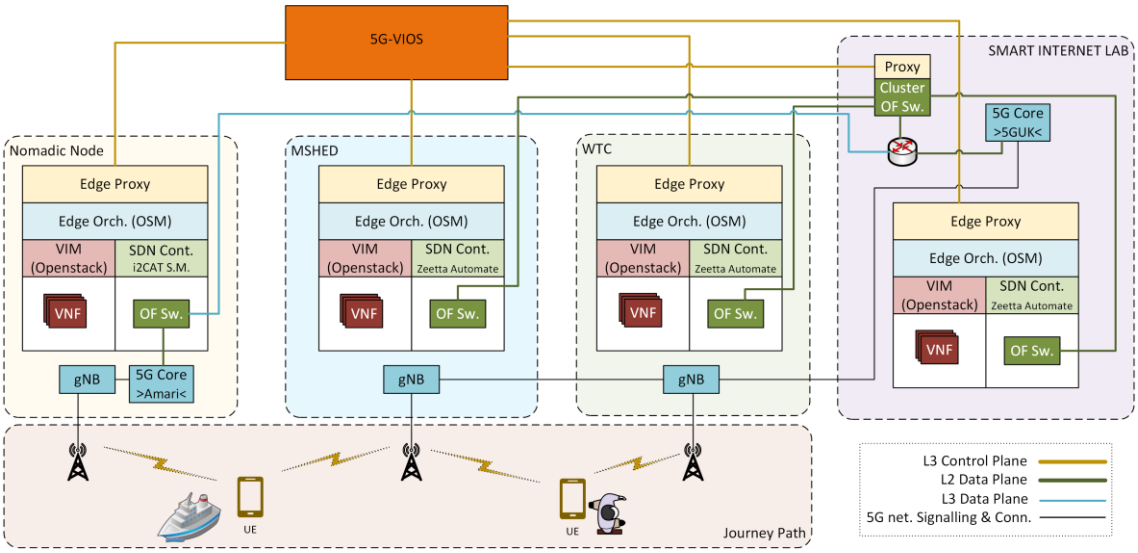

Figure 2-14: E2E network architecture for demonstration digital mobility

Furthermore, 5G NR and Wi-Fi solutions are integrated in the 5GUK test network to support the required mobility services at the nomadic edge while also improving the 5G coverage at the area surrounding SS Great Britain, and at locations where the 5GUK coverage is not sufficient. In addition, a Slice Manager component is responsible for network slicing at the nomadic edge.

Compute resources are available at MSquare, MShed and Smart Internet Lab network edges, all of them being capable of providing the required MEC services to the mobility applications. Additional compute resources are also available at the Nomadic edge. In order to reduce the edge services provisioning time and service mobility latency, MEC capability must be deployed closer to the end-user, i.e., at the network edges (MShed, MSquare, SS Great Britain). Despite the relatively weaker backhaul performance at SS Great Britain in terms of latency and throughput, local MEC services ensure seamless mobility within the required latency/throughput KPIs.

For more information regarding Multi-Domain Orchestration, 5G-VIOS, Inter-Edge Connectivity Manager, automation, slice management as well as integration of 5G NR and Wi-Fi please refer to [2-9] and [2-24].

2.6.5 Architecture for professional content production

The aim is to develop, integrate, validate and demonstrate specific 5G components in E2E 5G infrastructures consisting of core network (5GC), radio access network (RAN) and end devices for professional audio-visual (AV) media content production (see Figure 2-15). Three specific use cases (UC) are addressed for its deployment, integration, and evaluation: (i) live audio production, (ii) multiple cameras wireless studio, and (iii) live immersive media production.

The live audio production use case (UC1) implements a full integration of audio capture devices, 5G RAN and the production site. For the multiple camera wireless studio use case (UC2), a set of wireless cameras contribute AV content via 5G to a remote or on-site production room. Finally, the third use case delivers live immersive media services (UC3) through a set of cameras wirelessly connected via 5G to the production room, from where the content will be delivered on site via millimetre waves (mmWave) or remotely.

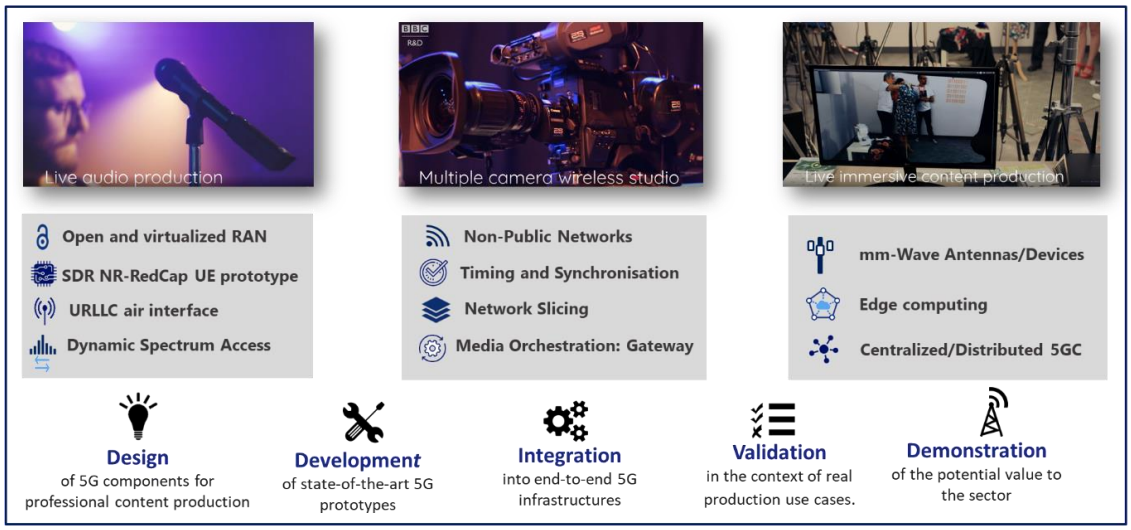

Figure 2-15: 5G key enablers for professional AV content production

For each use case, three fully functional network infrastructures and testbeds are provided, located in: (i) Sophia Antipolis, France, for UC1, (ii) Aachen, Germany, for UC2 and (iii) Segovia, Spain, for UC3. These infrastructures support 5G 3GPP Release 15 at the beginning of the project and 3GPP Release 16 by the end of the project [2-25]. Note that there are no content production specific items in Release 15 or Release 16. For this reason, partners may try and adapt some of these releases to inform requirements for Release 17/18 and explore Release 17 extensions.

The most stringent requirements are associated with the capture of content using uplink connections, where content acquisition devices such as cameras and microphones are connected to a 5G network to convey live content from a specific event, such as a music festival or a sports game, to the studio [2-25].

The goal is to go beyond existing capabilities and technologies. Integrating audio PMSE applications into 5G will facilitate new ways of AV production. The use cases architecture consist of the following 5G components:

- *End devices*: 5G-enabled wireless microphones and IEM systems as well as Software Defined Radio (SDR) prototypes for the live audio production use case; SMPTE (Society

of Motion Picture and Television Engineers) 2110–5G gateway and 5G modems for the multiple camera wireless studio use case; and free-viewpoint (FVV) systems for the live immersive media production use case (UC3).

- *Radio Access Network*: dynamic spectrum access techniques and virtualized RAN to deliver true multi-vendor, disaggregated and RAN intelligent control (RIC) services for UC1; RAN equipment working on the 3.7-3.8GHz band for UC2; and mmWave equipment for UC3.
- *Core Network*: For all use cases, a complete and flexible 5G core is used, which includes additional new network functions, network slicing solutions based on SDN as well as edge computing processing.
- *Orchestration and management mechanisms*: media orchestration and control implemented via operational control gateway and operational control adaptation layer implemented through media gateway.

2.6.6 Intent-based E2E network slice deployment for verticals

A vertical service layer on top of the 3GPP slice management system, as proposed in [2-28] and [2-29], provides the management logic to coordinate the provisioning and the actions controlling the lifecycle of vertical services deployed in 5G networks. Starting from verticals' intents, expressed through vertical service blueprints and descriptors, this layer identifies the characteristics of the end-to-end network slices required to meet the application requirements, selecting the suitable slice templates. Such templates are then used by the slice management entities to drive the provisioning of the network slice subnets related to the access, core and transport networks, together with the virtual functions or applications associated to the vertical service, on the basis of the slice and service profiles (see Figure 2-16). Further details on the approach to manage network slices for concurrent vertical services, translating the service requirements and arbitrating the slice resources across multiple services, are described in section 5.2.1.

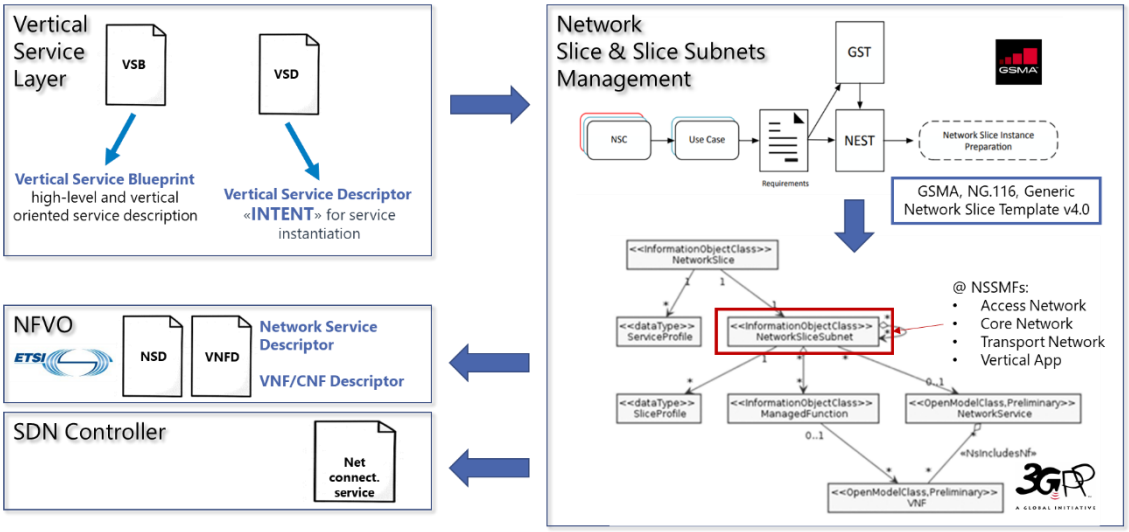

Figure 2-16: From vertical's intent to end-to-end network slice deployment

2.6.7 NetApp principles and implementation aspects

A Network Application (NetApp) is a software piece that interacts with the control plane of a mobile network by consuming exposed APIs (e.g., Northbound APIs of 5G core and/or MEC APIs) in a standardized and trusted way (i.e., for a 5G network a NetApp should be CAPIF [2-26] compliant) to compose services for the vertical industries. A NetApp provides services to vertical

applications either as an integrated part of the vertical application or by exposing APIs, which are referred to as business APIs.

The NetApp ecosystem is more than the introduction of new vertical applications that have 5G-interaction capabilities; it refers to the request for a separated middleware layer that will simplify the implementation and deployment of vertical systems at large scale (considering also the adaptation needed for Non-Public 5G Network – 5G NPN deployments). This is the same request that triggered the development of Vertical Application Enablers (VAE) by 3GPP SA6 [2-27].

Considering the level of interaction and trust, the NetApps are classified to:

- Third-party NetApp. NetApp that resides at a trusted third-party domain. A third-party NetApp consumes Northbound APIs and, also, supports trust mechanisms and security policies defined by the network for the verticals.
- Operator NetApp. NetApps that reside at the operator domain, considering mainly NPN deployments, and, potentially, it can have further access to 5G network capabilities, beyond those provided through the Northbound APIs (e.g., vertical specific functionality at the OSS for slice management) and are available in a third-party NetApp.

Considering the way that the services are provided to verticals, the NetApps are classified to:

- *Standalone NetApp* that provides complete services to one or more vertical industries, either directly or through its integration to a vertical application. A NetApp that is integrated into a vertical application, enhances the functionality of the application by adding network management and monitoring capabilities exposed by the 5G network.
- *Non-Standalone NetApp* that operates as a wrapper of Northbound APIs to expose services through Business APIs. It is an auxiliary non-standalone software piece (in the sense that it becomes functional when its business APIs are consumed by an app). A Non-Standalone NetApp allows vertical applications to be developed/upgraded (and take advantage of the 5G exposure capabilities) without changing integral parts of their software, i.e., only by consuming the business APIs.

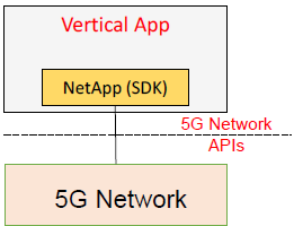

Figure 2-17: Third-party Standalone NetApp representation

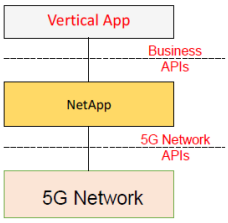

Figure 2-18: Third-party Non-standalone NetApp representation

From architectural perspective, a NetApp is part of the Vertical Application Server (VAS) as defined by [2-27].

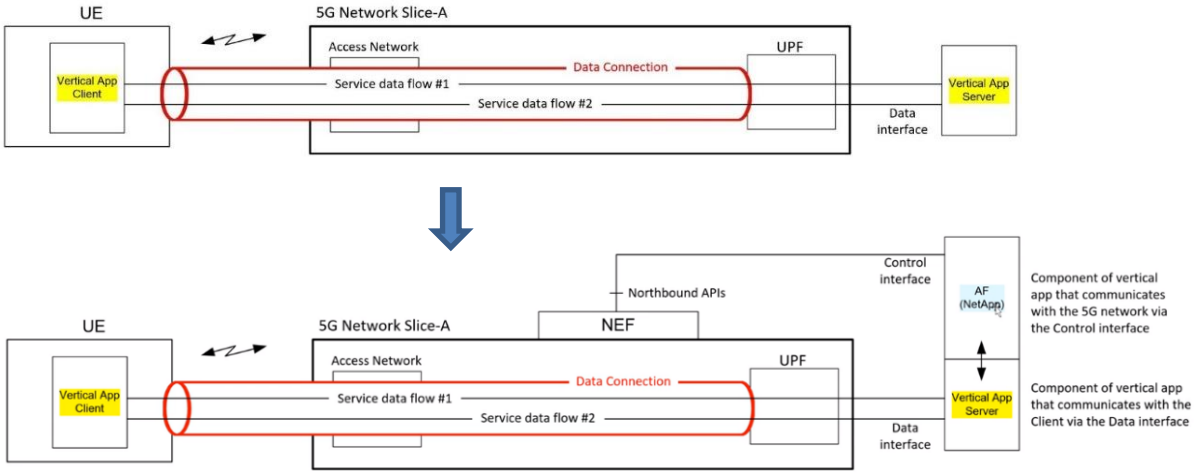

Figure 2-19: Adding the NetApp concept in the service provisioning chain

As Northbound APIs are considered the NEF, SEAL, and any other APIs emerge through 3GPP Release 17 (e.g., FF VAE). Trust and security aspects for consuming those APIs are addressed by the CAPIF core function.

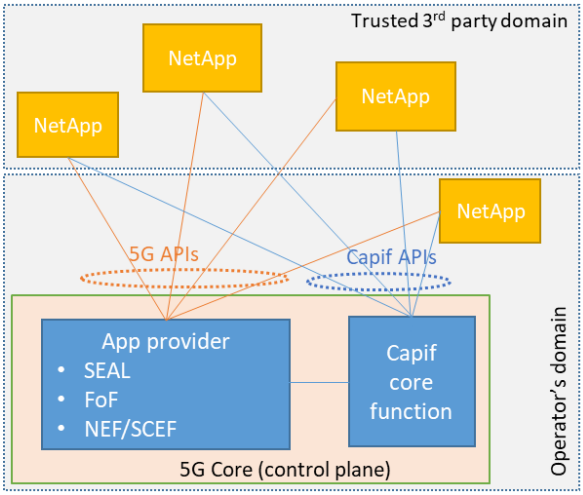

Figure 2-20: NetApps consuming 5G Northbound and CAPIF APIs

The following implementation remarks can be made in relation to the NetApp concept.

- A NetApp can be virtualized/containerized to reside at any trusted 3rd party domain or in the operator's domain. Container based NetApps are considered in the EVOLVED-5G project
- Any NetApp includes a client to consume 5G APIs. The Basic NetApp expose REST APIs (business APIs) as well.
- The NetApps are instantiated during the development time of a VAS.
- The NetApp developer creates the required APIs (other implementation options might use API frameworks)
- NetApp will essentially be a small REST API app

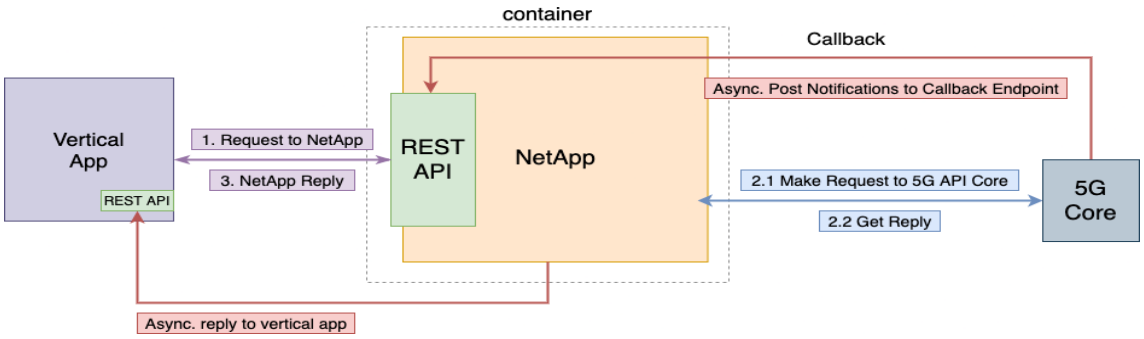

Figure 2-21: NetApps implementation flow

2.7 Public-Private Network Interoperation

Table 2-7: Public-Private Network Interoperation

Architectural solution	5G PPP Project	Additional Reference
Public-Private Network Interoperation	5G-VINNI	[2-31]

The system demonstrated in [2-31] can be a facilitator for PNI-NPN provisioning, where the experimentation facility is taking the role of PLMN, and vertical provider sites (e.g., private sites like industry 4.0 factories, campus, transportation hubs, etc.) are taking the role of private networks. There are two basic options to provide a PNI-NPN, namely: (i) access to the NPN can be made available using dedicated Data Network Names (DNNs), or (ii) a network slice can be dedicated to an NPN with various levels of shared resources and functions between the NPN and PLMN. In [2-31] the second option is assumed.

Besides allowing the concurrent execution of multiple services on a common shared network infrastructure, network slicing for PNI-NPN provisioning can be used, providing private sites with dedicated slices using Network Slice as a Service (NSaaS). Figure 2-22 illustrates how the facility operator can rely on NSaaS capabilities for the provisioning of a PNI-NPN towards a customer, typically an industry vertical. This PNI-NPN, which is deployed across one PLMN and the vertical's premises, can be seen as an end-to-end network composed of two differentiated segments: one private, consisting of network functions deployed in-house, using private 5G resources; and one public, consisting of network functions built upon public 5G network resources. The following PNI-NPN features can be implemented using the NSaaS approach:

- The public segment is made available by the PLMN in the form of a dedicated slice, and provisioned by the experimentation facility using NSaaS. In this service provisioning, the facility operator and the vertical play the roles of CSP-A and CSC-A, respectively.
- The vertical adds the private segment to the network slice obtained from the experimentation facility. The resulting combination (PNI-NPN) is a new network slice. Following 3GPP TS 28.541 Network Resource Model (NRM) [2-32] the PNI-NPN's public segment can be modelled as a network slice subnet. In this case, the vertical plays the role of NOP-B.
- The vertical uses the network slice to provide (non-public) communication/digital services to its customer(s). In this regard, the vertical and its customer(s) play the role of CSP-B and CSC-B, respectively.

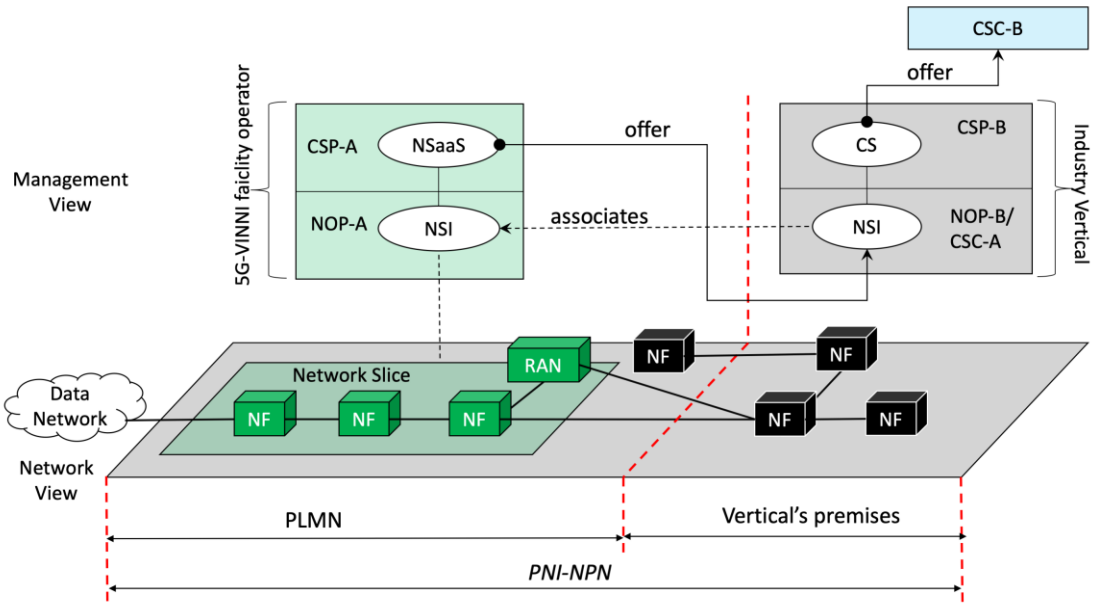

Figure 2-22: Network Slice as a Service in 5G-VINNI

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3 Radio and Edge Architecture

The deployment of upcoming 5G technologies is causing key architectural changes based on new paradigms in the radio access design such as disaggregation, extreme densification, virtualisation and edge computing. In this chapter, the architectural aspects related to radio access network (RAN), edge computing, and localisation technologies in beyond 5G solutions are discussed.

3.1 RAN architectures

Beyond 5G RAN architectures are facing unprecedented challenges on several fronts, some of which will be discussed in this section. The leveraging and integrating the 5GNR, and legacy cellular radio interfaces, with non-3GPP access technologies such as the traditional ones operating in unlicensed spectrum (Wi-Fi) and newer ones operating on visible light wavelengths (LiFi) are key to enable the aggregation of further spectrum as a key requirement to support 5G use cases. A practical approach to address the issue is to, firstly aggregate the non-3GPP access technologies, i.e., Wi-Fi and LiFi, and then integrate them to 5GNR, e.g., by means of introducing enhancements on the 3GPP access traffic steering, switching and splitting (ATSSS). On the other hand, the emergence of beyond 100 GHz (THz) communications technologies introduces new challenges in connectivity, both in maintaining a stable link when there is no line-of-sight, and also in creating multipath richness to exploit radio channel capacity. One way to approach this problem is by employing AI assisted Reconfigurable Intelligent Surface (RIS) to direct the radio signal into one or more desired/preset directions. Another aspect in the design of advanced RAN architectures is the alignment of any proposed radio architecture to the principles defined in O-RAN alliance to support and accelerate innovation and commercialization in RAN domain with multi-vendor interoperable products and solutions that are easy to integrate in the MNO's network and are verified for different deployment scenarios. The network applications (xApp) facilitating such integrations are crucial for the new radio architectures. In addition to the above, network slicing, as one of the innovations introduced in 5G, provides tailored networking solutions to vertical services over a common infrastructure. Network slicing in the RAN domain is mainly based on resource allocation. In the end, use case specific architectural considerations for media production environments are presented, focusing on three specific scenarios introduced in Chapter 2.6.5.

Section	Title	Project	References
3.1.1	Multi-technology wireless access network	5G-CLARITY	[3-3], [3-4]
3.1.2	Enhanced ATSSS	5G-CLARITY	[3-3], [3-4]
3.1.3	THz RIS and AI based Radio Access Optimisation	ARIADNE	[3-10]
3.1.4	O-RAN Alliance xAPPs	5G-CLARITY	[3-3], [3-4]
3.1.5	Integration of 5G RAN with Audio Capture Devices and Production Site	5G RECORDS	[3-38]
3.1.6	Intro and inter slice scheduling algorithm	5G-DRONES	[3-37]

3.1.1 Multi-technology Wireless Access Network

Multi-technology wireless access networks can be considered as an integrated network across a wide range of 3GPP (LTE, 5GNR) and non-3GPP (IEEE 802.11 Wi-Fi) access technologies. When the term non-3GPP access is used, a general understanding is on utilizing Wi-Fi networks. However, recent efforts on optical wireless communications pave the way of light-based wireless systems, termed light fidelity (LiFi), to be part of IEEE 802.11 family as IEEE 802.11bb. Having multiple non-3GPP access networks has enabled a different categorization of multi-technology wireless access networks as:

- All 3GPP: includes 3GPP-only access technologies, particularly LTE and 5GNR.
- Non-3GPP only: includes non-3GPP access only technologies, namely Wi-Fi and LiFi.
- 3GPP and non-3GPP: comprises a combination of 3GPP and non-3GPP access technologies, such as LTE/5GNR with Wi-Fi/LiFi.

Specifications for aggregation within 3GPP access networks, e.g., dual connectivity (DC) and multi-radio dual connectivity (MR-DC), and between 3GPP and non-3GPP access networks, e.g., LTE WLAN aggregation (LWA), WLAN radio level integration with IPSEC tunnel (LWIP), and recently non-3GPP inter working function (N3IWF), have already been defined by various 3GPP technical specifications. However, aggregation within non-3GPP access network has only been covered by high level research efforts that combine the high-speed downlink data transmission and higher spectral efficiency capabilities of LiFi and the ubiquitous coverage of Wi-Fi networks [3-1], [3-2]. A practical approach on integrating Wi-Fi and LiFi networks within a single SDN enabled layer 2 (L2) network is proposed [3-3], [3-4], with the following motivation in mind for using a customized L2 SDN network: (i) to provide the ability to control the path followed by packets belonging to different slices within the L2 segment with fine granularity as compared to a standard IEEE 802.1 Ethernet segment; and (ii) to support seamless mobility, meaning that when user devices roam through the various Wi-Fi and LiFi APs connected to the L2 SDN network, forwarding paths can be automatically updated. Once the Wi-Fi and LiFi networks are integrated in order to compose a single non-3GPP access network, the existing mechanism to integrate 3GPP and non-3GPP networks such as N3IWF or trusted network gateway function (TNGF) can be used in combination with 3GPP access traffic steering, switching and splitting (ATSSS) framework to have an integrated 5G/Wi-Fi/LiFi network. Figure 3-1 illustrates an overview of the 3GPP and non-3GPP based multi-technology wireless access networks.

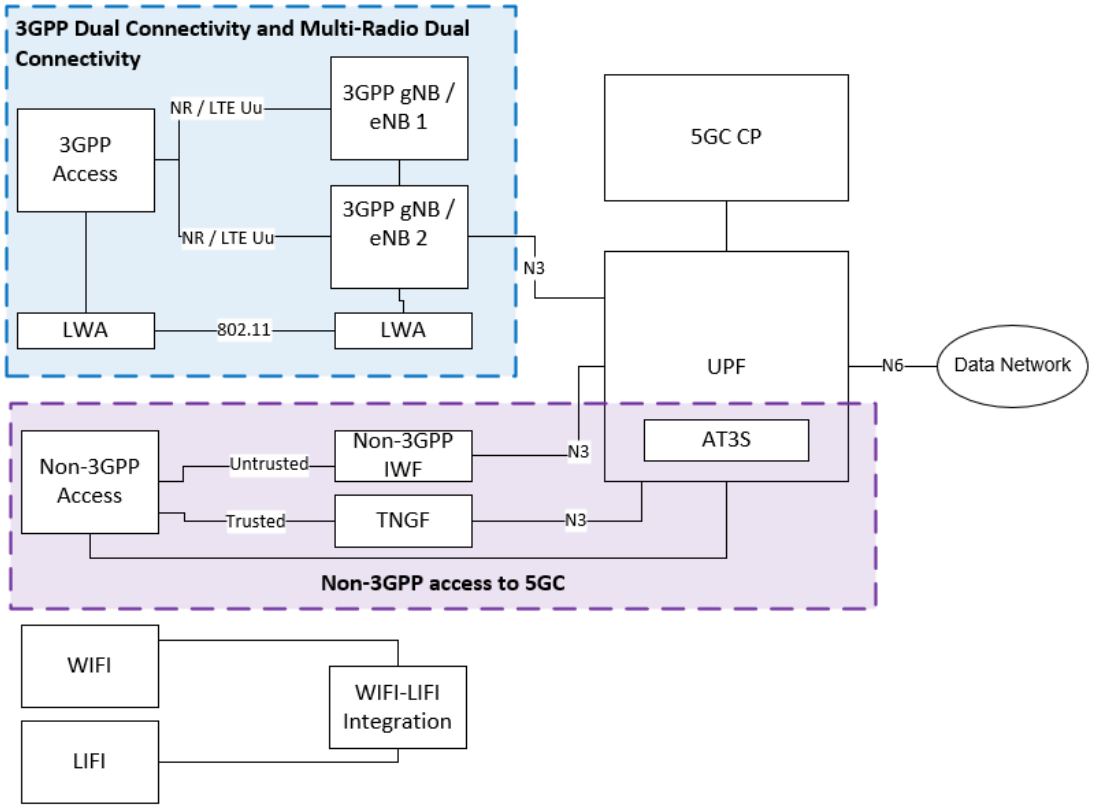


Figure 3-1: Overview of the multi-technology wireless access networks

3.1.2 Enhanced ATSSS

3GPP Release 16 Access Traffic Steering, Switching, and Splitting (ATSSS) framework considers steering procedure to send a traffic flow through 3GPP (5GNR) and/or non-3GPP network (integrated Wi-Fi/LiFi network) in four different modes as active-standby, smallest delay, load-balancing and priority-based. When either the active-standby or priority-based steering mode is selected, a priority information element is used to indicate at which condition 3GPP or non-3GPP access network is used to transmit the data flows. However, when the load-balancing steering mode is selected, a weight factor is used to indicate the proportion of the traffic to be forwarded to 3GPP and non-3GPP access networks.

The traffic steering, switching and splitting strategies enforced via ATSSS rules are based on predefined values for either all traffic types or some specific traffic type such as UDP or TCP to a specific IP address or port. For example, if the load-balancing steering mode is selected, a predefined percentage value has to be used for 3GPP and non-3GPP access networks, such as 20% for 3GPP and 80% for non-3GPP. In another example, the priority-based steering mode can be selected to prevent congestion over 3GPP network. Then, high priority is assigned to non-3GPP network to offload the 3GPP network traffic. All these rules are preconstructed and ordered in a way that as long as a data flow matches a rule, the data flow gets routed according to this rule and the remaining rules are not considered. While traffic is routed according to a specific rule, sudden changes on the network status such as link availability due to CSI fluctuations, link blockage or network congestion will not be incorporated to traffic routing. In this context, an enhanced ATSSS framework, named eAT3S, is proposed to resolve the issue by introducing another steering mode, named *real-time steering mode* [3-4]. The real-time steering mode is described as the ATSSS rule with the highest priority (Rule #1) and will be adaptive to link conditions and network status. An example flowchart for ATSSS rules with eAT3S real-time steering mode is shown in Figure 3-2. Based on the given flowchart, if there is a congestion on

non-3GPP network and the load-balancing steering mode is used to enforce 80% for non-3GPP network, the real-time steering mode/rule modifies/overwrites the weight factor for each access network to 40% for 3GPP and 60% for non-3GPP to optimally utilize available 3GPP and non-3GPP access networks, aka the integrated 5G/Wi-Fi/LiFi network.

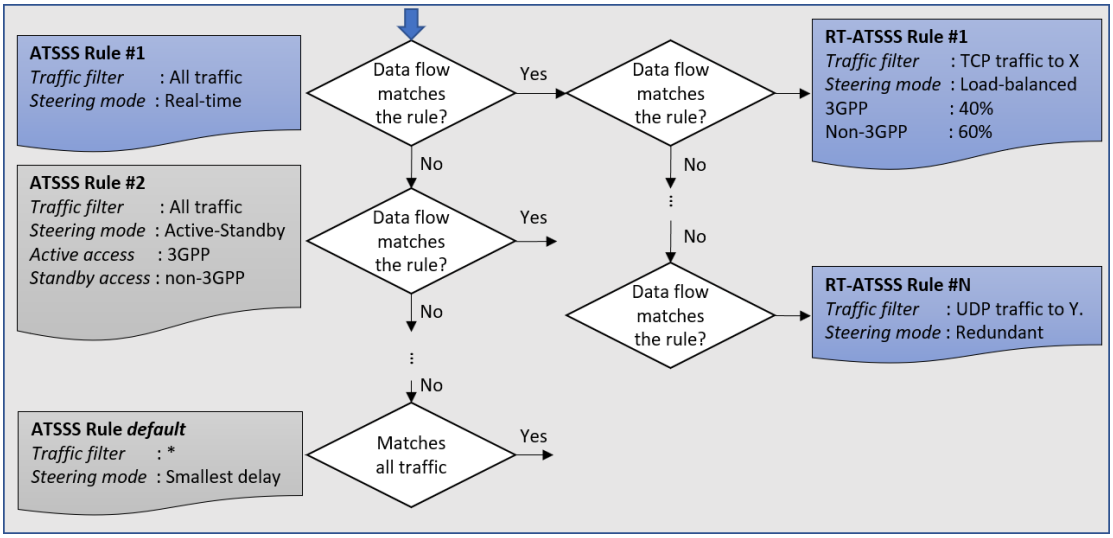


Figure 3-2: An example of the proposed ATSSS rules with eAT3S real-time steering mode. Blue rule boxes represent the eAT3S rules and grey rule boxes represent the existing ATSSS rules.

3.1.3 RIS and AI based Radio Access Optimization

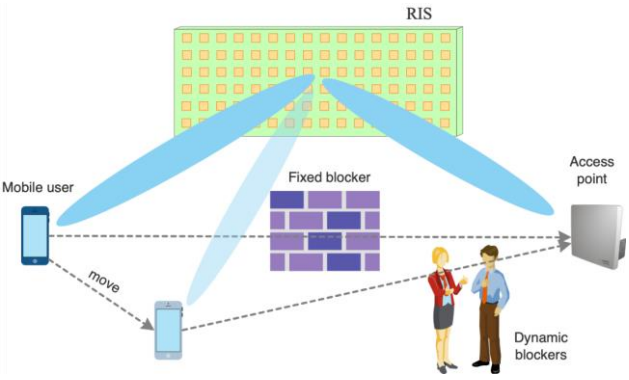
Bringing to fruition the notion of AI-aided D-band wireless beyond 5G networks entails the challenges of devising a flexible and powerful ML-based wireless network optimization framework, introducing novel propagation and channel modelling principles and developing cutting-edge technology components, such as beamforming antenna arrays, metasurface-based intelligent materials, RF-frontends, baseband processing, medium access control protocols [3-5], [3-6], [3-7], [3-8], [3-9].

In this section, the technology and concept of RAN with metaserface is introduced, and then three deployment scenarios for it are discussed.

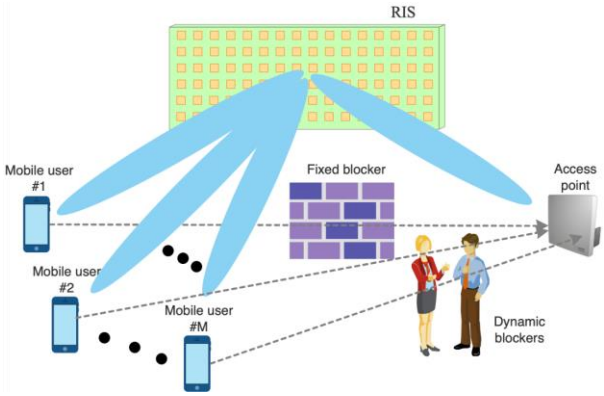
3.1.3.1 RAN with Smart Surfaces

The RISs are expected to significantly improve wireless systems performance when the line-of-sight (LOS) path is either permanently or temporarily blocked. One of the greatest challenges in the reconfiguration of the RIS is beam tracking, since the reconfiguration often needs to be realized in a faster pace due to the possible movement of the users. In addition, due to the challenging nature of pencil-beam tracking in scenarios involving movement of users, it may be necessary that the beamwidth of the transmit and receive antennas is *increased* so that the possible misalignments do not cause a substantial drop in signal quality.

RIS can independently configure the phase-shift of the incident electromagnetic (EM) wave. This motivates the investigation of two key functionalities of RIS, namely (i) beamforming, and (ii) broadcasting. An illustration of the scenarios corresponding to these functionalities is provided in Figure 3-3. Even without reconfiguration, the metasurface can be used to overcome the limitations of the NLOS scenario by reflecting and focusing waves to the desired location/direction. Moreover, it can be used for enriching the multipath profile by reflecting waves into several directions behind obstacles, creating multiple reflections in the indoor scenario.



(a)



(b)

Figure 3-3: (a) RIS-assisted beamforming, and (b) RIS-assisted broadcasting

The ***RIS-assisted beamforming scenario*** is when a single TX communicates with an RX through a RIS. The TX and RX are equipped with multiple antennas and can perform analog, hybrid, or digital beamforming, based on the number of the available RF chains. Additionally, RIS consists of a number of unit cells. Each unit cell can independently phase shift the incident EM wave. The signals reflected by all the unit cells of the RIS to the RX are aligned in phase in order to enhance the received signal power. In other words, the RIS can operate as an analog beamformer, whose characteristics depend on the RIS unit cell dimensions, radiation pattern, and number.

When a UE initially requests access to the RIS-assisted system, an initial access procedure needs to begin in order for the RIS to acquire knowledge concerning the TX-RIS and RIS-RX channels and to decide which unit cells should be turned ON and OFF. However, conventional RIS structures are passive units without any sensing capabilities; thus, channel estimation is not an easy task. A possible approach to channel estimation might be to divide the total estimation time into a number of periods. During each period, a different subset of unit cells will be ON, while all other unit cells subsets will be OFF. Energy detection will be performed at the RX, in order to determine the optimum RIS configuration. The main problem of such an approach is that as the number of unit cells increases, the channel estimation time also increases. Inspired by this, this scenario motivates the use of *machine learning* approaches that may limit the *initial setup latency*.

The indoor wireless environment constantly changes due to the existence of dynamic blockers and UE movement. As a result, the RIS should be continuously fed with new configuration parameters, in order to provide almost-uninterrupted connectivity with almost zero *adaptation-latency*. As in the initial access phase, the use of exhaustive search approaches would result in unacceptably high latency. Therefore, ML-based approaches need to be introduced. Apart from latency, these approaches need to guarantee high reliability, by minimizing the beam misalignment and the probability of blockage.

The ***RIS-assisted broadcasting*** scenario, a single AP is used to serve several UEs through a RIS. This setup can be used for both uplink and downlink applications. Especially, a possible application in the downlink might be for a scenario in which the same content needs to be delivered to several UEs. We assume that the AP and the *n*th UE can perform analogue, hybrid, or digital beamforming, based on the number of RF chains. Additionally, RIS consists of a number of similar unit cells. Both the AP and the UEs point at the RIS. Initial access and localisation procedures are performed for each UE, in order for the AP to acquire knowledge concerning the UE positions and channels. As in the previous scenario, this procedure will require the use of ML. Next, a clustering problem is formulated and solved by the AP. The solution of this problem is the RIS configuration that determines the RIS half power beamwidth. This setup is of high interest since it can enable access schemes, such as frequency division multiple access (FDMA) and non-orthogonal multiple access (NOMA).

3.1.3.2 Deployment scenarios

To realize this vision, the presented discussions is focused on carefully devised deployment architectures, which reflect the B5G requirements and expectations as described in Figure 3.4.

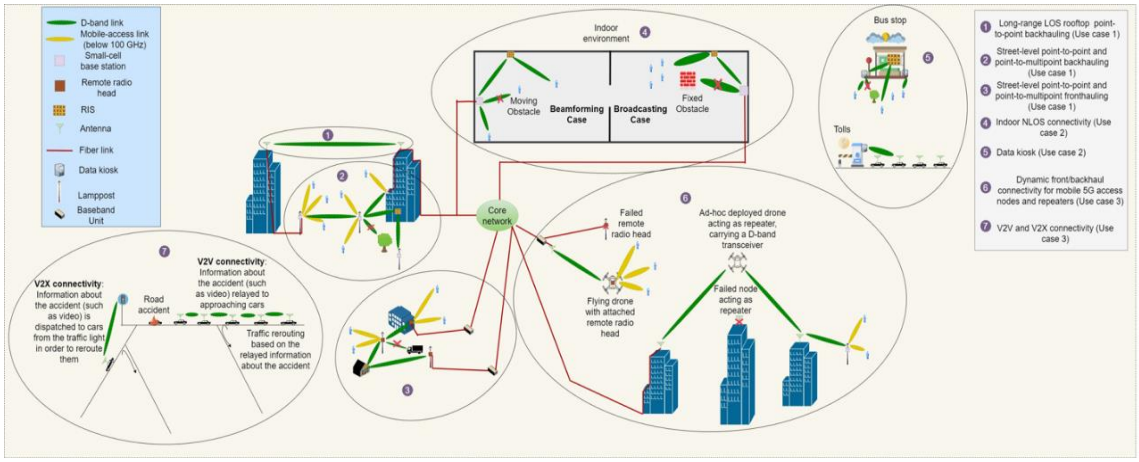


Figure 3.4 Reconfigurable surfaces deployment scenarios

The first deployment scenario to be considered is "**outdoor backhaul/fronthaul networks of fixed topology"**. Due to the forecasted exponential data rate increase, next-generation wireless backhaul/fronthaul networks will need to migrate towards the beyond 100 GHz spectrum in order to accommodate, through the higher offered bandwidth, the ever-increasing data-rate demands of mobile users. Hence, D-band comes as a solution to the expected capacity bottleneck of current outdoor backhaul/fronthaul networks. This deployment scenario can be considered as any of the following:

- Long-range LOS rooftop point-to-point backhauling
- Street-level point-to-point and point-to-multipoint backhauling/fronthauling

In the street-level scenario, the corresponding backhaul/fronthaul nodes are mounted on street objects, such as lampposts, or next to small-cell and remote radio head (RRH) nodes. Such communication can be either LOS or NLOS through RISs. In the latter case, when the LOS link between a transmitter and its intended receiver is blocked, the communication is assisted through an RIS acting as a reflector that is mounted on some nearby surface.

In the second deployment scenario, the "**advanced NLOS connectivity based on metasurfaces"**, a dynamically reconfigured RIS is used to track slowly-moving users. This reconfiguration occurs at a much higher pace than in the corresponding scenarios discussed for the *outdoor backhaul/fronthaul networks of fixed topology*, which introduces substantial challenges regarding

the type of switching elements among the unit cells that can achieve this, and also the tracking of the position of users and the estimation of their channels. The NLOS connectivity deployment scenario can be any of:

- RIS-based indoor advanced NLOS connectivity
- Data kiosk

Data kiosks are entities that allow the transfer of a very large amount of data in a very short time interval or offer very high data-rate at extremely low latency. In addition, to allow range extension of the data kiosks while at the same time counteracting possible blocked links due to passing users, for instance, we assume data kiosks that can steer their beams towards nearby RISs that act as reflectors and guide the redirected beams towards the intended users.

The third deployment scenario discussed here is the **"ad hoc connectivity in moving network topology"**, which is suitable for emergency scenarios in future networks where the deployment of the D-band spectrum is considered essential. The deployment scenario can be any of:

- Dynamic front/backhaul connectivity for mobile 5G access nodes and repeaters
- V2V and V2X connectivity

Drones are essential in emergency cases when backhaul/fronthaul nodes stop operating due to malfunction or in physical disaster scenarios. Due to the failure of an RRH, a drone is deployed with attached RRH to serve the affected users.

Vehicles can be equipped with D-band transceivers for reliable fast communication of road/traffic conditions to preceding cars. For instance, in case of a road accident on a highway the leading vehicle that has a LOS view of the accident can obtain a real-time video streaming from the accident that is relayed via LOS D-band links to approaching vehicles (V2V). In addition, a traffic light located close to the accident dispatches the real-time video streaming concerning the accident to vehicles approaching from other directions (V2X).

3.1.4 O-RAN Alliance xApps

The proposed radio architecture in this section [3-3] is aligned to the principles and reference architecture defined in O-RAN Alliance, which builds and extends on some of the 3GPP-defined normative interfaces leveraging SBA, CUPS and disaggregated RAN approaches. The O-RAN Alliance reference architecture is depicted in Figure 3-5.

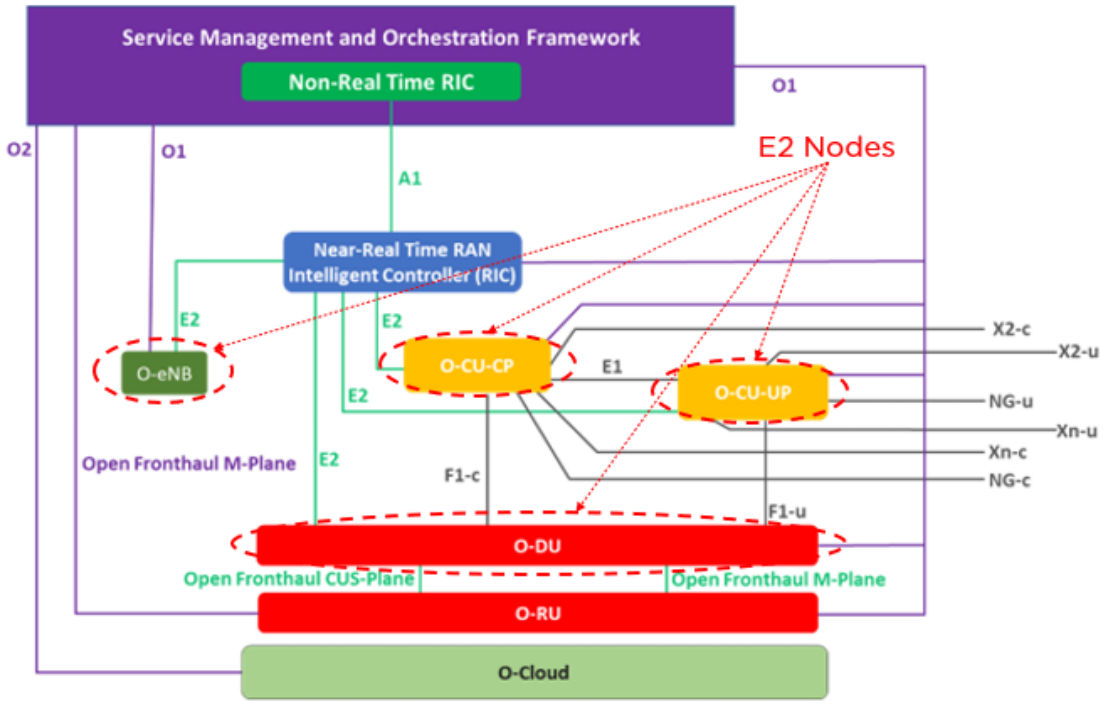


Figure 3-5: O-RAN reference architecture

The considered functions include near-RT-RIC and non-RT-RIC xApps enabled by the Accelleran dRAX™ solution as shown in Figure 3-6 [3-4]. The near-RT RIC is a logical function that enables near real-time control and optimization of E2 nodes (e.g. gNB-CU-CP, gNB-CU-UP, gNB-DU), functions and resources via fine-grained data collection and actions over the E2 interface with control loops in the order of 10 ms-1s.

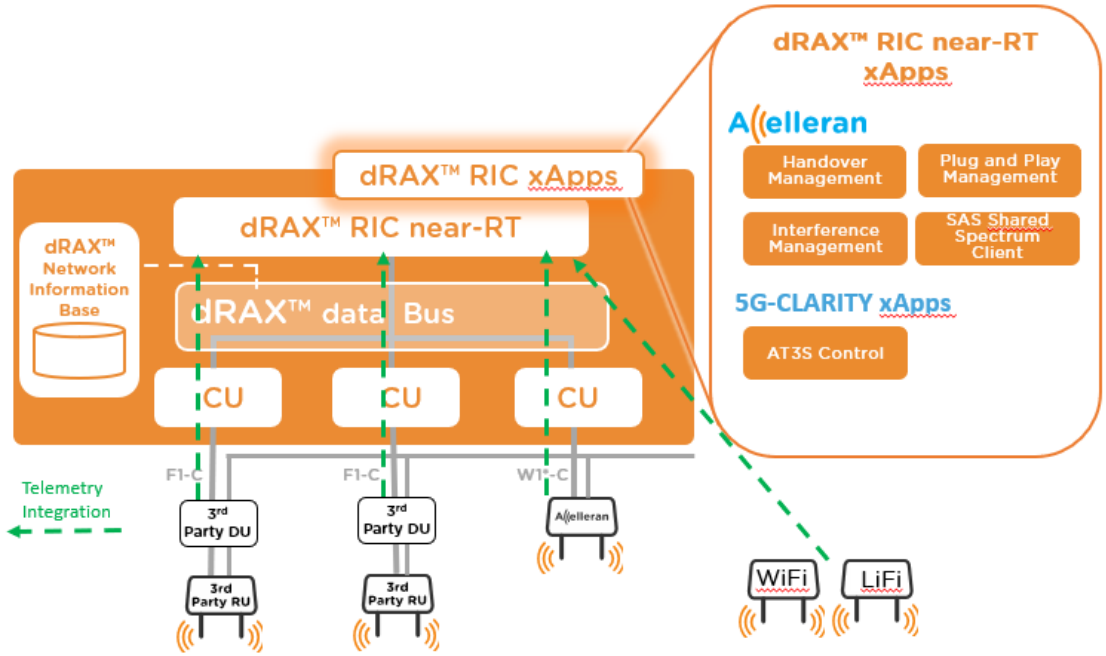


Figure 3-6: Accelleran dRAX™ with multi-WAT telemetry

The Accelleran near-RT-RIC can host different xApps that have access to the Accelleran data-bus to collect near real-time information and provide value added services. Typical default Accelleran xApps relate to usual network functions associated to handling a cluster of 5GNR small cells such as plug and play, interference management, handover management, etc. In this

specific scenario, the Accelleran dRAX is enabled with multi-WAT telemetry data from 5GNR, Wi-Fi and LiFi which is exposed via the Accelleran data-bus to the AT3S controller multi-WAT xApp as described in [3-4, Section 2.2]. Leveraging on Accelleran hosted xApps, the use of a dynamic spectrum access paradigm in 5G-NR can also be demonstrated via a spectrum access system (SAS) shared spectrum client which supports the use of co-existence groups. This could be used in coordination with other xApps responsible for typical SON functions such as interference management, handover management and automatic neighbour relation functionality.

3.1.5 Integration of 5G RAN with Audio Capture Devices and Production Site

This section describes how 5G connectivity is provided to all the necessary media equipment present in a media production environment. In Section 2.6.5, three specific use cases (UC) for system deployment, integration, and evaluation have been introduced: (i) live audio production, (ii) multiple cameras wireless studio, and (iii) live immersive media production. Section 2.6.5 presented also the key enabler and 5G components that facilitate the use cases. Herein we describe the architecture deployed for each use case and describe the involved components.

For **UC1**, 5G Ultra Reliable Low Latency Communications (URLLC) is the radio interface capable of meeting the stringent requirements of live audio production scenarios: latency, reliability, time synchronization and spectral efficiency. UC1 RAN architecture will use an open virtualized RAN aligned with the O-RAN Alliance. It provides an open and extensible software framework for the control plane functions of 4G and 5G RAN and follows the Open RAN architecture principles defined by both 3GPP and the O-RAN Alliance. The O-RAN 5G SA vRAN solution consists of a near-RT RIC, CU-CP, CU-UP and xApp framework components. Implementing 3GPP Control User Plane Separation (CUPS) allows the user and control planes to be fully decoupled. It supports 5G gNB using standards-based DU/RUs from the developing ecosystem of 5G Open RAN.

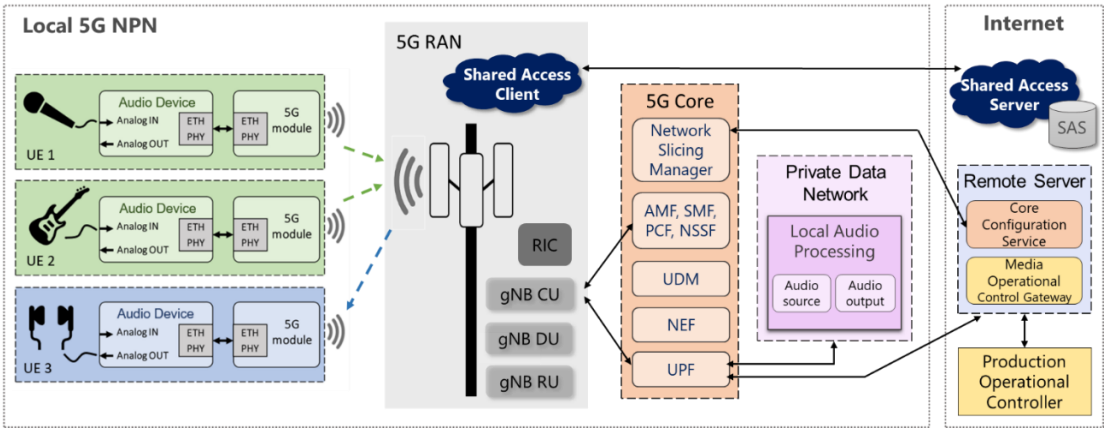


Figure 3-7: Architecture of the live audio production use case (UC1)

For **UC2**, the 5G system (5GS) is initially based on 5G Non-Stand Alone (NSA) setup and will migrate during the project to a SA (Standalone) setup. For the NSA 5GS, the RAN nodes include eNBs (for LTE anchor) and gNBs. The lab test system can be operated with different radio carriers. The prime focus is on the 3.8GHz industry band (mid band). Support for high band radio carriers needs to be coordinated. For the trial system, the plan is to work with the Industry Campus Europe (ICE) and to leverage the outdoor coverage. The architecture for the Industry Campus Europe Network is very similar as the lab setup. The outdoor coverage is realized using 3.7 GHz to 3.8GHz NR carrier (Industry spectrum). 5G modems will also be developed to connect the necessary media equipment with the 5G network, accessing it via the above mentioned gNBs.

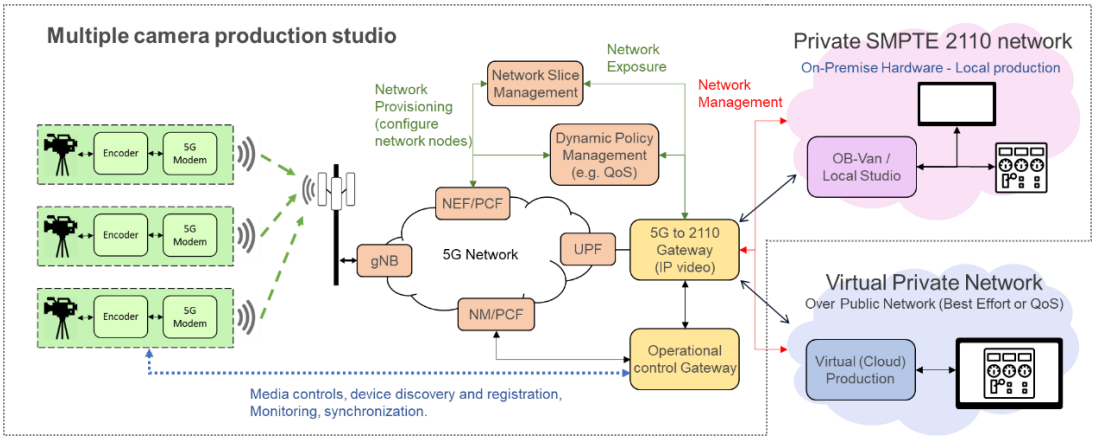


Figure 3-8: Architecture of the multiple camera wireless studio use case (UC2)

For **UC3**, a complete 5G infrastructure will make use of the 26 GHz 5G mmWave spectrum on a NSA 3X deployment, composed by: (i) compact, high-power small cells that will be used as eNBs and gNBs to offer a wide range of deployment options to ease installation considerations, and (ii) 5G Gateways (Fixed Wireless Access Customer Premise Equipment) that will be used as access points to the 5G network for the media acquisition equipment. In addition, an open edge server that supports edge and far-edge cloud deployments will be installed. The solution is complemented with a real-time, OPNFV compatible, OpenStack distribution built to provide the performance and low latency required by solutions like Cloud RAN. The open edge server is fundamental to distributing computing capacity in the network and driving the implementation of Cloud RAN, Multi-access Edge Computing (MEC) as well as5G.

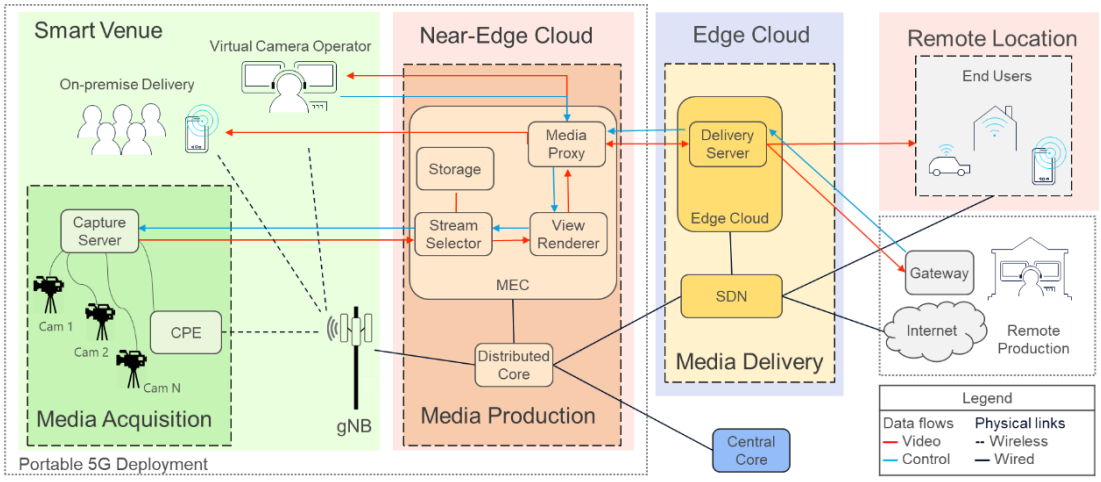


Figure 3-9: Architecture of the live immersive media production use case (UC3).

3.1.6 Intra and inter slice scheduling algorithm

In 5G networks, users must have guaranteed access to available resources and different services at any time. The Network Slicing (NS) concept is one of the major breakthroughs introduced by 5G standards. It provides tailored networking solutions to vertical services over a common infrastructure. It is defined as a logical network having specific capabilities and characteristics, to support a particular service type with Service-Level Agreements (SLA) agreed beforehand.

Network slices include both Control Plane and User Plane network functions in the 5G core network (5GC) as well as the 5G access network. A given User Equipment (UE) may also have access to multiple slices over the same radio interface. In addition, an operator can also deploy different instances of the same slice to serve different groups of UEs.

In the RAN domain, network slicing is mainly based on resource allocation algorithms. Their role is to make sure that every slice has enough radio resources to meet the agreed SLA, and to ensure isolation between all slices. Slice isolation is an important requirement, because it enhances both slice security and slice privacy, by ensuring that the performance of each slice is not affected by the others.

Therefore, the performance of RAN slicing, in terms of resource utilization, mainly depends on scheduling algorithms conception. The objective of this scheduling is to perform the most efficient allocation by minimizing the number of unused resource blocks. For example, the architecture could implement two levels of scheduling: inter-slice and intra-slice. The inter-slice algorithm is responsible for allocating resource blocks to each slice depending on their needs and the allocation policy. This allocation can be fixed, in that case, the computational cost will be low, but resource blocks can be unused, or the algorithm can be run periodically to ensure a more dynamic and thus more efficient allocation. Intra-slice algorithms are responsible for allocating resources to users inside each slice.

In order to optimize resource allocation in the RAN, we propose a dynamic scheduling algorithm, capable of offering the required quality of service to the slices on the radio segment, in an efficient way. The goal is to treat differently each type of service: eMBB, URLLC and mMTC defined in 5G standards for example or any other type of service, in order to meet their respective requirements.

On the inter-slice level, the algorithm will first allocate the minimal resources requested by each slice. If there is not enough available resources to satisfy minimal demands, slice priorities will be taken in account. After this first step, remaining resources will be put aside in a “resource pool”. Then, based on their level of priority, each slice will be able to take resource blocks from the pool, until it is empty. Different metrics will be used to set slices priorities, like required throughput and latency for example.

On the intra-slice level, each algorithm will be adapted to the type of service associated. For example, in a URLLC slice where the critical requirement is low latency, allocation will favor users with close deadline packets.

This algorithm is designed to be more dynamic and adaptive to user requirements, in order to provide an efficient allocation and a maximal resource utilization.

3.2 Edge architectures

The relevance of edge-based RAN architecture to enable mobile/multi-access edge computing in order to provide latency, throughput and reliability requirements of 5G and B5G solutions was discussed in the previous white paper [3-11]. As noted in that white paper, there is no single edge-based RAN architecture that can provide various requirements from every vertical. Therefore, this section extends the edge architecture options and provides detailed deployment concepts for different vertical use cases. Specifically, as different services have different requirements on location, performance, security and availability, which calls for various types of edge clouds, a classification of the Edge Cloud is presented. Then the concept of autonomous edge (AE), to be a method to optimise the data processing at the edge but near the source of data, is introduced. Use cases for such deployments are characterised by specific requirements and options. One further challenge is on management and configuration of the physically distributed infrastructure, e.g., via introducing the Cloud RAN, which can be addressed by using AI and ML algorithms. One of the use cases where Edge computing could play a crucial role is in connected and automated mobility (CAM) services where, for instance, the end-to-end latency and reliability across MNOs is a requirement. On the other hand, in case extreme low-latency and stringent legal

requirements on data security and privacy, *on-premise edge* computing could be proposed. Finally, a Cloud Native approach on resource and workload orchestration, using Kubernetes, to create cloud native MEC platform is discussed.

Section	Title	Project	References
3.2.1	Edge cloud classification	5G VINNI	[3-12], [3-13]
3.2.2	Autonomous edge computing	5G VINNI	[3-13]
3.2.3	ML for edge resilience	5G VINNI	[3-14]
3.2.4	Edge computing for CAM applications	5G-CroCo	[3-15]
3.2.5	On-premise edge computing	5G-CLARITY	[3-4], [3-16]
3.2.6	Kubernetes based MEC platform	5G ZORRO	[3-17], [3-18]

3.2.1 EDGE - Cloud classification

There will be different type of edge clouds depending on use cases to be served and requirements from applications being hosted in the edge cloud [3-11]. The drivers for edge cloud are highly varied and the realization of the drivers requires different capabilities of the edge cloud. Services such as low latency applications, autonomy, third-party applications, cloud RAN and analytics can have different requirements on location, on performance that needs to be supported in the infrastructure, on security and on high availability. The edge cloud types discussed in this section are illustrated in Figure 3-10 and described as follows [3-12]:

- **Regional Edge Cloud**; hosting network functions and applications to improve efficiency and latency, but also robustness and resilience. edge cloud infrastructure can be operated by the mobile operator or public cloud providers. Typically located at the main transport network locations, which are already established within secure buildings. The number of locations, where regional edge cloud deployments are placed, depends on the size of the country and transport network layout but typically is in the range of 10s.
- **Access Edge Cloud**; hosting mainly cloud RAN and not for content distribution. Small size and simple setup at high number of locations per country due to strict latency requirements for cloud RAN. With full cloud RAN, i.e. DU virtualisation, there will be a need for several 100 and up to a few 1000 per country.
- **Enterprise Edge Cloud**; hosting network functions for serving enterprise use cases. Located at or close to customer premises. There will be varied implementations adopted for the specific use cases, ranging from small deployments with basic infrastructure such as for low latency applications to larger deployments hosting the complete mobile core network to ensure autonomy and NPNs. Enterprise applications might also be hosted in enterprise edge cloud. The number of enterprise edge clouds depends on enterprise customer cases.
- **Device Edge Cloud**; hosting only enterprise applications and no network functions. Located at customer premises (typically connected to the CPE) such as for data analytics and hosting or enterprise applications. The number of device edge clouds depends on enterprise customer cases.

The deployments of these different edge clouds are based on actual drivers and business needs, examples of which are provided in [3-13], along with operational and deployment models. Orchestration of differing Edge Cloud types is considered in the Management and Orchestration chapter of this document.

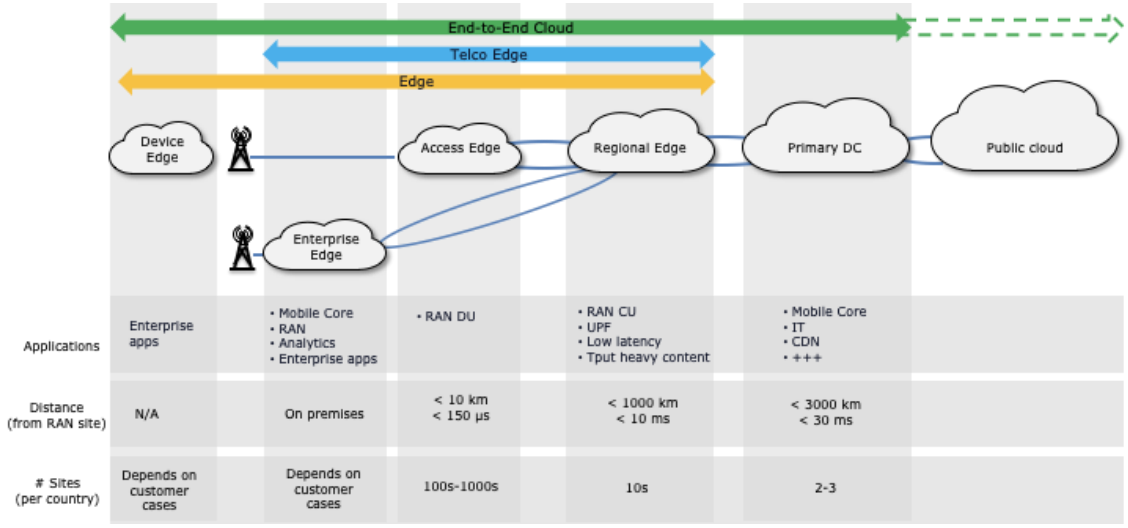


Figure 3-10: Edge cloud types

3.2.2 Autonomous EDGE computing

Autonomous Edge (AE) is a method of optimizing cloud by performing data processing at the edge of the network, near the source of the data [3-13]. This reduces the bandwidth needed for connection to the core network, by performing analytics and knowledge generation at or near the source of the data, as well as by providing Core Network capabilities in the edge site.

AE can be used to implement a wide range of technologies including device, network, cloud/fog computing, AR/VR, and AI. Under certain implementations, where key core network functions are deployed at Edge servers, service of applications can be maintained should the Edge site be disconnected from the central Cloud, hence the description of this implementation as autonomous – the Edge retains functional capability without a dependency on the connectivity to the remainder of the network. The extent of this retained functionality depends on the split between Edge-based and Cloud-based functions.

AE use cases are characterised by specific requirements that include:

- Low latency
- High bandwidth
- Isolation/security
- Availability & Reliability
- Cost Reduction
- Content delivery, e.g., CDN
- Data transfer, e.g., analytics
- Compute off-load
- Scalability
- Regulations

In the example of an AE implementation in Figure 3-11, infrastructure at the edge site supports both core network functions like V-RAN and Packet Core and third-party workloads, as well as infrastructure on the central site with similar deployment capabilities.

Autonomous Edge options are further described in [3-13].

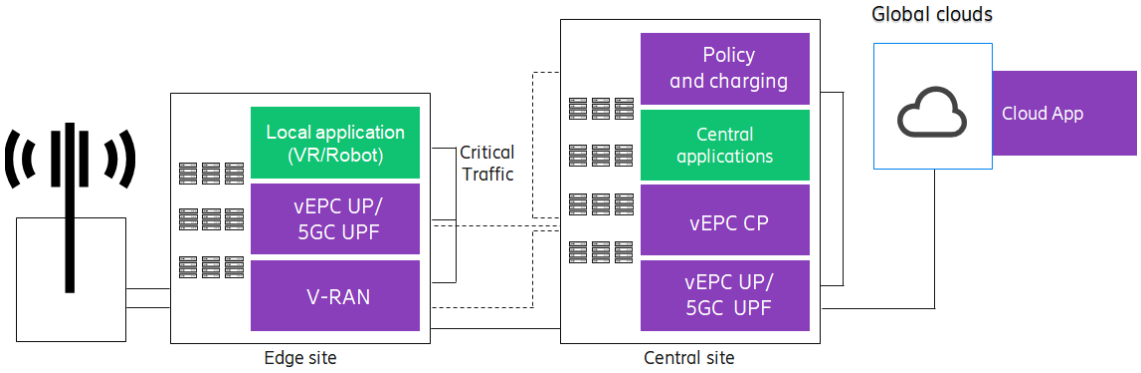


Figure 3-11: Distributed cloud with autonomous edge

3.2.3 Machine learning for edge resilience

The massive deployment of IT infrastructure is motivated by multiple factors, e.g., the emergence of technologies such as AR/VR, autonomous cars, drones, IoT for smart cities, with efficient real-time processing requirements at the network edge. An additional factor is the emergence of Cloud RAN, based on the virtualization, disaggregation and partial centralization of the RAN components. As a result, a significant part of the network infrastructure is likely to become distributed because it is deployed in a large number of physical locations, which makes global network security and dependability more challenging to guarantee.

Machine Learning (ML) has enabled new possibilities to enable autonomous network management towards the materialization of self-configuration, self-optimization, and self-healing, to cope with the new challenges raised by the proliferation of edge points of presence. ML provides the required toolset to evolve from a reactive paradigm to a proactive one. Applying ML techniques to available operational data allows the prediction of future problems and the implementation of new processes to prevent degradations from occurring, creating a new pipeline of precocious diagnosis followed by preventive actions. ML enables the precocious diagnosis of network failures, malfunctions and cyber/physical attacks and ultimately avoids the manually intensive management operations.

Figure 3-12 illustrates the basic configuration for an example proof-of-concept and use case workflow. The use case is based on a 5G network in which the probability of infrastructure fault is assessed making use of ML techniques through continuous analysis of alarms and trouble tickets. If a potential fault is identified, a set of different mitigation actions can be executed depending on the perceived probability of failure or malfunction.

The use case is focused on the migration of edge infrastructure from an edge Point of Presence (PoP) to another edge PoP (from Edge PoP1 to Edge PoP2). Further details of this work can be found in [3-14].

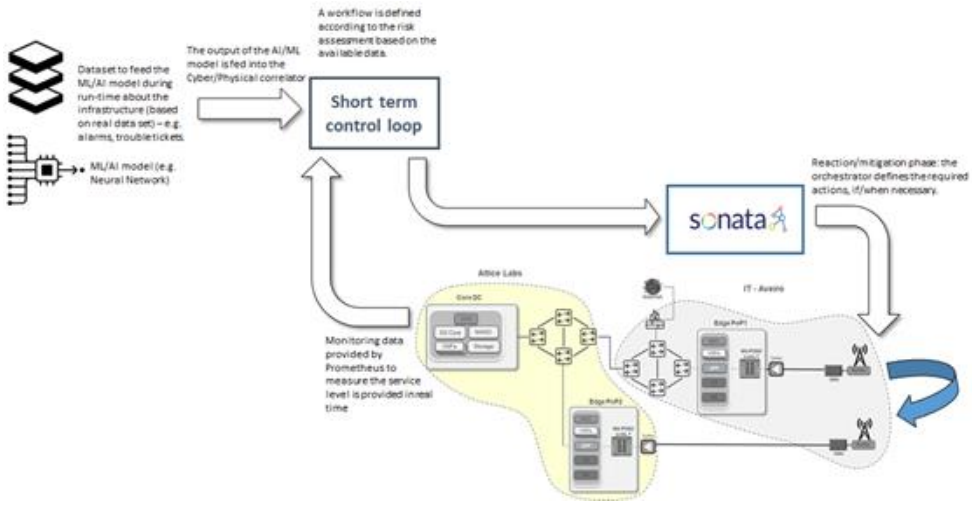


Figure 3-12: Basic use case workflow

3.2.4 Edge computing for CAM applications

Mobile Edge Computing/Cloud (MEC) enables to provide computational and hosting capabilities close to the end-user [3-15]. It furthermore enables Mobile Network Operators (MNOs) to extend their offerings beyond just connectivity sparing the service consumer from requiring two agreements, one for connectivity and a separate one for hosting/computation. The MNO gains full control over the end-to-end path from server to the vehicle. From this, a cross-MNO challenge arises, as it cannot be assumed that all vehicles use the same MNO. Connected and Automated Mobility (CAM) services like Anticipated Cooperative Collision Avoidance (ACCA) require defined end-to-end latency and reliability across MNOs. To achieve controlled QoS across multiple MNOs, two solutions based on shared data centres are identified. For the first one only the MEC hosts are moved to such data centres and wide area network providers need to assure controlled QoS between these data centres and those with the gateway located at the MNO Core Network. For the second solution also, the gateways are moved to shared data centres as a part of the Core Network which means the Packet Data Network Gateway (P-GW) for non-standalone 5G, or the User Plane Function (UPF) for standalone 5G, are also moved. The other solution, which does not rely on shared data centres, is based on purchasing wide area network services with controlled QoS between data centres of MNOs where the gateways are located as described in Figure 3-13.

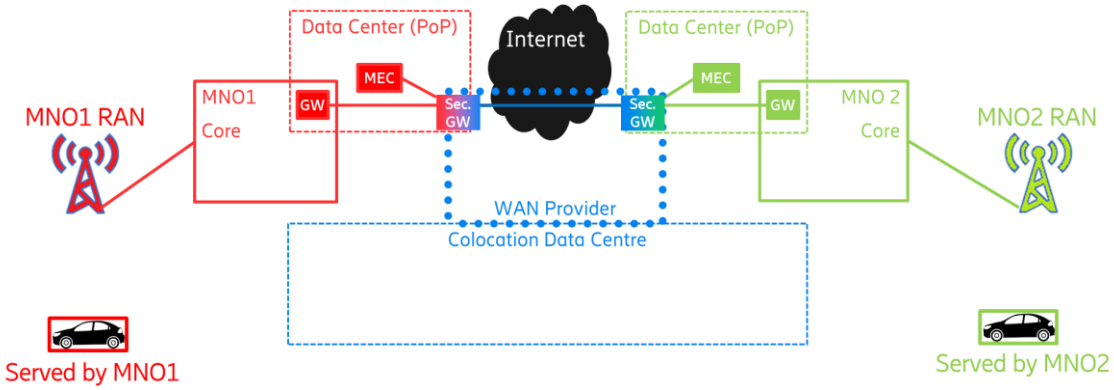


Figure 3-13: MEC Hosts Interacting through Controlled WAN

Another challenge arises from crossing borders. Cross-border/-MNO handover assures seamless service continuity when crossing country borders and with that also switching MNOs. As for every normal radio handover, the gateway remains unchanged. So, the vehicle is served by the

radio network of an MNO in the country it just entered while all its data traffic, including the one from and to MEC hosts, is still routed through a gateway of an MNO in the country it just left. This breaks the MEC paradigm of hosting and computation close to the vehicle, as the paths between the two MNOs can be very long. Above described cross-MNO solutions might not be applicable for MNOs of different countries. They are more intended for MNOs serving the same country. In case of non-standalone 5G, where a 4G Evolved Packet Core (EPC) is used, the only way to switch from such so-called "Home Routed Roaming" situation to "Local Breakout Roaming" is disconnecting the packet data network connection associated with the gateway of the MNO in the previous country and establishing it again. The network in the country currently serving the vehicle is then configured to use a gateway close by, which results in Local Breakout Roaming. The drawback is a service interruption that can last several hundred milliseconds. Standalone 5G with 5G Core introduces Service and Session Continuity mode 3, also known as "make-before-break" gateway switching, allowing to first connect to the new gateway and then releasing the packet data network connection from the old one. By this, an uninterrupted transition within the mobile radio network is achieved.

Even with this, challenges remain. The modem in the vehicle will obtain a new IP address and the application, potentially with support from the operating system, needs to switch from the MEC host in the old network to one in the new network. A number of use-case-specific methods on how the gateway and MEC host transitions can be done, and what triggers can be used to start using new MEC hosts and/or gateways and when to release the connection to the new ones are presented in [3-15]. There are different classes of use cases having similar communication patterns that could be request/reply, as used for HD Mapping to download HD map tiles, but also publish/subscribe as done for ACCA to receive Hazard Notifications.

3.2.5 On-premise edge computing

On-premise edge computing represents an enterprise edge cloud scenario where the entire hosting environment is deployed within the customer premises. In comparison to regional edge cloud scenarios, whereby the customer workloads are migrated to MNO edge platforms (located at properly reconditioned central offices), on-premise computing is typically more expensive for the customer, which is now in charge of all the site planning related activities, e.g., hardware and software acquisition, integration of edge platform solution with existing IT and network systems, etc. However, this approach sometimes constitutes the only solution for the customer to enable extreme low-latency use cases and meet stringent legal requirements on data security and privacy, as typically occur in Industrial IoT (IIoT) scenarios or mission-critical vertical industries that requires the use of standalone non-public networks (SNPNs).

The edge computing infrastructure builds upon a commodity (e.g., x86 or ARM based), containerized (e.g., k8s based) NFVI augmented with technologies that allow boosting the performance of compute-intensive workloads. These technologies, arranged into the so-called *accelerators*, allows overcoming the limitations imposed by virtualization overheads, and that has caused the NFV technology to reach a productivity plateau. The accelerators are used in conjunction with general-purpose computing capacity such that CPU-intensive tasks (e.g., security, packet processing) can be offloaded from CNFs to accelerators, with the rest of CNF operations executed with the general-purpose computing capacity. As a consequence, an improvement in the overall performance can be achieved, freeing up also more CPU cores that can be now dedicated to host new CNFs, and therefore, new workloads.

Figure 3-14 captures the state-of-the-art on these accelerators, including both hardware acceleration (e.g., GPUs, FPGAs, Smart NICs, NPUs) and software acceleration (e.g., DPDK, SR-IOV, PCI-pt) solutions.

Another relevant issue for on-premise edge computing scenarios is how to distribute workloads on the available substrate, especially when their functional scope and scalability is quite diverse, or when there is a security related reason to arrange them into separated groups. In this context, the concept of clustered NFVI applies. This principle allows having separate execution environments within the same NFVI, by defining different resource zones. A resource zone is a set of NFVI resources logically grouped according to physical isolation and redundancy capabilities, or to administrative policies for the NFVI.

Based on the above-referred principle, two separate resource zones can be defined, i.e., RAN cluster and primary cluster. The definition of these resources zones allows to keep the workloads related to RAN separated from any other workload. While the RAN cluster is for the exclusive use of CNF instances providing RAN related functionality (e.g., 3GPP vRAN, O-RAN near-RT-RIC and hosted xApps) and management (e.g., telemetry agents, EMS, SMO), the primary cluster provides an on-premise CNF execution environment to host any other (not RAN-related) functionality. Examples of workloads that can be deployed on this cluster include 5GC network functions, value-added services, and service applications.

Figure 3-15 shows the infrastructure stratum, where both clusters are captured [3-16].

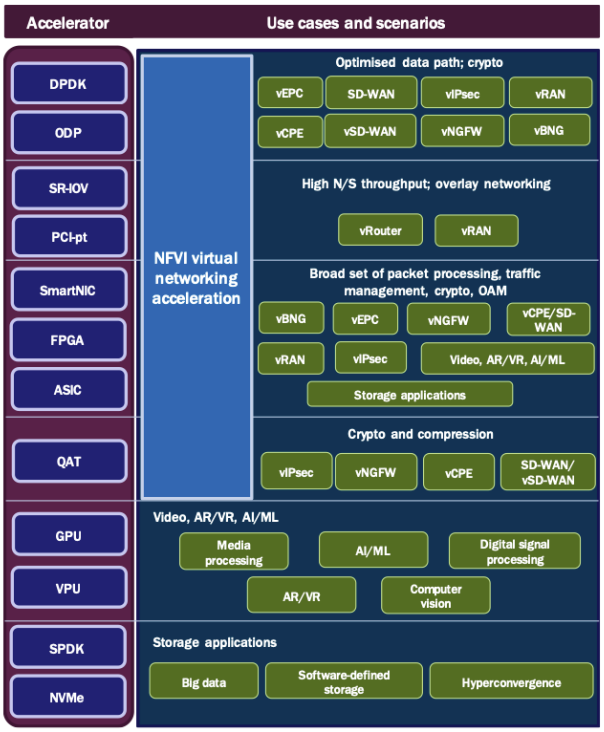


Figure 3-14: Acceleration technologies and use cases

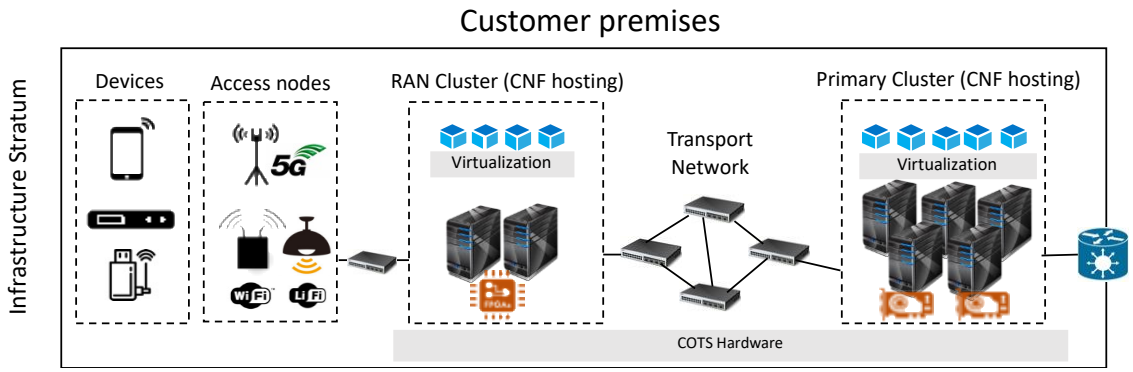


Figure 3-15: Infrastructure stratum [3-16]

3.2.6 Kubernetes based MEC platform

The realization of vCDN use cases requires MEC platform at telco edge to deploy and operate vCDN components in slice data-path [3-17]. Such use cases require dynamic spawning and decommissioning of vCDN components based on where and when the demand for specific content goes up and down over time. The need for 5G slices is thus envisioned to be able to dynamically scale up and down, expanding to additional MEC locations as needed, as shown in Figure 3-16 where MEC host in one location is not enough to handle all the demand and the slice is extended to additional, sometimes third-party MEC host.

A proposed architecture supports slice elasticity through combining several approaches and technologies [3-18]. Here the emphasis in on adapting Cloud Native approach for resource and workload orchestration. This approach is intent-based and is embodied by Kubernetes (k8s) which can be extended through an operator framework to create the Cloud Native MEC Platform (CNMP). In addition, k8s and Argo workflow engine [3-19] can be used as a basis for the Intelligent Slice and Service Manager (ISSM), as shown Figure 3-17.

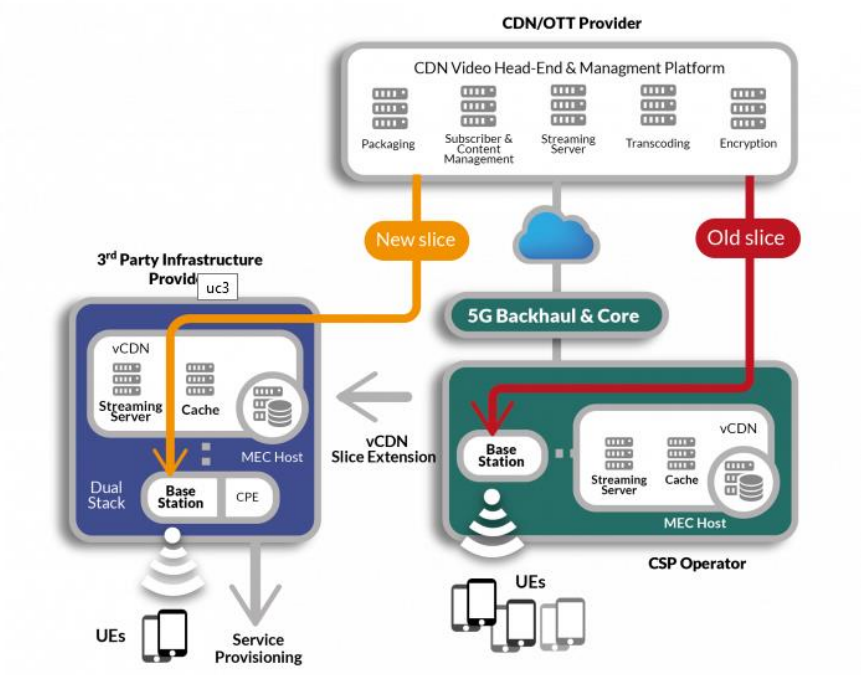


Figure 3-16: vCDN use-case with elastic MEC-enabled slices [3-17]

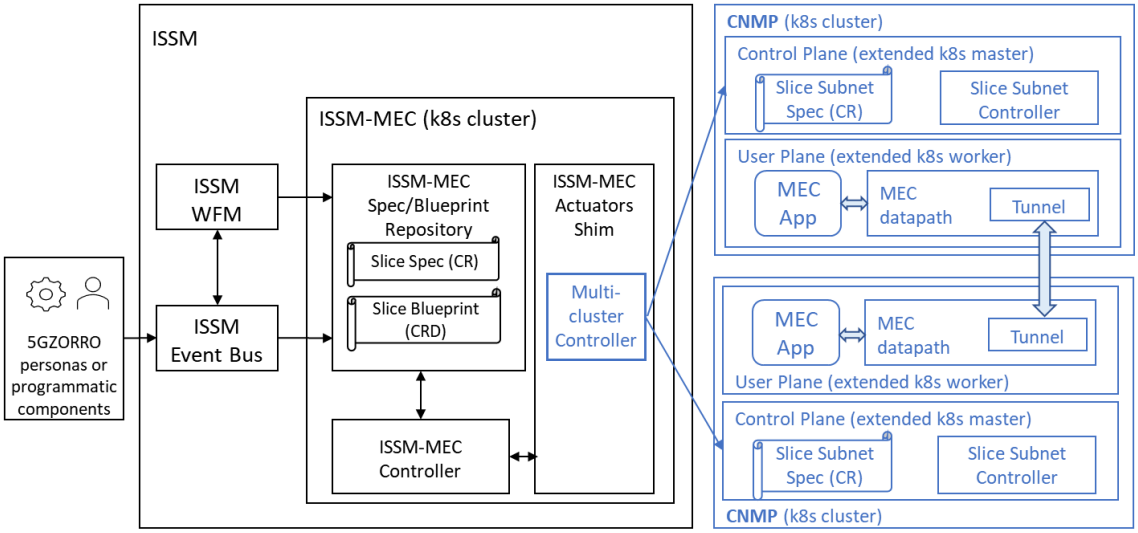


Figure 3-17: Cloud-native MEC platform

ISSM transforms slice definition provided as high-level intent into slice realization over multiple 5G environments, some implemented with traditional OpenStack virtualization and OSM, while some enabled with CNMP instances. ISSM contains a shim layer, called ISSM-MEC, to be based on Open Cluster Management for k8s [3-20] and capable to control multiple remote k8s clusters so we can orchestrate slice lifecycle over multiple MEC instances. All the managed MEC clusters are enhanced with slice lifecycle management capability through control plane agents, e.g., to create slice subnets, to deploy and configure data-plane components (UPFs), and to create and manage cross-cluster tunnels.

3.3 Positioning Methods

5G positioning is a natural component in many anticipated 5G industrial use cases and verticals such as logistics, smart factories, autonomous vessels and vehicles, localized sensing, digital twins, augmented and virtual reality. Although the history of positioning in cellular networks dates a couple of decades back, the requirements has never been as demanding as today, e.g., with Industry 4.0, positioning use cases come with a plethora of performance requirements in terms of accuracy, latency, availability, reliability, and more. In this section first the localisation enablers, not only those based on 3GPP technologies, but the solutions considered to integrate with non-3GPP technologies and device-free localisations are introduced. Then enhanced localisation solutions for two important application/vertical is discussed, i.e., a highly accurate localisation solution for Industry 4.0 applications, and an enhanced localisation for vehicular scenarios.

Section	Title	Project	References
3.3.1	Localisation enablers	LOCUS	[3-21], [3-22], [3-23], [3-24]
3.3.2	Positioning technologies for Industry 4.0	5G-CLARITY	[3-4], [3-16]
3.3.3	Enhanced vehicle localisation solutions	5G CroCo	[3-28]

3.3.1 Localisation enablers

The 3GPP defines positioning architectures and methods to fulfil regulatory requirements and provide added value services to the end users. Current 5G localisation solutions rely on single-value metrics such as uplink time-difference-of-arrival (UL-TDoA), downlink time-difference-of-arrival (DL-TDoA), received signal strength indicator (RSSI), and angle-of-arrival (AoA). Localisation accuracy depends heavily on the quality of such estimates, which degrades in harsh propagation environments. Advanced localisation techniques in the form of architectural components are discussed in this section, called "localisation enablers", that apart from being based solely on 3GPP (5G) technology they consider integration with non-3GPP technologies and device-free localisation. Localisation enablers provide the localisation mechanisms by utilizing the properties of radio signals associated with a given UE (or the user). More specifically, the enablers are divided into the following categories (detailed information can be found in [3-21]-[3-24]):

3.3.1.1 Advanced localisation techniques in 5G

The requirements and constraints of diverse mobile terminals (smartphones, wearables, cars, etc.) as well as the three main service classes enabled by the 5G technology are:

- Machine Type Communication (mMTC): two possible single value metrics have been proposed in 3GPP for mMTC and IoT scenarios, i.e., modified Observed Time Difference Of Arrival (OTDOA) and/or Uplink Time Difference of Arrival (UTDOA). The techniques for UTDOA estimation that comply with the network communication constraints of the mMTC service class are proposed. Also, it is preferable to use **energy and bandwidth-efficient** alternatives to OTDOA and UTDOA that provide additional mobility detection capabilities with increased robustness against Doppler impairments [3-22].
- Ultra-Reliable Low-Latency Communications (URLLC): the ability to allocate mini-slots for URLLC-based applications in 5G-NR complicates the design of PRS and TRS reference signals for OTDOA. Solutions to **reduce the localisation service response time** to a few milliseconds for URLLC applications are of interest. The combined use of fast time-based and angle-based methods to provide key breakthroughs for ultra-fast localisation need to be investigated.
- Enhanced Mobile Broadband (eMBB): **lightweight mmWave localisation algorithms**, which exploit the specific capabilities and beam patterns of analog/hybrid beamforming antennas of mmWave cellular systems, could be useful.

In order to increase the localisation accuracy, efficient and scalable Bayesian filtering algorithms are employed for localizing multiple and fast-moving terminals [3-23]. A further improvement in terms of localisation accuracy can be achieved by relying on localisation algorithms that fuse different metrics, e.g., using joint likelihood functions that account for the correlation among different metrics and mitigate the impairments caused by multipath and NLOS conditions.

In addition to localisation accuracy, the update rate of information as well as privacy and security will be critical application-driven requirements. For example, developing localisation enablers to support the emergencies is a key area. In particular, 3D indoor localisation represents a vital tool for the emergency and security services in case of events like multi-store building fire, kidnap and terrorism incidents, as well as indoor medical emergencies. In developing such enablers, the use of quickly deployed drones at different heights has to be considered that can provide increased 3D localisation accuracy with the support of the fixed 4G/5G network infra-structure.

3.3.1.2 Localisation based on non-3GPP technologies

The observables that can be extracted with non-3GPP technologies (e.g., 802.11 with multiuser MIMO and fine time measurements) serve as input for technology-agnostic and low-complexity algorithms for heterogeneous data fusion. In addition, dimensionality reduction techniques are complemented with machine learning and deep neural networks to extract the main features from a rich and heterogeneous set of measurements with diverse sources of noise. Moreover, the need to investigate communication protocols to support the integration of diverse technologies has to be identified [3-24].

3.3.1.3 Device-free localization

In addition, increasing attention is recently being devoted to device-free localization, i.e., the capability of detecting and tracking objects that do not communicate within the localisation infrastructure. These technologies rely on the signal designed for target detection and localisation (active radar) or on signals emitted by other sources of opportunity (passive radar) that are exploited for localisation. Signals for backscatter (illuminator of opportunity) can be both 5G gNBs as well as transmitters already deployed in the environment for other purposes. In contrast to 5G terminal localisation, device-free localisation can take advantage of any modulated signal at any frequency of operation. In this respect, a network of receivers (gNBs as well as community-based deployments of spectrum sensors) could be exploited, whose frequency configuration is adapted to the accuracy requirements of the specific scenario. The challenge in this domain is the design of novel, optimized, low-complexity algorithms that allow to develop a flexible and reconfigurable passive localisation system integrating 3GPP cellular localisation with non-3GPP technologies.

3.3.2 Positioning technologies for Industry 4.0

High accurate positioning is of essential significance for many industry verticals, which are highly dependent on the 5G technology. These industry verticals increasingly rely on the combination of communication capabilities together with high accuracy positioning services offered by 5G technologies [3-25], [3-26].

In the last decade, global navigation satellite systems (GNSSs) were able to fulfil the needs of many applications requiring high accuracy UE positioning. Additionally, with the latest developments in this field, including real time kinematics (RTK), a centimetre-level UE positioning is possible. Nevertheless, this is limited to outdoor environments, where line-of-sight (LOS) reception of the satellite signals is possible.

The 3GPP Rel-15 introduced the 5GNR technology and also RAT-independent positioning capabilities. RAT-dependent positioning capabilities were first introduced in Release 16, which considers, as well, positioning capabilities for commercial use cases, such as:

- Horizontal positioning error < 3m for 80% of UEs in indoor deployment scenarios.
- Vertical positioning error < 3m for 80% of UEs in indoor deployment scenarios.
- End to end latency < 1 second, etc.

For many use cases from the industry verticals these requirements would not be sufficient. Therefore, according to 3GPP Rel-17 “Study on NR Positioning Enhancements”, sub-meter positioning accuracy is required for general commercial use cases, and the positioning accuracy should be better than 0.2 meters for IIoT use cases. The required latency should be better than 100 ms and for some IIoT use cases even in the order of 10 ms.

Automated guided vehicles (AGVs) are used in factories and warehouses to move materials and products from place to place. The use of these systems in industrial environments demands more

and more precise positioning capabilities, calling for even more stringent requirements than those specified in Release 17. They require sub-10 cm positioning accuracy and millisecond latency. In this context, beyond 5G systems must consider novel approaches to fulfil the target requirements. RAT-independent approaches involving sub-6 GHz, mmWave, LiFi and optical camera communications (OCC), are being developed for precise positioning of AGVs in production floors [3-27].

There are several reasons for using jointly multiple positioning technologies. The first reason is that different technologies may provide different levels of performance targets making their combination complementary, and to enable large scale, dense coverage of the area of interest. Additionally, the position estimates from multiple technologies can be merged to obtain a better position estimate. The localisation data provided by these technologies is collected at a localisation server [3-16] and further processed to obtain high accuracy position estimation. Different strategies for merging the position estimates can be considered, together with the deployment of different machine learning algorithms in order to obtain better position estimates.

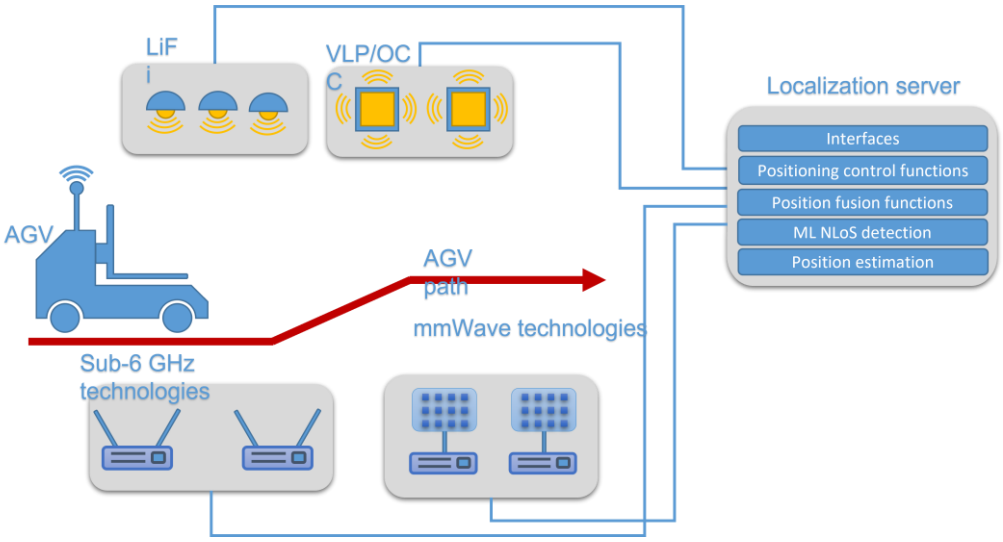


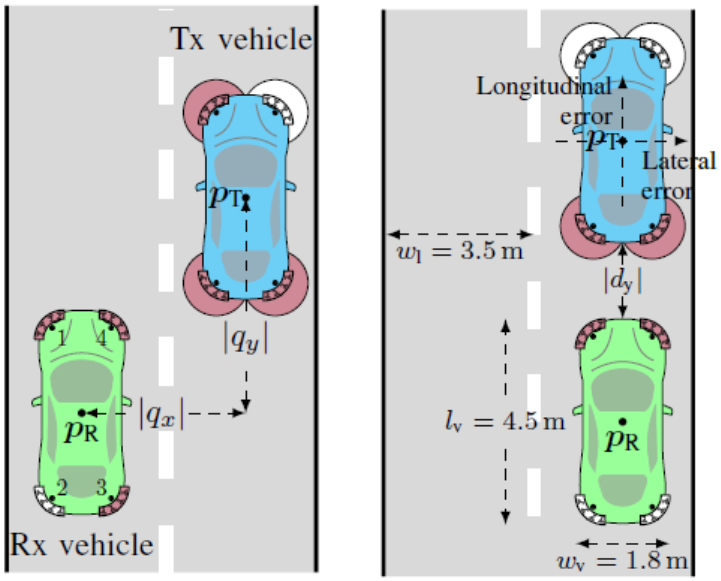
Figure 3-18: Simplified architecture of the multi-WAT positioning system

The Sub-6 GHz positioning technology enables the use of multiple positioning methods for indoor scenarios, e.g. DL-TDOA and, additionally, technologies like UL-TDOA used together with Wi-Fi, Bluetooth and other range-based methods. The implementation is carried out using software defined radios (SDRs), requiring the software implementation of the algorithms and the associated signal processing. Using a channel bandwidth of 160 MHz a positioning precision of 20 centimetres is achieved [3-4]. A custom 60 GHz system is used for mmWave indoor positioning, which is capable of using channel bandwidths of up to 2 GHz, enabling extraordinary positioning precision reaching centimetre and even sub-centimetre level. The system uses a two-way ranging (TWR) between the UE and multiple APs to then estimate the position using trilateration [3-4]. LiFi is the third technology that could be used for both data communication and positioning. Multiple LiFi nodes must be deployed and the distance between the LiFi access nodes and the UEs is estimated based on the received signal strength. Having a dense deployment of LiFi access nodes would enable visibility of a few of them by a single UE. This would allow for high precision UE positioning based on trilateration. Finally, OCC can be also considered as a complementary technology for position estimation. Intensity modulated light sources are used as an access/anchor nodes for positioning as well as for data transmission. A UE equipped with a visible light camera is used to locate these light sources and to decode their IDs and positions. Based on their positions, as seen on the camera, the position of the UE is estimated.

3.3.3 Enhanced vehicle localization solutions

Although a combination of GNSS and vehicle sensors can satisfy most of the minimum requirements of the different vehicular use cases, in some locations where satellites cannot be easily tracked, like urban or rugged areas, it could lead to inaccuracies of several meters and significant latencies. In this discussion, three positioning solutions to enhance vehicle's location are considered, following the terminology described in TS 38.305 [3-29], that is, RAT-dependent, RAT-independent and hybrid.

The RAT-dependent method is based on using receiver measurements on the 5G NR side-link to provide relative position information between a transmitting vehicle and a receiving vehicle. In particular, the measurements will be beam based, focusing on the use of Frequency Range 2 (FR2) (above 7 GHz) potentially included in future 3GPP specification releases of 5G New Radio V2X side-link. The measurements, which are based on Angle-of-Arrival (AOA) and Time-of-Arrival (TOA), and the resulting relative positioning estimate could be furthermore combined or fused with other on-board sensors on the vehicle (i.e., lidar, radar, camera, etc.) to provide higher reliability and accuracy. The main goal is to meet the 5G NR V2X relative position requirements [3-30] which state that the relative lateral positioning accuracy should be 0.1 m between UEs and the relative longitudinal positioning accuracy should be less than 0.5 m between UEs. These relative position requirements were derived to support coordinated manoeuvres between vehicles i.e., overtaking, lane merging and platooning. Examples of overtaking and platooning manoeuvres are depicted in Figure 3-19. We will focus on the performance for different types of position measurements and the performance differences for different locations of beam forming antenna arrays on the vehicle.



(a) Overtaking scenario. (b) Platooning scenario.

Figure 3-19: Overtaking and Platooning Scenarios

The RAT-independent solution is based on the hybridization of different technologies to provide a more accurate location of the vehicles. In particular, GNSS, inertial systems and Ultra-wideband (UWB) relative positioning [3-31]. Using UWB technologies makes it possible to measure distances with a precision of several centimetres based on the Time of Flight (TOF) of messages sent between two endpoints. Thus, knowing the distance from the device to be located, referred to as tag, to three or more reference devices, referred to as anchors, it would be possible to calculate the relative position of the tag through trilateration. Anchors are considered static

references, which, thus, can be accurately geopositioned by professional topographers to minimize errors. Hence, UWB systems would require the deployment of dedicated anchor devices on the road but would serve to improve the precision of GNSS technologies in use cases which demand lane accuracy. This supports considered vehicular use cases and supports specific cases, e.g., prioritizing emergency vehicles such as ambulances and other blue light services. Such enhanced positioning system is envisioned to be used in conjunction with vehicular communication to provide the position of the vehicles whenever necessary. Figure 3-20 shows an example on how the enhanced positioning system could be employed to facilitate the priority access of an ambulance in a crowded road. In this case, UWB anchors would be installed as an element of the road infrastructure; for example, they could be deployed in street-lamps (depicted as yellow circles in the figure) and traffic lights at street crossings. First, the ambulance will accurately locate itself using the enhanced positioning system to determine its position with lane accuracy. This information will be sent by the CCU. Secondly, vehicles in the path will be notified and will also accurately locate themselves and for this benefit from the UWB architecture.

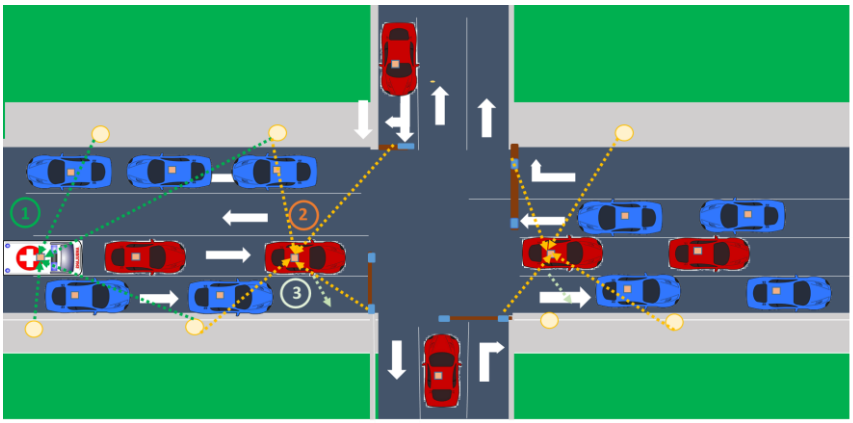


Figure 3-20: Enhanced positioning system based on UWB to facilitate the driving of priority vehicles

A third precise positioning method introduced is a hybrid approach based on 3GPP GNSS Real-Time Kinematic (GNSS-RTK). With 3GPP Rel. 15, the GNSS-RTK was introduced to the LTE standard [3-32] to provide correction information to GNSS signals, allowing to reach centimetre-level accuracy [3-33], [3-34]. With Rel. 16 the same solution was formally also standardized for 5G New Radio [3-35] but the name “LTE Positioning Protocol (LPP)” was kept. Before being standardized in 3GPP, GNSS-RTK was already possible as the required correction information can be provided through any IP-based data connection. The main advantage of the 3GPP standardized GNSS-RTK solution is the option to broadcast the correction information within a System Information Block (SIB) transmitted by eNBs or gNBs. This allows to substantially reduce the data volume for correction information as this information is the same for all receivers within a given area. The 3GPP specifications also allow unicast transmission of the information. In this case there is no advantage from reduced data volume, but it can be used without requiring special features in the RAN on g/eNBs or UEs. The solution can still benefit e.g., from authentication through the 3GPP core network and from location information of the cells to deliver the right correction information according to cell location. Figure 3-21 depicts the 3GPP GNSS-RTK architecture according to [3-36]. It is part of the 3GPP Location Service architecture which covers all generations starting from 2G. The newly added NF Evolved Serving Mobile Location Center (E-SMLC) is therefore also commonly called Location Server. Many 4G and 5G modems also include a GNSS receiver and could therefore use the 3GPP GNSS-RTK solution in a positioning engine on the modem to improve position accuracy and provide precise GNSS positions to other functions of the unit hosting the modem. Until such integrated solutions are available, the modem can provide the RTK-GNSS assistance information to a separate positioning

engine, e.g., a software application running on the unit hosting the modem, to provide precise GNSS positions

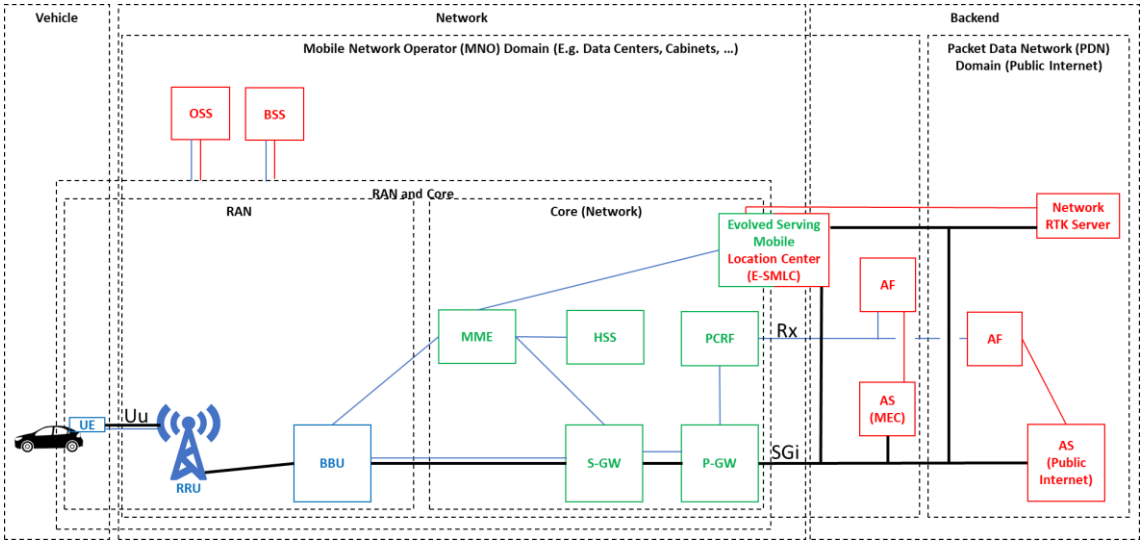


Figure 3-21: 3GPP GNSS-RTK Architecture

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4 Core & Transport Architecture

4.1 Introduction

With the increased complexity of 5G networks, the demand of having an intelligent, automated coordination between the RAN, the mobile core network and the transport network seems the reasonable choice. With 5G (and later 6G) providing a tremendous increase in capacity, along with more stringent requirements in terms of performance, the requirements must not only be met by the 5G system but also by the underlying transport network. Particularly for the latter, apart from capacity increase and interface density requirements in the RAN, disaggregation in both RAN and core network can have impact in the transport network architecture [4-1]. This architecture needs to be highly scalable and future proof, to enable deployment and operation of new revenue generating services, being the transport network key to provide the required interfaces and performance in an intelligent and coordinated way.

To reap 5G's full benefits, the 5G Core should migrate to a cloud native approach, as the network needs to be established as a valuable and agile platform for value creation where new services, to a large extent, are conceived through collaboration and co-creation through partnerships or ecosystems. The 5G Core will enable new use cases and innovation in areas such as ultra-low latency and mission critical networks that were not addressed in detail so far.

Multicast and broadcast services have been provided by several operators over their mobile networks to efficiently deliver multimedia content to multiple users while consuming a minimum of radio and network resources. The support of multicast, broadcast and integrated data analytics framework in the 5GS is relevant.

4.2 5G Core Network

The new 5G core network (5GC) can accompany this radio flexibilization through the support for slicing, enabling operators to set up different flavours of core network functions and to add novel network functions to flexibly control user sessions in a variety of ways from the same core network. Such creation and addition of new serving instances is explicitly supported by the dynamic resolution of the serving instance by dedicated functions e.g., network repository functions (NRF) in the novel Service Based Architecture (SBA) of 5GC.

4.2.1 Cloud Principles in 5G Systems

"Cloud-Native" is the name of an approach to designing, building and running applications/virtual functions fully exploiting the cloud delivery model. Cloud-Native approach is the way applications are created and deployed, not where they are executed. The 5G-PPP Software Networks Work Group highlights the value and challenges of becoming Cloud-Native in [4-2]. Cloud-Native applications are developed with tools that allow them to take full advantage of cloud benefits, meaning they can be built and changed more quickly, are more agile and scalable, are more easily connected with other apps. New operational tools and services like continuous integration, container engines and orchestrators are pillars of this transformation.

Cloud native stands in stark contrast to a before-5G telco-world, where concepts around NFV and the provisioning of network functions (NFs) as VNFs have seen some adoption especially after the adoption of softwarisation concepts to decouple the function from the hardware it is supposed to run.

Architectural solution	5G PPP Project	Additional Reference
Adopting Cloud Principles throughout 5G System	FUDGE-5G	[4-3], [4-4]
5GC NFs Transitioning to Cloud Native NFs	FUDGE-5G	[4-5]

4.2.1.1 Adopting Cloud Principles throughout 5G System

The microservice engineering methodology, commonly known as the 12-factor app methodology [4-3], goes beyond the concept of softwarising functions. It describes architectural concepts on how an application must be realised in order to run in a cloud native system that focuses on scaling cloud-native containerized network functions (CNFs). Most importantly, CNFs are stateless software components that can be freely scaled up and down in the number of instances to cope with an increase in requests enabling the economy-at-scale.

Cloud native orchestration encompasses three main areas:

- The logic to decide how many CNF instances are required in which lifecycle state and - if multiple physical locations are available - also where they are being instantiated
- The translation of application KPI or Service Level Agreement (SLA) requirements into monitoring policies to trigger the logic described above

Descriptor definitions and information models that allow humans or machines to interact with the orchestration layer through well-defined programmable APIs.

4.2.1.2 5GC NFs Transitioning to Cloud Native NFs

One of the key design choices when realising an application in a cloud native fashion is the separation of packet routing, application monitoring and analytics (M&A), and service orchestration from the actual application whose sole objective must focus on processing incoming requests and returning a response. The naming ontology of services over the internet, i.e., Fully Qualified Domain Names (FQDNs), is being used to allow the logical separation of functions which form the application. Thus, each client is fully aware about the FQDN of the next function (server), which can serve the request the client aims to issue.

However, how an application – which is decomposed into a set of functions realised as microservices – is initially orchestrated and lifecycle managed at run time must not become part of the application. This allows a truly cloud native realisation of the application where testing, staging and production environments can use the same code base without any modifications. Furthermore, and most importantly for telecommunication systems, how requests are being routed to the instance which can serve them, and which particular instance to choose in the first place, must be also fully decoupled from the actual application. This capability, commonly referred to as "service routing", is baked into all microservice management systems via sidecars and load balancers. However, those systems are operating within their own realm only and do not offer service routing across multiple islands, as this would require a system-wide understanding of the network, its resources and current state.

4.2.2 5G Multicast

5G Multicast is the first Third Generation Partnership Project (3GPP) technology that enables point-to-multipoint communications inside the 5G Core Network and the 5G RAN [4-11]. It increases the efficiency in the network resources used, avoiding possible congestion occurring inside the transport network.

3GPP is in the middle of standardisation effort for Rel-17 across RAN and System Architecture (SA) groups, with the new features fixed in December 2019. One of these features involves the support for multicast and broadcast communications, with a Work Item affecting the radio part, and two of them located at the 5G Core network.

Architectural solution	5G PPP Project	Additional Reference
Broadcast extensions for 5GC	5G-TOURS	[4-12]
Opportunistic Multicast	FUDGE-5G	[4-6], [4-7], [4-8]

4.2.2.1 Multicast extensions for 5GC

A possible implementation of the 5G Multicast architecture is tackled in [4-12] , which is shown in Figure 4-1. It leverages from the TR 26.802 reference architecture [4-13] . The green blocks in Figure 4-1 highlight the components being under development.

The system will be developed into *Universitat Politècnica de València* campus premises using the open-source software Open5GCore [4-14]. The software-based 5GC will be enhanced with the proper NFs to allow multicast capabilities. Open5GCore will be connected and tested with simulated multicast RAN environment, if no commercial equipment is available by the end of 2021.

In addition, multicast 5GC system will include an application layer forward error correction (AL-FEC) technology to improve the transmission protection. The technology used will be Raptor codes latest version, RaptorQ. The combined solution enables scalable and efficient data delivery even in the most challenging environments.

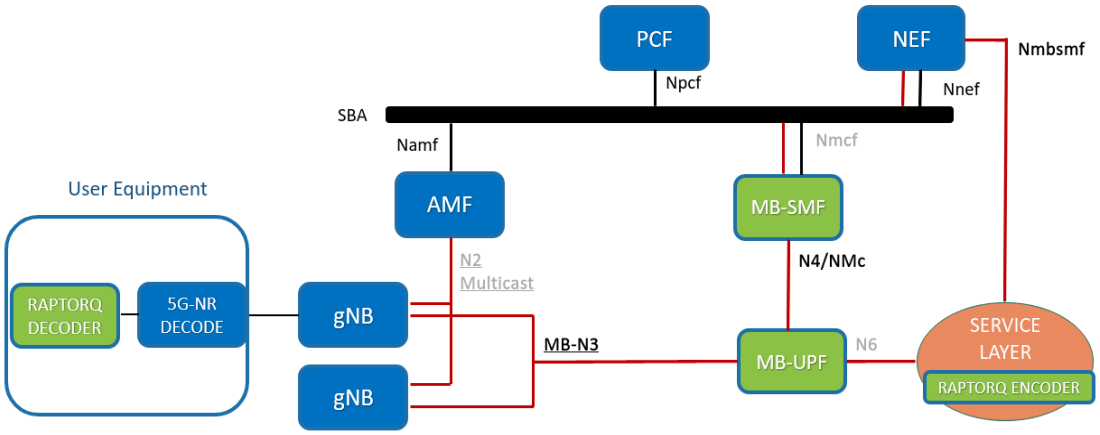

Figure 4-1: 5G multicast architecture [4-6]

4.2.2.2 Opportunistic Multicast

Another flavour of a multicast transmission on the 5G user plane has emerged, called Opportunistic Multicast (OMC) [4-6], [4-7]. This technology utilises Information-Centric Networking (ICN) principles for the delivery of HTTP responses in a multicast fashion to clients without the need for any protocol changes in either IP endpoint (client or server). The technology is referred to as Name-based Routing (NbR) and operates transparently between IP endpoints without any changes required to their IP stack. OMC is being introduced into the user plane relying on an 802.3-based networking fabric between UEs and User Plane Functions (UPFs). This innovation allows *n* clients that request the same HTTP resource, at roughly the same time, to receive the HTTP response as a multicast delivery through the network over L2. If all clients of

the same 5GLAN virtual group are synchronised in their sending of HTTP requests and, therefore, being placed into the same OMC group for receiving the HTTP response, the cost savings over conventional IP equal the number of clients in relation to the actual UPF topology and the location of UEs. OMC will be brought to the 3GPP user plane and integrated with the 5GC NF Session Management Function (SMF).

The revised 5GC system architecture is illustrated in Figure 4-2 and only affect the UE and UPF that implement NbR. In order to not require the introduction of ICN control messages in the 5G control plane, as described in [4-9], an "in-band" signalling is proposed which operates over an already established PDU session of type Ethernet.

Furthermore, the introduction of NbR on the 5G user plane also argues for a transitioning of N4 into Nupf and the usage of an SCP for the communication between the two 5GC NFs.

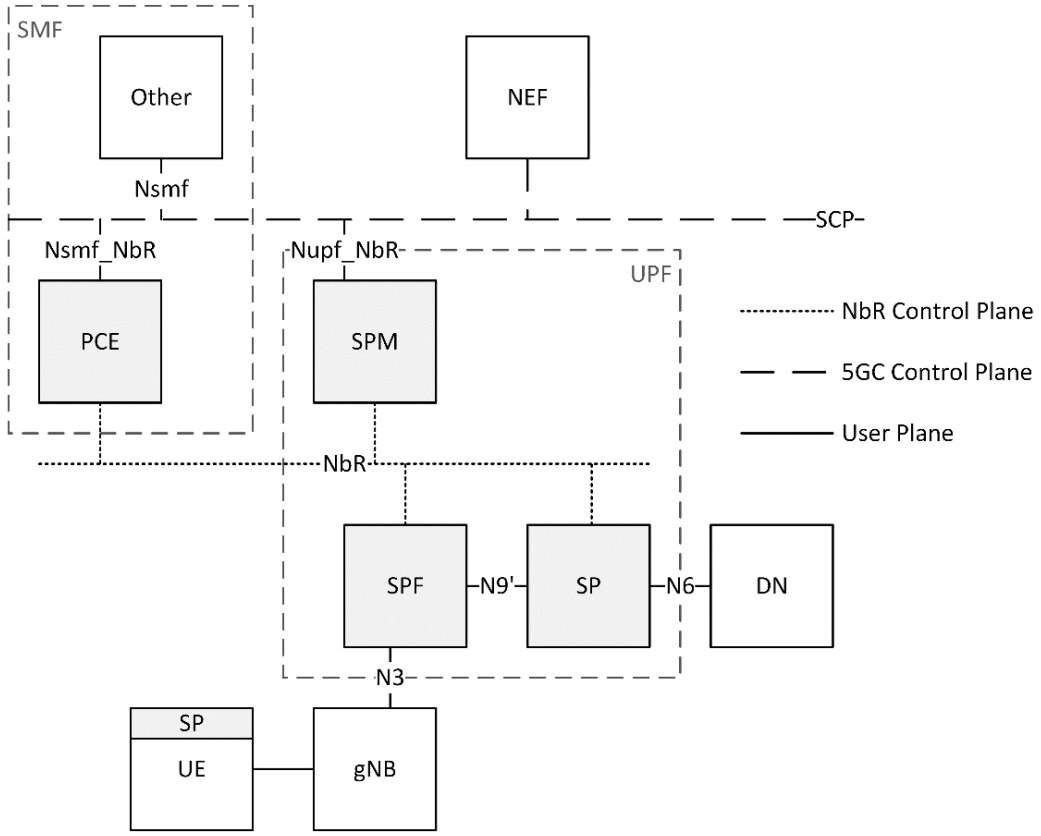

Figure 4-2: Proposed 3GPP architecture for Name-based Routing on the user plane, UE mode [4-7]

Figure 4-3 illustrates the user plane protocol stack for the UE mode. With the NbR layer extended to the UE, the UE mode only supports the PDU session type Ethernet. The payload can be any IP-based protocol with NbR offering special service routing capabilities for HTTP (including TLS-based HTTP communication), including OMC.

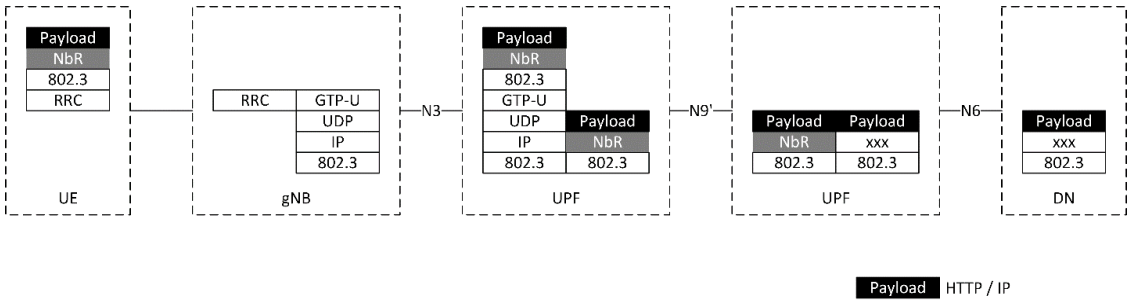

Figure 4-3: Name-based Routing user plane protocol stack for UE mode over 802.3

4.2.3 5GLAN

The 5GLAN feature allows the integration of mobile networks as part of an existing IT infrastructure. 5GLAN reduces the need for Ethernet cabling and exhibits similar connectivity properties. In traditional Ethernet communication, a device finds peer devices through discovery mechanisms based on broadcast, for example through the Address Resolution Protocol (ARP) or Universal Plug and Play (UPNP) [4-10].

In 5GLAN, a UE must obtain the identifiers of other UEs in the same private domain of 5GLAN-type services. The standardisation of 5GLAN is in progress [4-18], and a number of issues are listed for resolution, including:

- Network discovery, selection and access control.
- Network identification.
- System enhancements to support Time Sensitive Networking and time synchronization aspects.
- 5G LAN-type services such as group management, service discovery, selection, and restrictions.
- 5GLAN communication, including group communication, one to one, one to many communication.
- Isolation and security of 5GLAN groups.
- Accessing PLMN services via non-public networks and vice versa.

For 5GLAN case, it is essential to allow a UE to obtain the identifiers of other UEs in the same private communication of 5G LAN-type service for application communication use. In LAN networks, devices make use of discovery mechanism (e.g., Bonjour or UPNP) to discover other devices online to be used and their characteristics. This discovery mechanism makes use of the multicast capabilities of the network. Therefore, it is important that 5GLAN support discovery mechanisms.

On-demand establishment of a multicast communications within subset of UEs that are members of the 5G VPN, e.g., equipment A create a multicast on demand and B and C joins this multicast to receive A's multicast messages.

The 5GLAN Group may be dynamically created by an operator or possibly requested by Application Function via service exposure. Identities, a Non-public Network ID (NPN-ID) identifies a non-public network. The NPN-ID supports two assignment models:

- Locally managed NPN-IDs are assumed to be chosen randomly at deployment time to avoid collisions (and may therefore not be unique in all scenarios). Universally managed NPN-ID are managed by a central entity are therefore assumed to be unique.
- Identities, a Closed Access Group (CAG) ID uniquely identifies a closed access group (CAG) in a PLMN. PLMN ID consisting of MCC 999 (assigned by ITU for private

networks) and an MNC defined by 3GPP to identify the cell as part of a non-public network. The configuration of the UE is performed from a logical Application Function (AF) that configures the UE via the PCF directly or indirectly via the NEF first and the PCF second.

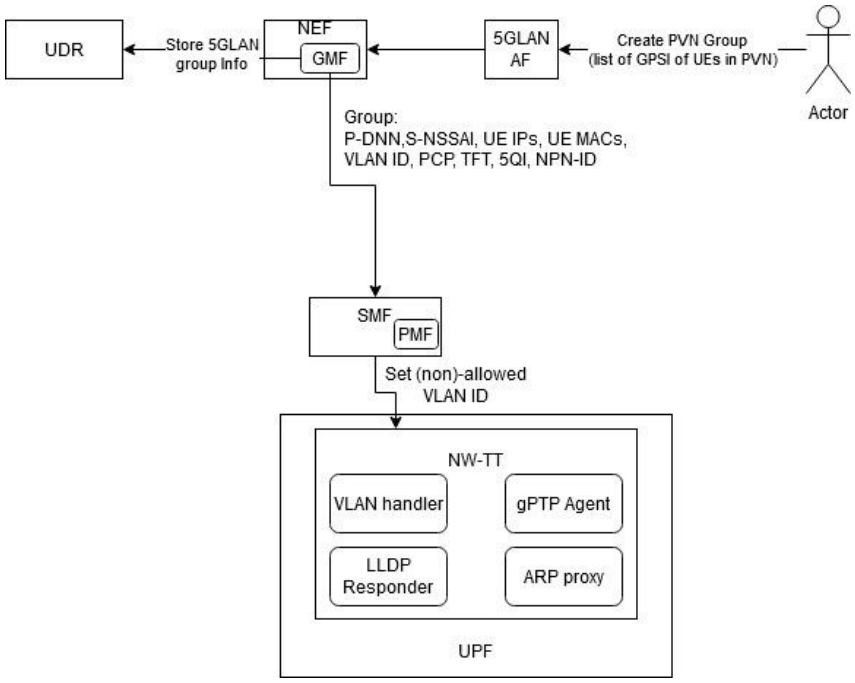

Figure 4-4: Realisation design of 5GLAN

4.2.4 5G Network data Analytics Services

Architectural solution	5G PPP Project	Additional Reference
M&A framework	5GENESIS	[4-19], [4-21]
Testing as a Service	5G-VINNI	[4-38], [4-39], [4-40], [4-41]
Localization Analytics as a Service	LOCUS	[4-22], [4-23]

4.2.4.1 Monitoring & Analytics

The instantiation of a M&A framework is crucial for 5G. In particular, this is due to the fact that the services provided by 5G systems have to comply with SLAs, which state the end-to-end (E2E) performance that have to be guaranteed to end-users and verticals, leading to the need for careful management and monitoring of the instantiated resources. Therefore, a 5G M&A framework should consider both end-users' and operators' perspectives, aiming at satisfying and improving user's Quality of Service and Experience (QoS/QoE) and operator's management and operational costs.

4.2.4.1.1 M&A framework

A M&A framework should comprise of Infrastructure Monitoring (IM), Performance Monitoring (PM), Storage, and Analytics. The M&A framework shall span across all layers of the Reference Architecture blueprint.

In particular, IM and PM probes mainly lie at the Infrastructure layer, in order to fulfil the requirement of tracking the status of components and functions, thus collecting large amounts of

heterogeneous parameters. Then, a management instance of the Monitoring is placed at the MANO layer, so that the parameters scraped from the infrastructure components (i.e., physical and virtual hosts) are redirected to a centralized collector, e.g., a Prometheus[2] server. The Coordination layer hosts the storage utilities and the Analytics functionalities. The Analytics results are shown in a dedicated visualization utility.

As anticipated above and depicted in Figure 4-5, the main connection point with the Reference Architecture [4-19] is the Experimental Life Cycle Manager (ELCM), whose main functionalities are the scheduling, composition, and supervision of experiments in the platforms, as detailed in [4-21].

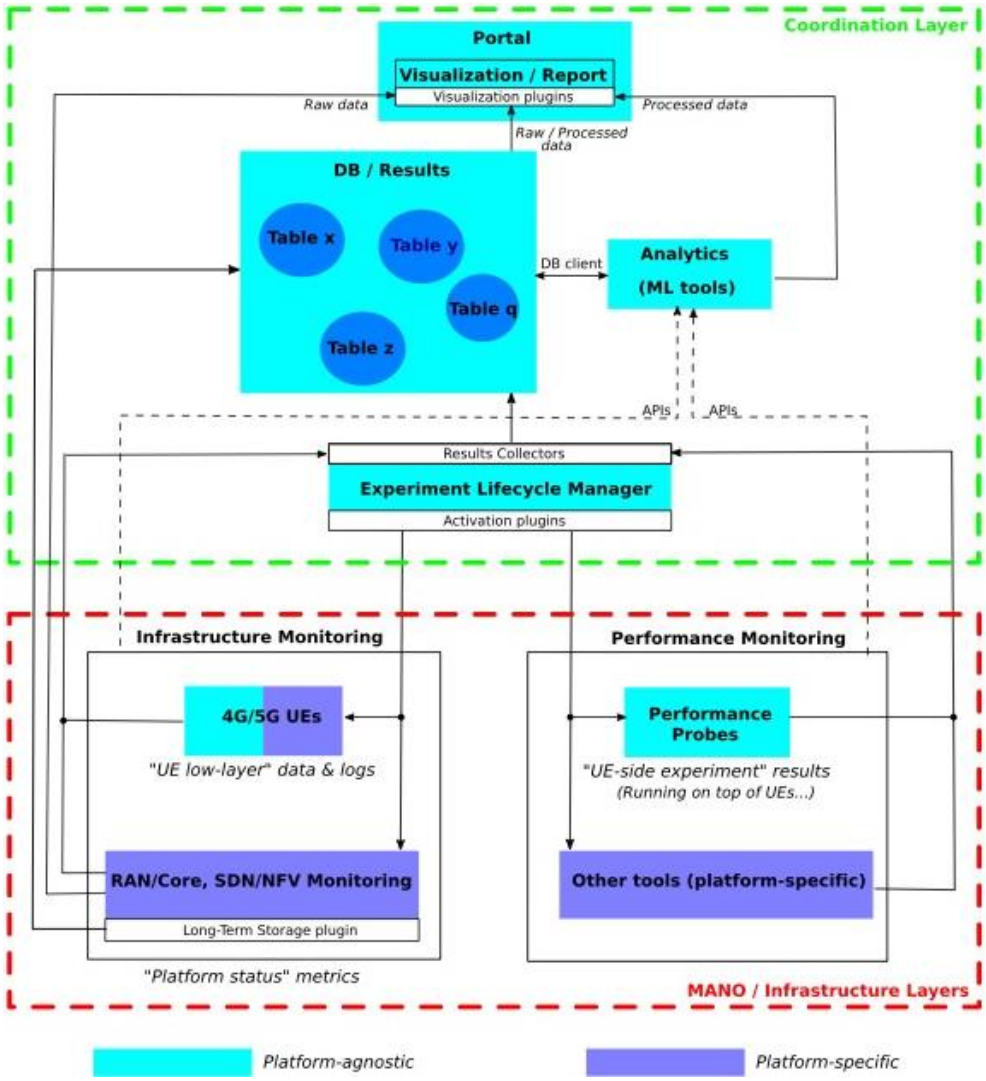

Figure 4-5: M&A Framework [4-19]

The ELCM activates on-demand IM/PM probes via the *Activation Plugins*, in order to start monitoring the components involved in a specific experiment, e.g., the components of a network slice, while actively running the experiment. The ELCM also automatizes both formatting and long-term storage of the data collected during the experiment execution, via so-called *Results Collectors*. The Keysight Test Automation Platform (TAP) software[3] deals with most of the

[2] https://prometheus.io, Accessed on: March 2021.

[3] https://www.keysight.com/en/pc-2873415/test-automation-platform-tap, Accessed on: March 2021.

ELCM operations, being the Activation Plugins *TAP Plugins*, while the *Result Collectors* are *TAP Result Listeners*.

A full-chain M&A framework for a reliable validation of 5G KPIs has been developed in [4-19]. The framework enables the analysis of experimental data collected by dedicated monitoring probes. This in turn allows to pinpoint the interdependencies between network configurations, scenarios and environmental conditions, and QoS and QoE KPIs, ultimately leading to the derivation of optimized management policies for further improvement of users', verticals', and operators' performance.

The M&A framework includes several Monitoring tools and both statistical and ML-based Analytics. It comprises three main blocks:

- *Infrastructure Monitoring (IM)*, which focuses on the collection of data on the status of infrastructure components, e.g., User Equipment (UE), radio access and core networks, Software Defined Network / Network Function Virtualization (SDN/NFV) environments, and distributed edge units;
- *Performance Monitoring (PM)*, which is devoted to the active measure of E2E QoS/QoE KPIs. These include traditional indicators, such as throughput and latency, but also other indicators tailored on specific use cases and applications (e.g., mission critical services and massive communications);
- *Storage and Analytics*, which enables the efficient management of large amounts of heterogeneous data, and drives the discovery of hidden values, correlation, and causality among them.

Among others, the M&A framework aims at providing the following Analytics functionalities:

1) *KPI Validation*, i.e., the execution of the KPI statistical analysis for validating a KPI [4-20];
2) *Time series management*, which allows to coherently merge the data coming from different probes, in order to perform further analyses. In an M&A system, this task is needed for several reasons. First, different sampling rates might be used by different probes. For example, QoS/QoE KPIs might be collected at higher sampling rates as compared to infrastructure data. Second, the probes might be not perfectly synchronized. Hence, time synchronization can be applied when the time series collected from different probes present similar sampling rates, while interpolation better suits situations where the probes use different sampling rates;
3) *Outlier detection*, in order to eliminate data obtained under incorrect functioning of the probes, which may negatively affect the analyses;
4) *Feature selection*, which allows to simplify the analyses by eliminating some of the collected parameters. As a matter of fact, 5G networks include a huge number of components. Hence, using ML and Artificial Intelligence (AI) approaches for network management and optimization could be challenged by the large amount of data that can be potentially collected; some of these data might be not useful and could negatively affect the analyses. Hence, feature selection algorithms can be used to remove redundant features, making the next analyses computationally simpler and faster. In general, feature selection allows to train ML algorithms faster, reduce model complexity and overfitting, and improve model accuracy;
5) *Correlation analysis*, which allows to highlight how system configurations and network conditions, collected via IM probes, are correlated and affect QoS/QoE KPIs, collected via PM tools. Revealing the correlation between IM and PM parameters allows to improve network management and derive better configuration policies for assuring SLAs.

Lack of correlation between parameters which are known to have dependencies is also a key indicator for pinpointing system malfunctioning and can help trigger needed fixes;

6) *KPI prediction*, which allows to build a model and estimate QoS/QoE KPIs by looking at other parameters, collected under different circumstances and scenarios. Being able to accurately predict a KPI would enable better network planning and management.

4.2.4.1.2 Testing as a Service (TaaS)

The concept of 'Testing as a Service' (TaaS) forms part of the offering for from an experimental platform to Vertical Industry partners. The testing architecture covers the Integration and Deployment stage of a vertical experiment, testing and experimentation services to the vertical service operators as well as to the Facility Site hosts, and to provide an automated testing service to the orchestration layer [4-35], [4-40].

Accompanying this is an associated Monitoring architecture. Such system is interleaved with the slice components and it is used to monitor all the components, from the virtualised infrastructure to the Quality of Experience (QoE) of the traffic carried by the network.

The testing framework is centred round the Test Executor, which controls the different components that play a role in a test, either testing tools, or System Under Test (SUT) elements.

Web services provide an interface towards the customer, enabling the design and execution of tests. APIs enable the southbound communication towards the different elements in the test. The testing tools are stored as images or snapshots available to the Virtual Infrastructure Manager (VIM) to be executed. Results are stored in a separate repository to be exposed to the Analytics components. A simplified Testing Architecture is displayed in Figure 4-6.

As displayed in Figure 4-6, the framework is complemented by a Test Cases Repository that enables quicker execution of testing life cycles. The foreseen Monitoring Service architecture is displayed in Figure 4-7.

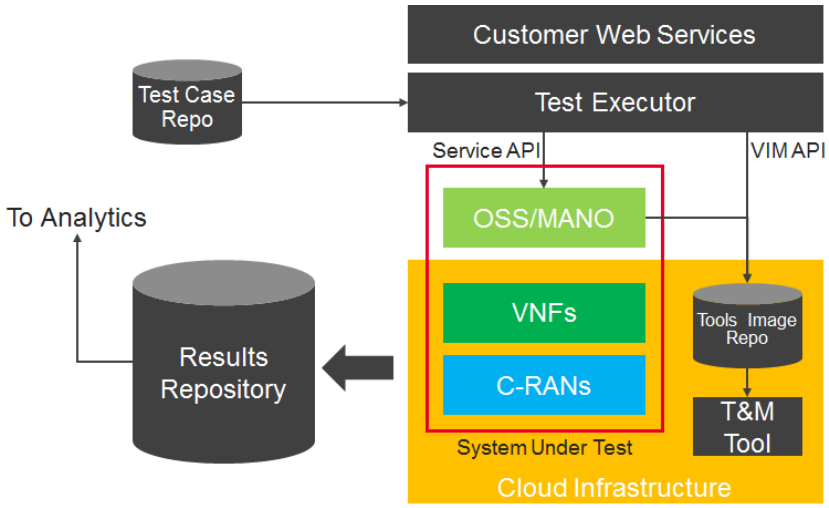

Figure 4-6: Testing Architecture framework

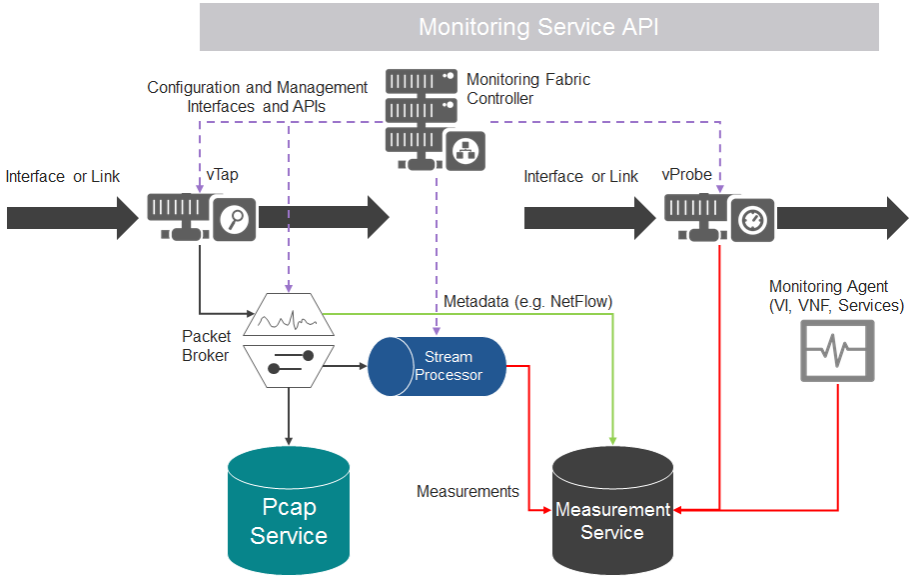

Figure 4-7: Monitoring Service Architecture [4-35]

Top Level descriptions of the architecture for Testing and Monitoring are described in [4-35], with a more refined version described in [4-39]. Implementation and operational details are described in [4-40] and [4-41].

4.2.4.2 Localization Analytics as a Service

Context-awareness is inherently dependent on location information of people and things. A location management layered infrastructure that improves localization accuracy and at the same time extends it with physical analytics is being developed [4-22], [4-23]. This infrastructure allows guarantees the end-users' right to privacy, building upon the ongoing work of 3GPP.

Localization, dedicated analytics, and their joint provision "as a service" will significantly increase the overall value of the 5G ecosystem and its evolution, as well as allow network operators to dramatically expand their range of offered services, enabling holistic sets of user, location- and context-targeted applications.

Architectural solution	5G PPP Project	Additional Reference
Localization Analytics as a Service	LOCUS	[4-22]
Localization-enabled smart applications	LOCUS	[4-23]

On top of innovative localization techniques, an additional layer of ready-to-use analytics is implemented to provide verticals with elaborate knowledge learned from localization data. Such analytics primarily leverage basic spatiotemporal features offline or in near real-time. These features include people's presence, positions, headings, velocities, and trajectories. Furthermore, the analytics possibly fuse these features with additional features using external multimodal data sources, such as counting cameras, video feeds, on-device sensors (e.g., smartphone sensors), wireless scanners, mobile service usage databases, map services (e.g., 2D or 3D maps), or demographic databases. All data will be processed through a dedicated hierarchical architecture, developed in the project and composed of virtualized platforms deployed at both the core and edge of the architecture, to guarantee low-latency, computationally efficient, privacy-aware, and scalable analytics. The latter is presented to verticals via a suitable interface and includes novel models to estimate, classify and predict statistical measures (e.g., individual and crowd dynamics, origin-destination (O-D) matrices, etc.).

Spatiotemporal analytics based on physical models adopt one of two main approaches: (i) "individual-centric" to associate the measured data to single targets/terminals, and run knowledge discovery separately on each of them; (ii) "crowd-centric" (global predictors) to associate the measured data directly to a group of users, and run a crowd-level analysis. The second results in lower dimensionality and complexity, but also coarser granularity of the result [4-24] . Crowd-centric approaches require less demanding statistical models as an input to the analytics [4-25]. However, the lack of accurate models has curbed the development of such approaches. In the few studies in the literature, regression methods (e.g., SVM) are used to that end [4-26] as well as deep learning time-series neural networks (i.e. RNNs and specifically Long Short-Term Memory – LSTMs that allows inherent support for processing sequences) among others [4-27].

The analytics on the localization data would enable new services in domains such as smart city and smart mobility. The data- and knowledge-driven applications built around the analytics based on localization data may provide improved public safety, tourism, transportation, event management, city engineering, and urban planning. As a proof of concept, the aforementioned approaches are applied to extract complex and meaningful features and behavioural (frequent and/or periodic) patterns, i.e., detection of points of interest or high people density locations, mining of mobility profiles and sequential patterns/trajectories. These will be further utilized in recommendation systems, e.g., to recommend through an App to a person the best place/ shop to visit in an indoor or outdoor setting based on the extracted information, similarities with other mobility profiles/ trajectories and –in the case of the person's explicit consent- the person's profile and preferences.

4.2.5 Services exposure – Application: localization

Architectural solution	5G PPP Project	Additional Reference
Services Exposure	LOCUS	[4-23]

In practice, offering localization analytics as a service to the Smart Network Management and 3rd party vertical applications, translates into the capability to expose services towards the Application Layer that allow the applications to access and consume localization related data, as well as analytics functions and ML model predictions according to the specific Smart Network Management or 3rd vertical requirements. Therefore, two main categories of services are defined, and as a consequence exposed by the platform [4-23]:

- Access to localization related data, through HTTP REST services that allow to both consume existing data, as well as possibly push new data into the platform (according to the security and privacy requirements and constraints regulated by the APIs)
- Access to analytics functions and ML model predictions, with two main options: i) HTTP REST services to access analytics and ML functions and consume their outputs based on regular request/response mechanism, ii) message bus based to enable applications to consume streams of data generated within the platform by localization analytics services.

For the message bus-based service exposure, the use of Kafka is assumed[4], as it can be considered as the de-facto standard solution for publish/subscribe and processing of streams of data in a production-ready and scalable way.

[4] Apache Kafka, http://kafka.apache.org/

The above-mentioned options for the exposure of and interaction with localization enabled services exposed by the platform are depicted in the form of high level communication diagrams in Figure 4-8 Figure 4-9 and Figure 4-10.

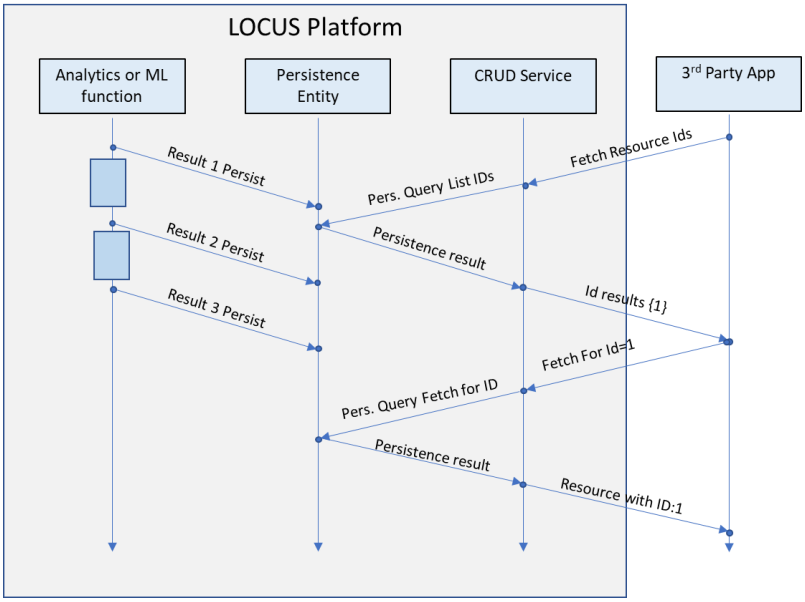

Figure 4-8: Expose CRUD operations on collection of structured or unstructured data

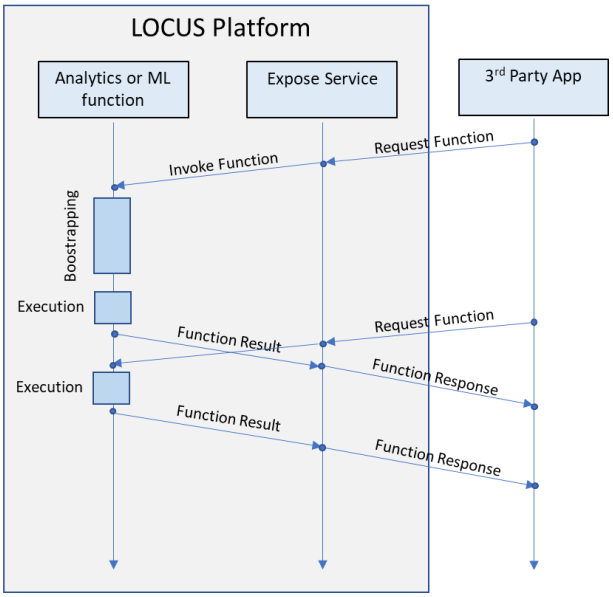

Figure 4-9: Analytics Function, ML model predict or High-Level Function as an on-demand REST service

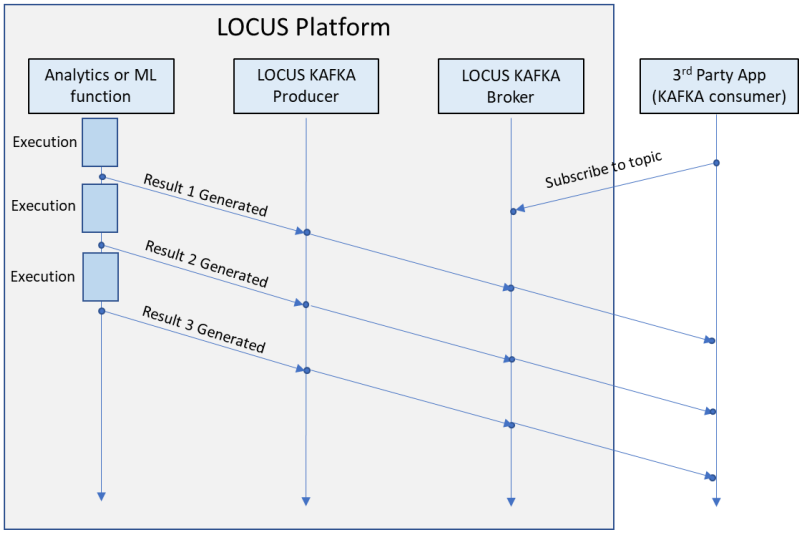

Figure 4-10: Expose Analytics Function, ML model predict or High-Level function as a Kafka Topic

4.3 Transport Architecture

The stringent demands on the transport network, when 5G networks support E2E services, come arise from increasing RAN and eMBB service capacity, new 5G-enabled services, network slicing and the dynamic deployment flexibility of the 5G RAN split architectural model. Moreover, the introduction of additional frequency bands and trends to use cloud technologies that pushes distributed cloud further out in the networks add on top of the existing requirements. These characteristics are especially manifested in the fronthaul portion of RAN transport where the latency, jitter, packet loss and synchronization requirements are very challenging. Enhanced automation capabilities in the operations and management domain represent a key requirement to meet these challenges.

Architectural solution	5G PPP Project	Additional Reference
Transport network supporting user mobility	5G-COMPLETE	[4-29]
Transport network supporting user plane resilience	5G-COMPLETE	[4-30], [4-31], [4-32], [4-33], [4-34]
Integration of satellite backhaul in 5G	5G-VINNI	[4-35], [4-36]
Backhaul automation	5G-VINNI	[4-38], [4-39]
Integration of transport and radio management for THz fronthaul links	TERAWAY	[4-43]

4.3.1 Transport network supporting user mobility

An optical transport network is proposed in [4-29], which interconnects a variety of general and specific purpose compute/storage and network elements adopting the concepts of hardware programmability and network softwarisation to support a variety of 5G-RAN deployment options. To achieve this, the optical transport network needs to provide the necessary interfaces to enable: i) disaggregation of Base Station nodes and, ii) separation of control plane (CP) and the user plane

(UP) entities. Through Base Station disaggregation, the RAN functions (including RU, DU, CU) can be physically separated and hosted at different locations.

Connectivity between the different elements can be provided over the optical transport through interfaces such as the O-RAN FH interconnecting the RU with the DU and the F1 interface interconnecting the DU with the CU. Separation of the CU Control Plane and User Plane enables flexibility in network deployment and operation, as well as cost efficient traffic management. The user plane provides connectivity of the UE and the Access Network (AN) (NGRAN in case of 5G) over the radio access technology, connectivity of the AN to the User Plane Function (UPF) over the N3 interface, connectivity between UPFs with different roles via the N9 interface, and finally connectivity from the UPF towards the external Data Network (DN) over the N6 interface [4-31]. User plane data that travel over N3 and N6 interfaces are carried over GPRS Tunneling Protocol User plane (GTP-U) tunnels. It should be noted that a big part of the user plane functionality in 5G Systems is handled by the UPF, which has to be designed to support challenging 5G services with very tight performance requirements. Part of the UPF's functionality is to set the data path between the UE and the Data Network and, as such, it is responsible for the PDU session establishment and the maintenance of the UE connectivity under user mobility.

To minimize the deployment costs of 5G systems, 5GRAN and 5G Core elements are hosted at the same compute nodes with the end-user applications. All these elements are implemented in software and are hosted in Virtual Machines (VMs) (or Containers) running on compute nodes placed at the network edge or deeper in the core network. However, the integration of MEC with 5G systems brings new issues and challenges that need to be resolved. On the one hand, edge nodes usually have limited capabilities and are responsible to provide services targeting small geographical areas. On the other hand, mobile users such as smartphones and intelligent vehicles, tend to frequently move in between those small covered areas. Therefore, a main issue that needs to be resolved is how network and compute resources are allocated when a user leaves the area of coverage of a MEC node and enters the area served by another MEC node [4-32]. Another challenging aspect is associated with the reservation of sufficient resources across all elements of the 5G system (RAN and CORE and transport network providing connectivity between these) to support mobility. As users move from one gNB to another, PDU sessions with the required QoS Flow Identifier should be established. This requires reservation of specific resources to set up the appropriate Data Radio Bearer (DRB) tunnels between the UE and the gNBs and N3 GTP-U tunnels between the gNB and the UPFs. In addition to the PDU sessions, for services requiring access to a specific data network (i.e., MEC server) N6 tunnels should be established between the UPFs and the MEC and maintained for the whole duration of the connection of the mobile user. Therefore, a critical decision that needs to be taken by the Session Management Function (SMF) is when and over which elements these sessions should be established to ensure service continuity.

To address this challenge, the adoption of joint user handover and VM migration to ensure service continuity in MEC-assisted 5G environments supporting advanced transport network connectivity has been proposed [4-33]. As an example of the supported functionality, consider the scenario shown in Figure 4-11 where a mobile UE moves from a source gNB to a target gNB. This relocation triggers a handover-related signalling procedure that is implemented in 5G systems using the N2 interface. In the simplest scenario where the UE moves from gNB1 to gNB2, the handover process will trigger SMF to establish a new N3 tunnel from UPF1 to gNB2. As the UE moves from gNB2 to gNB3 a new intermediate UPF (UPF2) is inserted by the SMF. This new UPF is hosted in MEC2 and is used to provide the necessary connectivity between the gNB3 and the APP server through UPF1. As before, the SMF will establish an N4 session with the UPF3 in order apply the necessary rules to UPF3 and create an N9 tunnel between UPF1 and UPF3 and an N3 tunnel between gNB3 and UPF3.

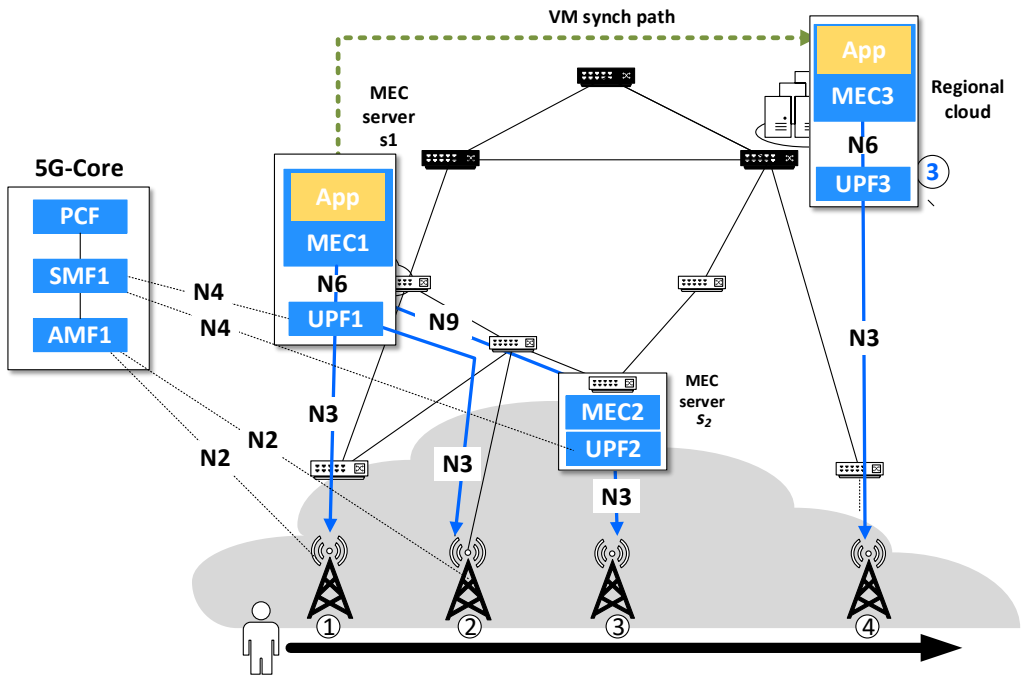

Figure 4-11: Joint user handover and VM migration problem to ensure service continuity in MEC-assisted 5G environments.

In the above cases the application server is hosted in MEC1 and therefore, the connection through the N6 tunnel interconnecting the MEC with UPF1 remains unaltered. However, as the user moves to gNB4 the distance between the UE and the VM where the APP server is hosted increases leading to an increase in the E2E delay. In this case, the application will be transferred to a server that is closer to the location of the mobile user. To realize this, a path interconnecting the source (MEC1) with the target (MEC3) server should be established to enable migration of the user context from MEC1 to MEC3. This process, also known as live Service Migration can be used to move active VMs (or containers) along with their applications to appropriate servers. When considering the concept of VM migration in 5G environments it is clear that this decision should be taken jointly with the placement of the UPF. In Figure 4-11 it is shown that once the migration has been completed a tunnel interconnecting gNB4 with MEC3 should be established through UPF3. It is obvious that to ensure service continuity for MEC-assisted 5G services a complex chain of several processes needs to be performed ensuring efficient allocation of connectivity between the UEs and the MEC nodes [4-31]. To successfully complete all these processes in a timely manner reducing service disruption, several issues need to be considered during the service provisioning phase including allocation of: i) sufficient network resources for the establishment of the necessary connections between the 5G RAN and the 5GCORE elements, ii) sufficient computational resources to host not only the virtualized 5G functions (CU, DU, UPF, etc.) but also end user applications and iii) availability of network resources for the interconnection of servers to perform live migration. In response to this, a multistage optimization framework has been developed in which a decision related to the placement of each VM to the appropriate servers is taken at each process stage. The objective of the proposed framework is to minimize the network cost for the provisioning of the services to the end users with the required KPIs. This cost function takes into account the weighted average of the utilization of the network and compute elements and a penalty when service latency increases. The analysis is based on realistic statistics for network traffic and users' mobility patters as well actual measurements for the VM migration process overheads.

To solve the problem of joint VM migration and mobility management in 5G systems, a 5G testbed has been deployed over a virtualized cloud environment allowing the accurate estimation of network and compute resources consumed during the establishment of new UE sessions. These measurements are coupled with actual network traffic and user mobility statistics collected over an operational mobile network system. Figure 4-12a shows an example of the network traffic generated during the migration from a source to a target MEC server as measured in a lab environment. In this example, the VM hosts a 4K streaming video server. During this live service migration process, the memory and disk state of the VM is transferred from the source host to the destination host. Storage transfer is performed through a steady throughput, while memory transfer though multiple synchronization iterations.

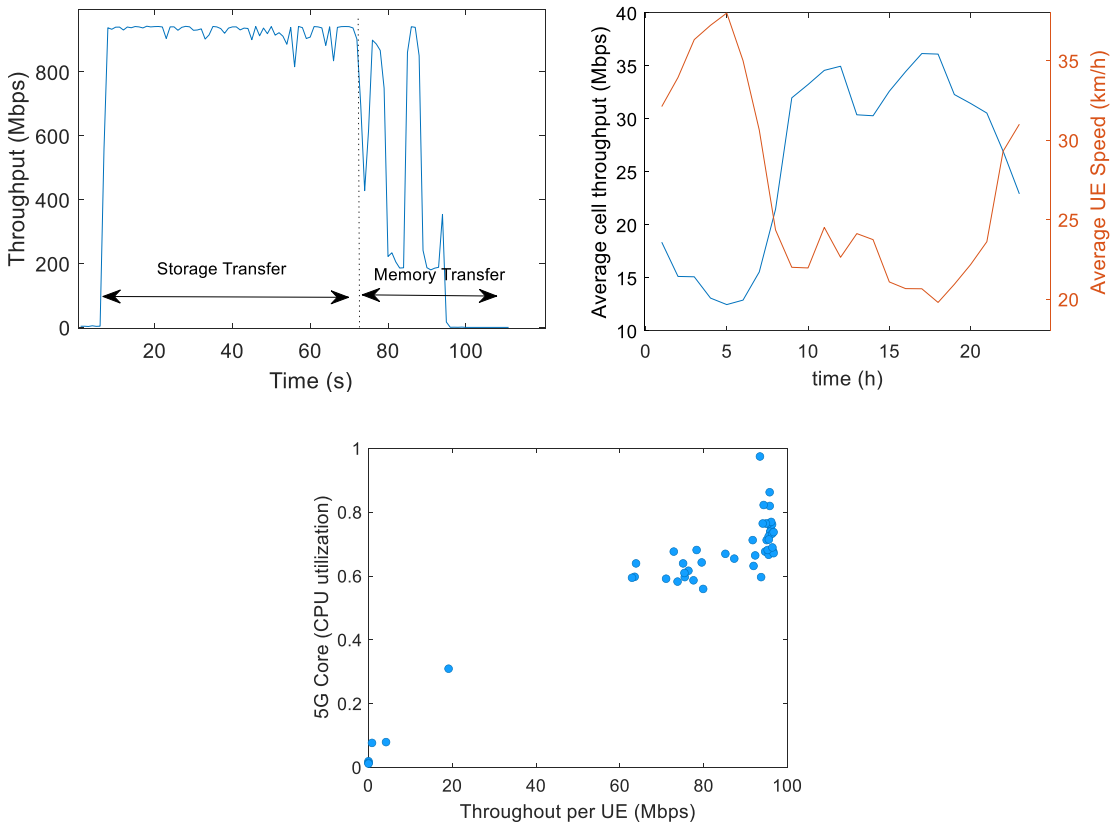

Figure 4-12: a) Time series showing the traffic generated during VM migration from a source to a target VM, b) Correlation between background mobile network traffic per gNB and speed per UE, c) Impact of average UE throughput on 5GC computational resources.

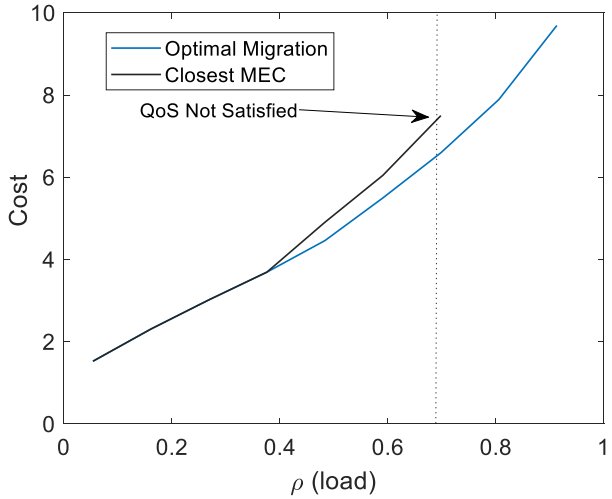

Figure 4-13: Total utility (cost) as a function of the traffic served per gNB

As mentioned above, a prerequisite for the success of the VM migration process is the availability of network and compute resources during the storage and memory copy phase. The availability of these resources depends on the area where UEs move and the background network traffic. Higher background network traffic is observed in densely populated areas (i.e. city centres) where the speed of the mobile UEs is lower. The interrelation between the average mobile traffic per gNB and the average speed per UE within the area covered by the gNB is shown in Figure 4-12b. The relevant traces have been captured from an operational mobile environment, whereas average speed statistics have been collected from GPS trackers. The impact of the mobile network traffic on CPU utilization of the virtualized 5G platform is shown in Figure 4-12c. As expected, the average traffic per UE increases the CPU utilization of the platform used to host the virtualized 5G system. It is concluded that possible migrations associated with a user moving from a gNB covering a sparsely populated region to a densely populated region, should be treated carefully as service disruptions may occur.

A comparison between the proposed VM migration scheme considering both the operation of the 5G system and the end user services with a policy that assigns VMs to the MEC closest to the UE is shown in Figure 4-13. The total cost is the weighted average of the network and compute cost (increases with the increase of the network resources used) plus the end user service delay (increases with the increase of packet latency in the PDU sessions). We observe that under low loading conditions both schemes have similar performance. Therefore, VM migration may be applied in both cases providing similar results. Under high loading, for the closest MEC VM migration policy, MEC resources are not sufficient to handle both operational and user services (i.e. 5G CORE, 5G RAN and application server). In this case, a migration (if allowed) will overload the system resulting in degradation of the system performance. On the other hand, the model that considers all components of the 5G network, will optimally place VMs to appropriate servers ensuring service continuity for a wider range of inputs traffic loads.

4.3.2 Transport network supporting user plane resilience

To address the high reliability requirements of URLLC services, the ETSI TS 123 501 V16.6.0 standard (2020-10) proposes that each UE configures two redundant PDU sessions, while the user plane paths of the two redundant PDU Sessions are disjoint. Redundancy in deployed 5G systems can be achieved in several ways. A possible approach is to provide protection against failures using redundant transmission on N3/N9 interfaces (see Figure 4-14). To ensure that the two N3 tunnels are transferred via disjointed transport layer paths, the SMF or PSA UPF should provide different routing information in the tunnel information (e.g. different IP addresses or different

Network Instances), and this routing information should be mapped to disjoint transport layer paths according to the network deployment configuration. The redundant transmission using the two N3/N9 tunnels is performed at QoS flow granularity and the tunnels are sharing the same QoS Flow ID. Another option is to set up two N3 and N9 tunnels between NG-RAN and PSA UPF for the URLLC QoS Flow(s) of the same PDU Session in order to support redundant transmission. This will be configured during or after a URLLC QoS flow establishment.

In the case of downlink traffic, the UPF duplicates the downlink packet of the QoS. Flow from the DN and assigns the same GTP-U sequence number to them. These duplicated packets are transmitted to I-UPF1 and I-UPF2 via N9 Tunnel 1 and N9 Tunnel 2 separately. Each I-UPF forwards the packet with the same GTP-U sequence number. The NG-RAN eliminates the duplicated packet based on the GTP-U sequence number. In the case of uplink traffic, the reverse functionality takes place, however, in this case the PSA UPF eliminates the duplicated packets based on the GTP-U sequence number.

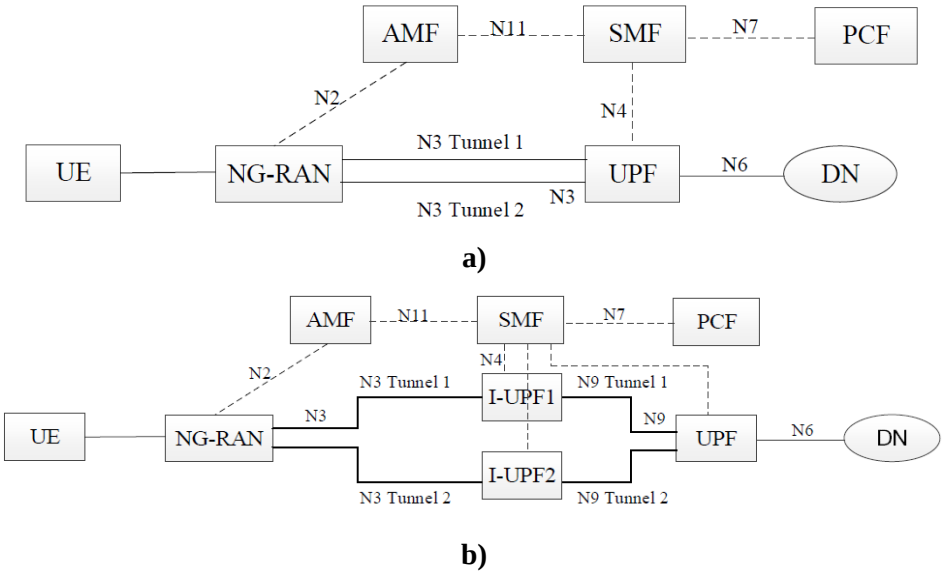

Figure 4-14: (a) Redundant transmission with two N3 tunnels between PSA UPF and a single NG-RAN node and (b) Two N3 and N9 tunnels between NG-RAN and PSA UPF for redundant transmission [TS 123 501 V16.6 2020-10]

Based on the discussion above it is clear that duplication of 5G-RAN and 5GC components for redundancy purposes leads to **increased requirements in the transport network**. An example is shown in Figure 4-15 where duplication of N3 tunnel elements doubles the transport network capacity requirements in some parts of the network. These requirements further increase when NG-RAN protection is also necessary as multiple fronthaul connections need to be established between the RUs and the DUs/CUs.

To address this issue, the concept of Network Coding (NC) is proposed aiming to offer redundancy by multiplexing flows traversing FH and BH transport nodes and, therefore, reducing the volume of the transmitted flows [4-34]. Using NC, as shown in Figure 4-16, two different traffic streams with the same source and destination nodes are routed through the network following diverse paths. These can be protected through their modulo-two sum that is generated at the source node and forwarded to the common destination node. This allows reconstruction of each one of the two initial streams at the destination node, in case of a failure along one of the two paths that the initial two streams are traversing. Thus, reducing the overall protection bandwidth requirement by half. Adopting this approach, simultaneous protection against optical network and/or compute element failures can be achieved. Although NC has been extensively used to enable protection against link failures, its application in resilient 5G networks has not

been proposed before. This can be attributed mainly to the overhead that the application of the modulo-two sum and the replication operations of NC introduce in practical systems, which may degrade the performance of 5G system. At the same time, flows arriving from different source nodes at the decode nodes should be synchronized.

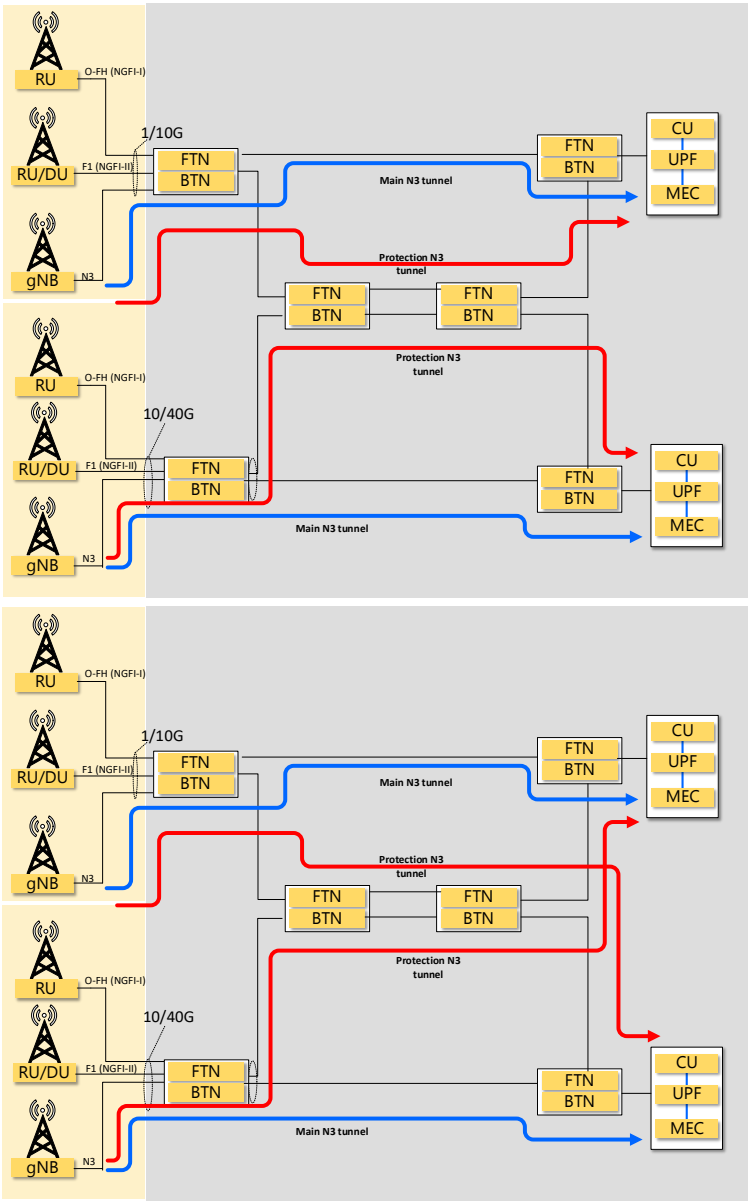

Figure 4-15: Protection of a 5G network from failures of compute and/or network elements through a) redundancy of N3 tunnels b) redundancy of UPF functions

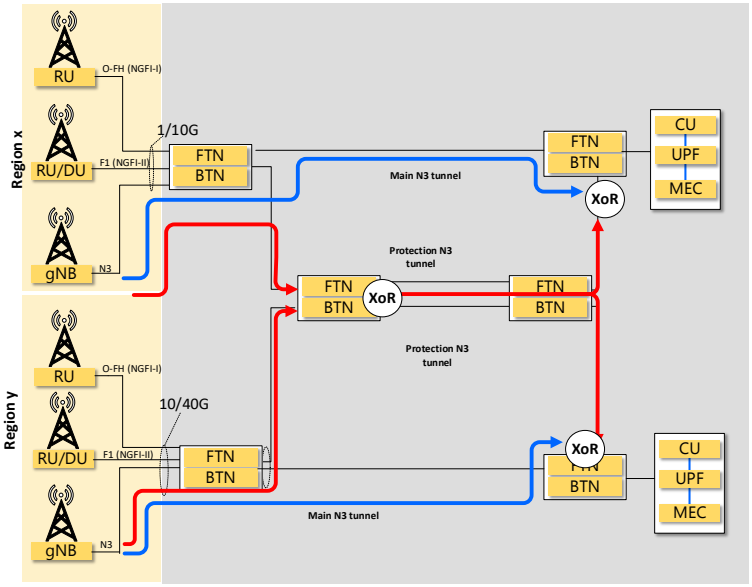

Figure 4-16: Network coding for service protection

To address these limitations, it is proposed to extend optical edge nodes functionalities, currently providing the interface between RANs and optical transport, with a solution that enables them to execute the coding and decoding processes at line rate, while meeting the delay and synchronization requirements of the FH and BH flows. In order to evaluate the network level benefits of the proposed approach, an optimization framework has been developed, which i) focuses on the design of a NC-enabled architecture that protects the system from possible network and/or compute element failures, and ii) minimizes buffering at the edge, while ensuring that all flows arrive simultaneously at their end points.

Network level evaluation

The performance of the overall system was evaluated through a purposely developed optimisation [4-34]. The input traffic data used have been experimentally produced through an OpenAirInterface (OAI) experimental platform. Once DU/CU requirements have been determined, the performance of the overall system with and without NC considerations was examined for the Bristol City topology shown in Figure 4-17 a). In this topology, RUs are attached to the edge node through Point-to-Point links. For this topology, DU/CU processing for Regions A and D will are provided by Server 1 whereas BBU processing for Regions B and C by Server 2. At the same time, the main FH connectivity is provided through links 1-5 and 3-6 for regions A, B, respectively. Protection of FH flows is provided through paths 1-2-4-6 for Region A, 3-2-4-5 for region B, 5-4-6 for region D and 6-4-5 for region C. The encoding (replication) processes for regions A, B are performed at nodes 2 and 4, respectively, while for Regions C and D decoding and replication operations are both formed at node 4. A comparison of the optical network utilization of the Bristol City network for the provisioning of URLLC services is shown in Figure 4-17b, with and without the adoption of NC. It is observed that, when NC is adopted, optical network utilization is reduced by approximately 33% leading to an overall reduction in the power consumption. The impact of the optimal placement of the buffering functionality on the optical nodes is shown in Figure 4-17c. When the Integer Linear Programming (ILP) scheme that minimizes buffering size for synchronization is adopted, the size of the buffers at the optical edge nodes can be reduced by 40%.

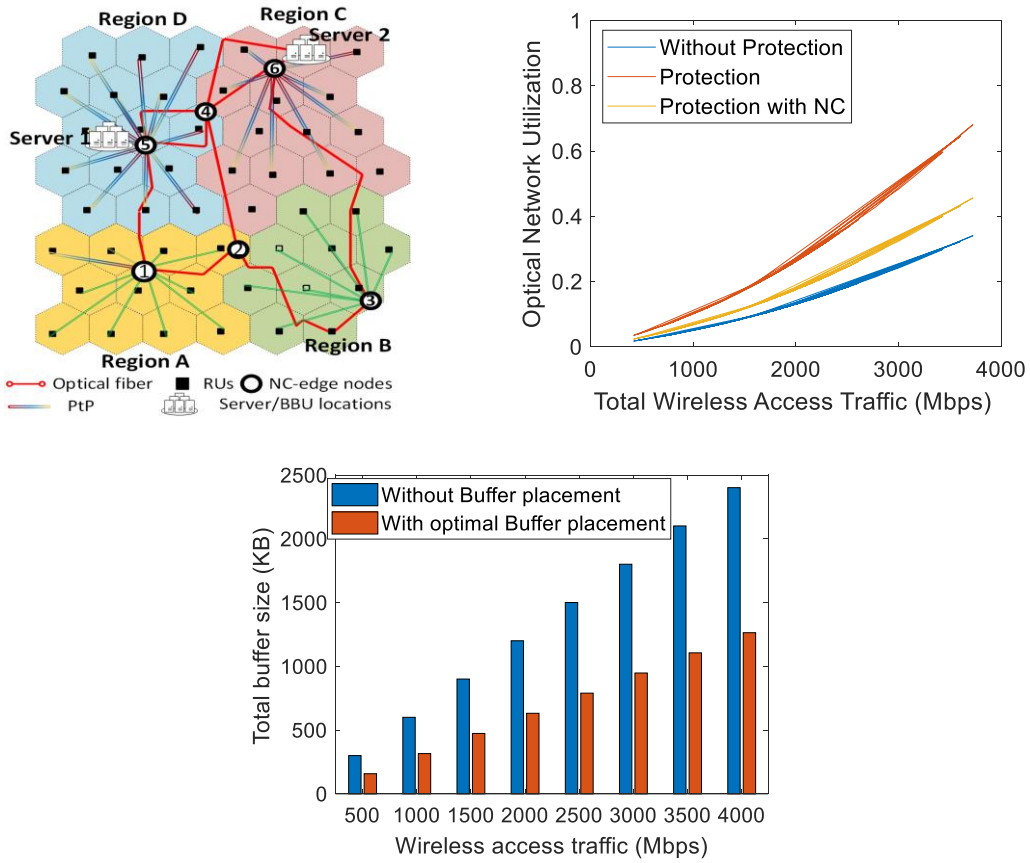

Figure 4-17: a) Bristol topology with NC enabled nodes; b) Optical network utilization with and w/o NC; c) Impact of optimal buffer placement at the optical edge.

4.3.3 Integration of satellite backhaul in 5G

Integration of a Satellite Backhaul link can be considered as specific instance of a link included in transit of 5G traffic. As a result of significant recent advances in satellite technology, satellites can deliver cost-effective high-performance solutions to unserved and underserved areas and MNOs can leverage satellite solutions even more efficiently than before. By adopting industry standard Ethernet service constructs and orchestration, it is possible for a satellite-based backhaul solution to plug seamlessly into an MNO's backhaul landscape – in the same manner as any terrestrial solution does. With the inter-carrier visibility and automation solution, coupled with the use of Metro Ethernet Forum (MEF) compliant LSO, it is possible for an MNO to turn every bit transported over satellite into a productive bit with no stranded capacity. Satellite players will 'plug into' the MNO ecosystem and become a true enabler of value-based outcomes.

At a high level, the key elements within a satellite backhaul network include:

- Space Segment: The Space Segment corresponds to the SES's owned and operated in-orbit transparent (bent-pipe) satellite fleet which interconnects the Satellite Remote and the Satellite Teleport.
- Satellite Remote (VSAT Terminal): The Satellite Remote is the section of a satellite network that sits on the subscriber's side of the connection. Its primary element is a satellite router, which is connected directly to a compact satellite antenna (VSAT), and also to one or more UE's (either directly, or indirectly via an access point). The satellite router passes information to/from the satellite, converting it between RF and IP formats for the up- and down-links, respectively.

- Satellite Teleport: The Satellite Teleport, as pictured on the right-hand side of the satellite link in Figure 8, refers to the satellite hub platform equipment that resides on the Satellite Network Operator's side of the network. It consists of a satellite antenna and ground segment infrastructure that communicates with the satellite, and typically forwards data to a mobile and/or data network.
- Satellite Radio Access Network (SatRAN): The SatRAN constitutes the link from the satellite router in the Satellite Remote (including the link to any directly-connected UEs) that extends over the space segment and terminates at the ground segment in the Satellite Teleport. Typically, a dedicated hardware element in the Satellite Teleport is responsible (at least in part) for the termination of the RF signal, and its subsequent conversion to IP (and associated processing).
- Satellite VNFs: One of the fundamental goals of NFV is to reduce the hardware footprint of network equipment by "softwarising" (i.e., virtualizing) network services, and subsequently consolidating numerous virtualized network functions on a single COTS platform. Examining the opportunities for virtualization of network functions in the satellite network, the options that represented the highest return in exchange for the lowest effort were those that were amenable to a so-called "lift-and-shift" approach. Simply put, such a process involves transferring the execution environment of a satellite function from bare metal or native OS, to a Virtual Machine (VM).

As can be also seen from Figure 4-18, this is the approach adopted by SES Networks when integrating their Satellite links into a 5G network architecture.

A satellite backhaul connectivity deployment includes an edge node and a central node connected using a satellite backhaul link. The UEs connect to the edge node which connects to the central node through a GEO/MEO backhaul link. The backhaul is seen as a transport layer for the messages between the edge and the central node. Because of this, the backhaul is as transparent as possible, while at the same time being able to assure a guaranteed communication quality. This can be configured statically or dynamically through the specific management interfaces.

Further details of the implementation are provided in [4-35] and the Luxembourg Facility Site high level design Annex of [4-36].

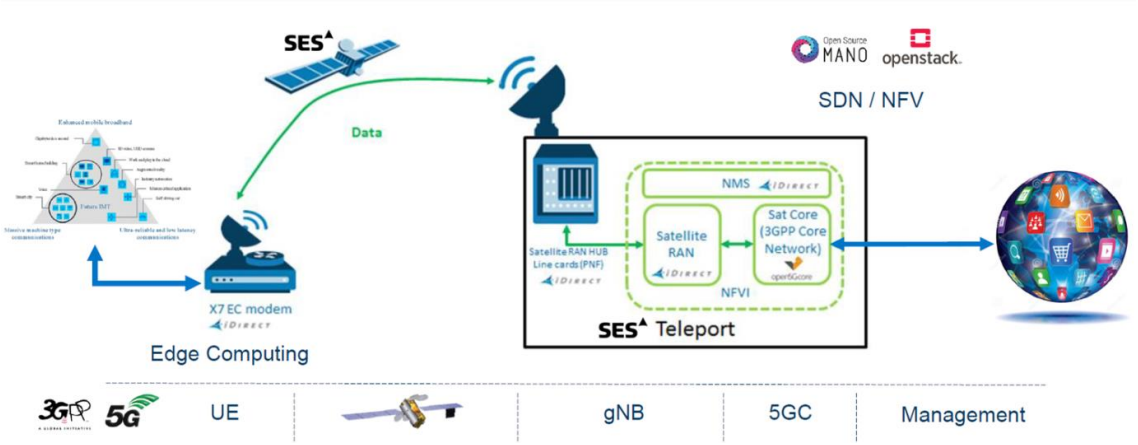

Figure 4-18: SES's GEO/MEO-based satellite backhaul offerings

4.3.4 Backhaul automation

For backhaul network automation, a hierarchical transport SDN controller architecture can be implemented, comprising domain controllers, the WIM and the orchestrator, as per [4-10]. However, the programmability and flexibility of SDN is not enough and further enhancements

are needed to augment the current automation scheme. Several new challenges are created as a result, as follows:

a) Automating complex human-dependent decision-making processes (e.g., managing and optimizing network and system configuration processes) by providing system and network intelligence tools and services.

b) Determining which services are offered, and which services are in danger of not meeting their SLAs, as a function of changing context.

c) Providing an experiential architecture (i.e., an architecture that uses Artificial Intelligence (AI) and other mechanisms to improve its understanding of the environment, and hence the operator experience, over time).

d) Improving infrastructure utilization and agility (response to real-time changes) while maintaining SLAs. The deployed networks and systems likely need to be aware of the needs of Services and Applications, and handle environmental changes in an automated way without human involvement.

e) Improving operator's personnel efficiency through improved management and automation, while providing increased visibility and a simplified interface between the operator and the networks and networked applications; this reduces errors and makes human-directed commands more efficient and intuitive.

A solution for these challenges can be based upon work in the ETSI's Experiential Networked Intelligence Industry Specification Group (ISG ENI).

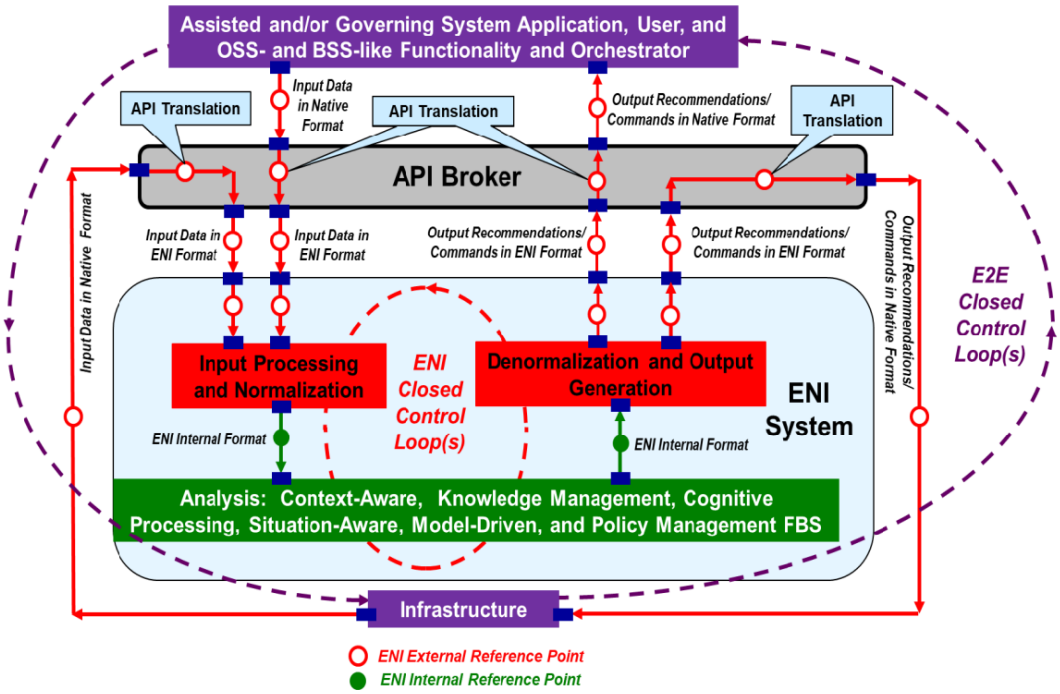

Figure 4-19: High-Level Functional Architecture of ENI when an API Broker is used

The Experiential Networked Intelligence (ENI) System is an innovative, policy-based, model-driven functional entity that improves operator's experience. ENI can be deployed as an external AI/ML entity, outside of an existing "Assisted System". Four classes of Assisted Systems are anticipated – from those capable of communicating with the operator only, to those where some information can be shared directly with ENI while the other has to go through the operator or other existing management tools. The Assisted System may also already have closed-loop control

or is a hybrid system where some modules enjoy the benefits of a closed-loop control while others do not, ENI can be directly coupled to influence the overall closed-loop control of the combined system.

A high-level Functional Block diagram that includes the use of an API Broker is shown in Figure 4-19, and defined in ETSI GS ENI 005 [4-37].

Each functional block is made up of specific capabilities as defined below.

Input processing

Data Ingestion Functional Block - The purpose of the Data Ingestion Functional Block is to collect data from multiple input sources and implement common data processing techniques to enable ingested data to be further processed and analysed by other ENI Functional Blocks.

Normalization Functional Block - The purpose of the Normalization Functional Block is to process and translate data received from the Data Ingestion Functional Block into a form that other ENI Functional Blocks are able to understand and use. Different data models are likely to be used by different ENI Functional Blocks. Each such data model typically uses different data structures, objects, and protocols to represent its concepts.

Analysis

Knowledge Representation and management - The purpose of the Knowledge Representation and Management Functional Block is to represent information about both the ENI System as well as the system being managed. Knowledge representation is fundamental to all disciplines of modelling and AI. It also enables machine learning and reasoning –without a formal and consensual representation of knowledge, algorithms cannot be defined that reason about the knowledge.

Context-Awareness Management - The purpose of the Context-Aware Management Functional Block is to describe the state and environment in which an entity exists or has existed. Context consists of measured and inferred knowledge and may change over time.

Situational Awareness Management - The purpose of the Situation Awareness Functional Block is for the ENI system to be aware of events and behaviour that are relevant to the environment of the system that it is managing or assisting. This includes the ability to understand how information, events, and recommended commands given by the ENI system will impact the management and operational goals and behaviour, both immediately and in the near future. Situation awareness is especially important in environments where the information flow is high, and poor decisions may lead to serious consequences (e.g., violation of SLAs).

Cognition Management - The purpose of the Cognition Management Functional Block is to enable the ENI System to understand normalized ingested data and information, as well as the context that defines how those data were produced. Once that understanding is achieved, the Cognition Management Functional Block then evaluates the meaning of the data and determines if any actions need to be taken to ensure that the goals and objectives of the system are met. This includes improving or optimizing different metrics such as performance, reliability, and/or availability.

Policy-based Management - Policy is a set of rules that is used to manage and control the changing and/or maintaining of the state of one or more managed objects.

There are three different types of policies that are defined for an ENI system:

- Imperative policy: a type of policy that uses statements to explicitly change the state of a set of targeted objects. Hence, the order of statements that make up the policy is explicitly defined.

- Declarative policy: a type of policy that uses statements to express the goals of the policy, but not how to accomplish those goals. Hence, state is not explicitly manipulated, and the order of statements that make up the policy is irrelevant. In this document, Declarative Policy will refer to policies that execute as theories of a formal logic.
- Intent policy: a type of policy that uses statements to express the goals of the policy, but not how to accomplish those goals. Each statement in an Intent Policy may require the translation of one or more of its terms to a form that another managed functional entity can understand.

Model Driven Engineering Functional Block - The purpose of the Model Driven Engineering Functional Block is to use a set of domain models that collectively abstract all important concepts for managing the behaviour of objects in the system(s) governed by the ENI System.

Output Generation

Denormalization Functional Block - The purpose of the Denormalization Functional Block is to process and translate data received from other Functional Blocks of the ENI System into a form that facilitates subsequent translation to a form that a set of targeted entities are able to understand. For example, different data models are likely to be used by different ENI Functional Blocks. Each such data model typically uses different data structures, objects, and protocols to represent its concepts.

Output Generation Functional Block -The purpose of the Output Generation Functional Blocks is to convert data received by the Denormalization Functional Block into a form that the Assisted System (or its Designated Entity) is able to understand.

This forms the basis of further work on Backhaul Automation as described in [4-38].

4.3.5 Integration of transport and radio management for THz fronthaul links

The terahertz (THz) frequency band is envisioned as a promising candidate to support ultra-broadband for beyond 5G (B5G) networks. The need for huge capacity at very low latencies highlights the need for making use of higher frequencies of the electromagnetic spectrum, where much larger bandwidths are available.

To integrate multi-transport technologies, including fixed and radio links, requires a novel design of a comprehensive SDN management architecture for joint optimization of radio and network resources. In this context, the proposed architecture [4-43] obtains the most added value out of use of THz technology integrated with SDN for mobile network beyond 5G. A seamless service and network management system that automatically guarantees the required level of quality has to leverage optical concepts and photonic integration techniques for an ultra-wideband and broadband wireless system as part of agnostic transport layer.

B5G networks will be adding new set of resources to be managed when including radio modules that will provide radio link within an existing transport network. Thus, the existing network functions will not only have to allocate resources to existing RAN and transport, but they will also have to manage the resources of transport nodes, i.e., fixed switches and radio modems that bring additional capacity to the transport. Moreover, the radio nodes would be added on need basis, thus the resources available would change depending on whether THz radio modems are integrated into the existing transport network. Therefore, x-Haul transport brings a new paradigm into the concept of dynamic on-the fly resource management that should combine not only RAN but also fixed and THz transport networks.

The management of this transport network require developing an innovative SDN controller that will perform the management of the network and radio resources in a homogeneous way [4-43] . The SDN functionality would be part of network function (NF), known as Mobile Backhaul Orchestrator (MBO), compliant with 3GPP specifications as part of the SBA.

The SDN controller is needed to manage the communication system in a centralized way, by receiving management requests (typically, provisioning, monitoring, fault reporting) at the network level, through the North-Bound Interface (NBI). These requests are elaborated and transformed into element-level management commands (typically, configuration, monitoring, subscription to notification events), that are sent to the managed network elements through the South-Bound Interface (SBI) of the controller. Figure 4-20 depicts the logical SDN management network architecture on the physical network and different priorities assigned to traffic based on VLANs that are also used in fixed networks.

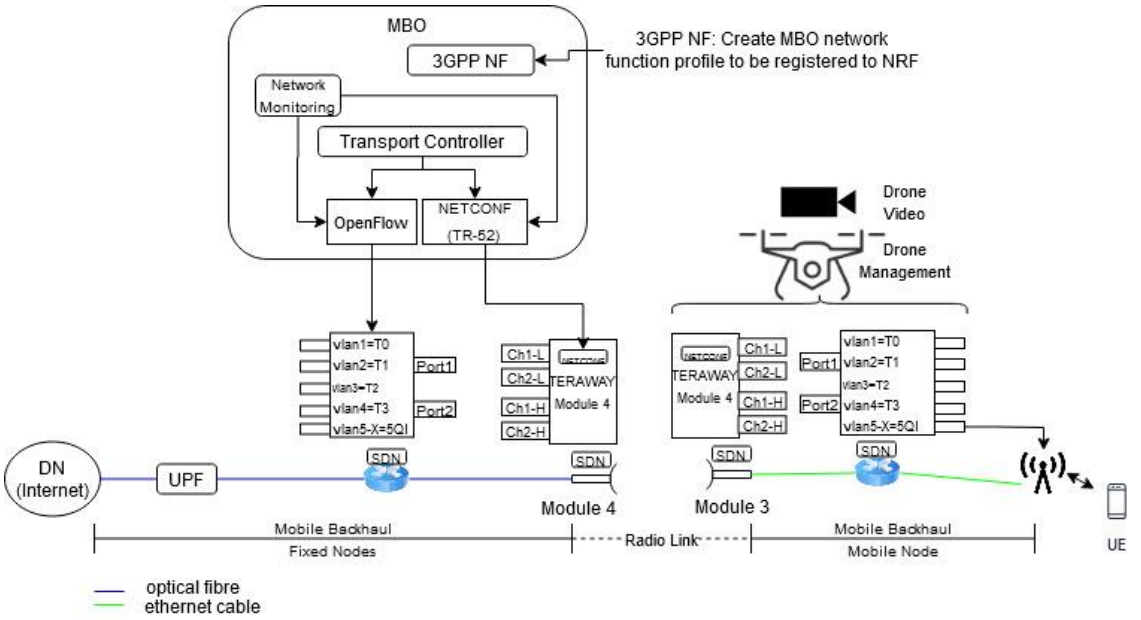

Figure 4-20: TERAWAY transport architecture with traffic classification

The transport SDN controller is composed by different subsystems, where each of them is a software module that communicates with a corresponding piece of software residing in the controlled network element. In the proposed transport management system, three kind of network elements are managed, each paired with a different subsystem.

The transport management system should be compliant with 3GPP specified QoS specifications. Thus, when transport management is used for providing backhaul or fronthaul communications, the 5G Quality Indicators (5QI) should be extended with transport management specific QoS parameters to deliver the high reliability and low latency slices. Thus, the transport management requires the integration of transport management as part of SBA architecture where the THz radio link part of the end-to-end network will be managed through MBO and hidden under 3GPP Transport Subnet Network Slice Management Service (TS-NSMS).

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5 Automated Management & Orchestration Architecture

5.1 State of the art of 5G M&O Architecture Design

This chapter introduces a new design of Management & Orchestration (MANO) architecture for 5G and beyond networks, leveraging on the existing MANO architecture and management framework as described in the recently published 5G PPP Architecture white paper [5-1], along with various different design and implementation choices. The design principles of the high-level MANO architecture presented in [5-1] are aligned with the ETSI [5-2] and 3GPP standards (e.g., [5-11], [5-12] and [5-67]), as well as from the architectures proposed by various projects from 5G PPP Phase II and Phase III (e.g., 5G-TRANSFORMER, 5G-VINNI, 5G-PICTURE, SONATA, 5GTANGO, 5G-MoNArch).

In [5-1], a consensus MANO architecture is introduced that summarizes a common view from the different 5G PPP projects. It supports: (i) the control of individual network functions; (ii) the chaining of individual functions into services; (iii) the ability to use different underlying execution environments, ranging from different virtualization techniques over different, specialized, accelerated hardware to different networking environments (wireless, optics, cable) – referred to as "technological domains"; (iv) the ability to work within or across different administrative domains, encompassing different network operators (to provide a service at vast geographic ranges across multiple operators) or companies from different business models (e.g., network operators and separated cloud infrastructure operators); (v) the ability to support a vast range of different applications with very different resource, deployment and orchestration needs as well as optimization goals (e.g., cost versus latency); and (vi) the slicing mechanisms to subdivide the infrastructure necessary to execute a service and carry its data in separate logical infrastructures with dedicated resources (or at least, guaranteed service performance). It is also conceivable to position a slicing system underneath or above a MANO system as well as inside it as an integral part.

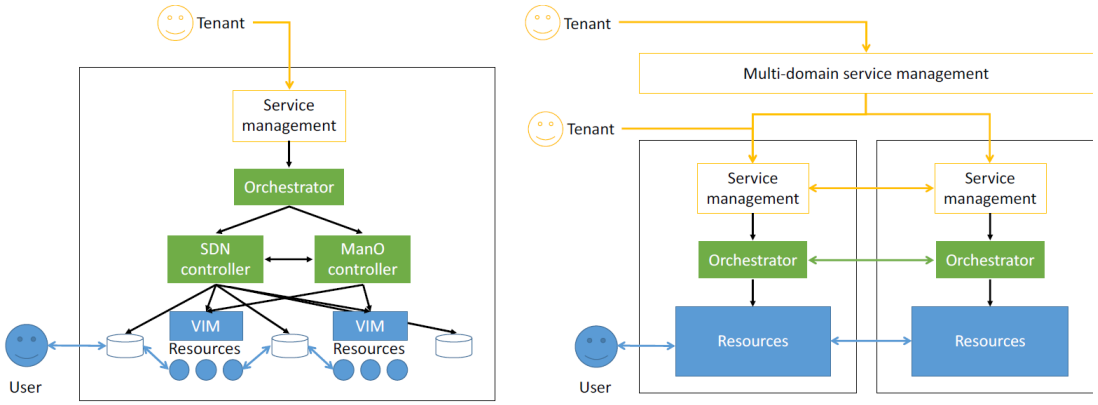

Figure 5-1: 5G PPP consensus MANO architecture for single-domain case (left) and multi-domain case (right) [5-1]

Beyond this consensus architecture, a variety of different architecture options have been also discussed in [5-1], such as integrated or segregated orchestration, flat vs. hierarchical orchestration, the relation of orchestration and slicing, methods for abstractions, conflict resolution, and handling of different time scales (short vs. long-term).

In terms of the implementation patters of the MANO, different options were presented. One is that of the monolithic orchestrator. In the reference architecture, an orchestrator has a lot of responsibilities. Realizing all these in a single, monolithic piece of software might be feasible, but at the cost of jeopardizing maintainability, dependability, and performance. Hence, more suitable implementation patterns are needed. To improve flexibility and to ease implementation of such a complex piece of software, the software engineering community has developed multiple approaches. One of these approaches is based on the notion of microservices, connected by a software bus that realizes a publish/subscribe paradigm between its components. Such a microservice-based orchestrator is not tied to a single machine. Provided that a suitable, well performing sub system is available, it becomes easy to distribute the orchestrator's components across multiple machines for improved dependability and performance.

To define a service or a slice, different types of descriptions have been proposed for many types of artefacts: from infrastructure, to functions, services, slices, policies, SLAs, tests, and possibly also to business objectives. This also includes a vertical mapping of defining vertical service blueprints and vertical service descriptors (VSD) to describe vertical services including their SLA requirements. Moreover, [5-1] also discussed a few additional aspects of Monitoring and DevOps for a continuous integration and continuous development of the Orchestration as well as the validation tools.

The design ideas and methods presented in [5-1] have built the fundamental basis for the MANO design for 5G. Based on the design in [5-1], this chapter aims to introduce architecture extensions and new concepts for the evolution of MANO architecture for the 5G and beyond networks, focusing on new approaches and methods for the enhanced slice management (Sec. 5.2), service and network automation (Sec 5.3), cloudification techniques (Sec. 5.4), enhanced monitoring and data management framework (Sect 5.5), and evolution of MANO design (Sec 5.6). It is important to point out, the architectures presented in this chapter have been defined in different projects and their terminology can be slightly different. Terms like *platform*, *orchestrator*, *slice manager* etc. must be contextualized in the scope of each particular architecture.

5.2 Enhanced Slice Management

The concept of network slices allows efficient sharing of 5G infrastructures among multiple tenants, building multiple logical networks over a common physical infrastructure in a flexible and customized manner. Slice management is a key feature of the 5G management system, to enhance the dynamicity and the efficiency of the network operation and to guarantee differentiated QoS levels on the basis of vertical services intents and requirements. Indeed, the management of network slices is tightly correlated to the dynamicity and the characteristics of the vertical services running on top of them, and their lifecycle management and automation is driven by the service demands. This leads to architectural solutions where vertical service and network slice management are strictly bound and their functionalities are coordinated in a cooperative manner, as proposed in Section 5.2.1.

Another major challenge for the slice management is the coordination of the end-to-end (E2E) network slice elements in virtualized environments, combining the orchestration of access and core network functions across edge and cloud domains, as analysed in Section 5.2.2. However, the orchestration of access and core virtual network functions, often combined with the provisioning of service level virtual applications, needs to be integrated with a proper configuration of the underlying transport network. This is critical to guarantee the interconnectivity among the virtual functions composing the E2E network slices and it requires the same level of dynamicity and deep integration with the overall resource orchestration strategies. Potential solutions relying on the Software Defining Networking (SDN) paradigm are

presented in Section 5.2.3, which also describes the enhancement on the slice management in terms of vertical-driven approaches and E2E slice management extensions towards the RAN and multi-domain environments.

5.2.1 Vertical-driven slice management

Table 5-1: Architectural solutions for vertical-driven slice management

Architectural solution	5G PPP Project	Additional Reference
Slice ordering architecture and lifecycle management	5G VINNI	[5-13], [5-15], [5-16], [5-17]
Slice Manager	5GENESIS	[5-19]
Composition and sharing of end-to-end network slices for vertical service arbitration	5Growth	[5-44], [5-45]

5.2.1.1 Slice ordering architecture and Lifecycle Management

Figure 5-2 shows an architecture for E2E network slices management, as documented in [5-13].

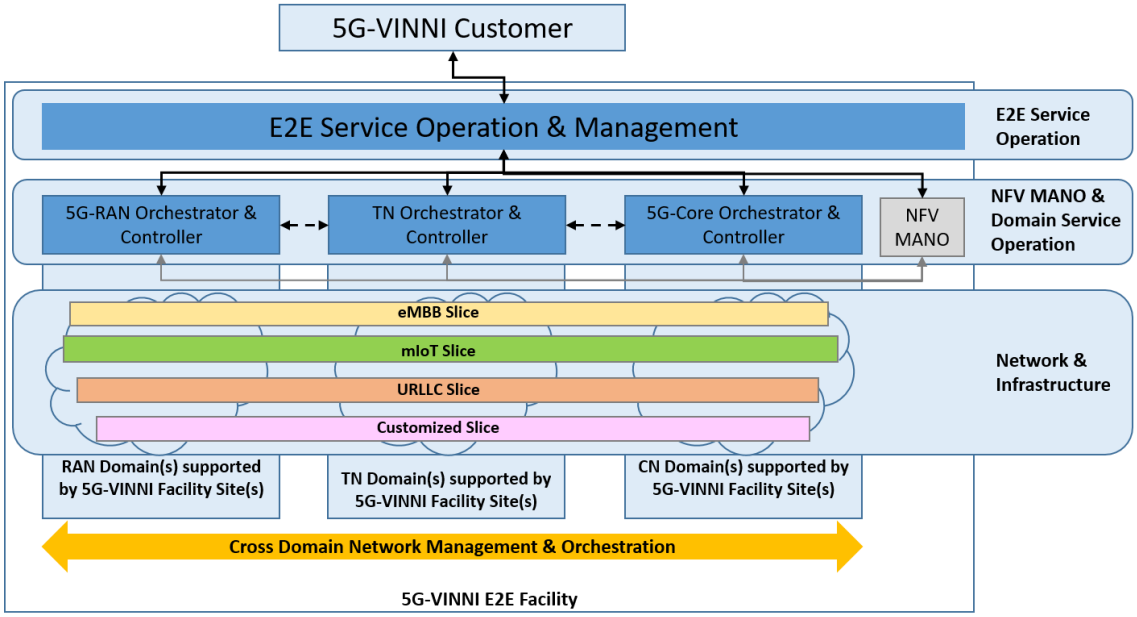

Figure 5-2: E2E Network Slicing Architecture [5-13]

The E2E Network Slicing architecture includes a customized network slice type in addition to eMBB, mIoT and URLLC. This customized network slice type, originally defined in GSMA Generic Network Slice Template [5-14], provides an execution environment for the delivery of communication/digital services that do not fall into a single 5G category. The use of Slice Templates is described extensively in [5-15].

Based upon this architecture, it is possible for a Customer to gain information from the Service Operation and Management layer regarding pre-existing slice types that have been defined in the overall system, and order service based on one of these, or to design a new slice template specific to their own requirements based on the Service Blueprint defined in [3]. Differing levels of 'capability exposure' for the different facility sites within the platform are identified in [5-16], enabling vertical experiments to be integrated to differing levels, dependent upon the capabilities that the Customers and their systems support.

The full process of slice lifecycle management in the slicing architecture is described in section 3.1 of [5-16] and is enabled by interfaces drawing on Standards definitions from ETSI NFV ISG, MEF and TMF, as described in [5-17]. It is made up of a multi-stage process comprising:

- Preparation phase to generate a suitable Service Blueprint
- Commissioning phase where a network slice instance is deployed
- Operation phase where is Network slice is in use
- Decommissioning phase where the network slice instance is withdrawn from service

This process is described in detail in [5-16].

5.2.1.2 Slice Manager

The Slice Manager is a key part of the facility [5-19] that coordinates network resources of the virtualised functions and services, managing the lifecycle of multiple virtual networks on top of a common infrastructure. The slice view is provided and controlled from a central software component, i.e., the Slice Manager, a standalone component that is implemented as part of the Coordination Layer and is deployed in all the system Platforms.

The selected technology for the management and virtualization in the facility is the open-source project OSM [5-20], which delivers an orchestration framework aligned with the ETSI NFV Information models. The OpenStack Virtual Infrastructure Manager (VIM) is used to control the pool of compute, storage and networking resources to create service chains and deliver the network services to the Experimenters. At the network Edge, to demonstrate the advantages of Multi-Access Edge Computing (MEC) capabilities, OpenNebula [5-21] is selected to provide a more lightweight performance and scalability of process compared to OpenStack.

The Slice Manager is part of a broader open-source project under the Apache 2 license in the open5GENESISsuite. Following 3GPP definitions (as depicted in 3GPP TR 28.801 V15.1.0 [5-12]), a Network Slice Instance (NSI) is a managed entity which can be described as the sum of various sub-slices of different network domains, such as the RAN, the transport network, the Core Cloud and the Edge Cloud. The Slice Manager is responsible for the communication with the underlying components of each Platform, as depicted in Figure 5-3, in order to provide the required resources across the different domains of the testbed and instantiate the network services that constitute an E2E communication service.

The Slice Manager is based on a highly modular architecture, built as a collection of microservices, each of which is running on a docker container. The key advantages of this architectural approach are that it offers simplicity in building and maintaining applications, flexibility and scalability, while the containerized approach makes the applications independent of the underlying system.

The Slice Manager provides a set of North-Bound REST APIs, which follow the Open APIs 3 specification, together with a built-in Swagger-UI tool, which is used for documenting, testing and consuming the API endpoints. These APIs can be consumed by the Experiment Life Cycle Manager (ELCM) or by the Slice Manager Administrator in order to trigger some of the Slice Manager functionalities, such as performing create, read, update and delete (CRUD) operations on NSIs, adding South Bound components of the underlying Platform or retrieving information about an instantiated 5G Network Slice.

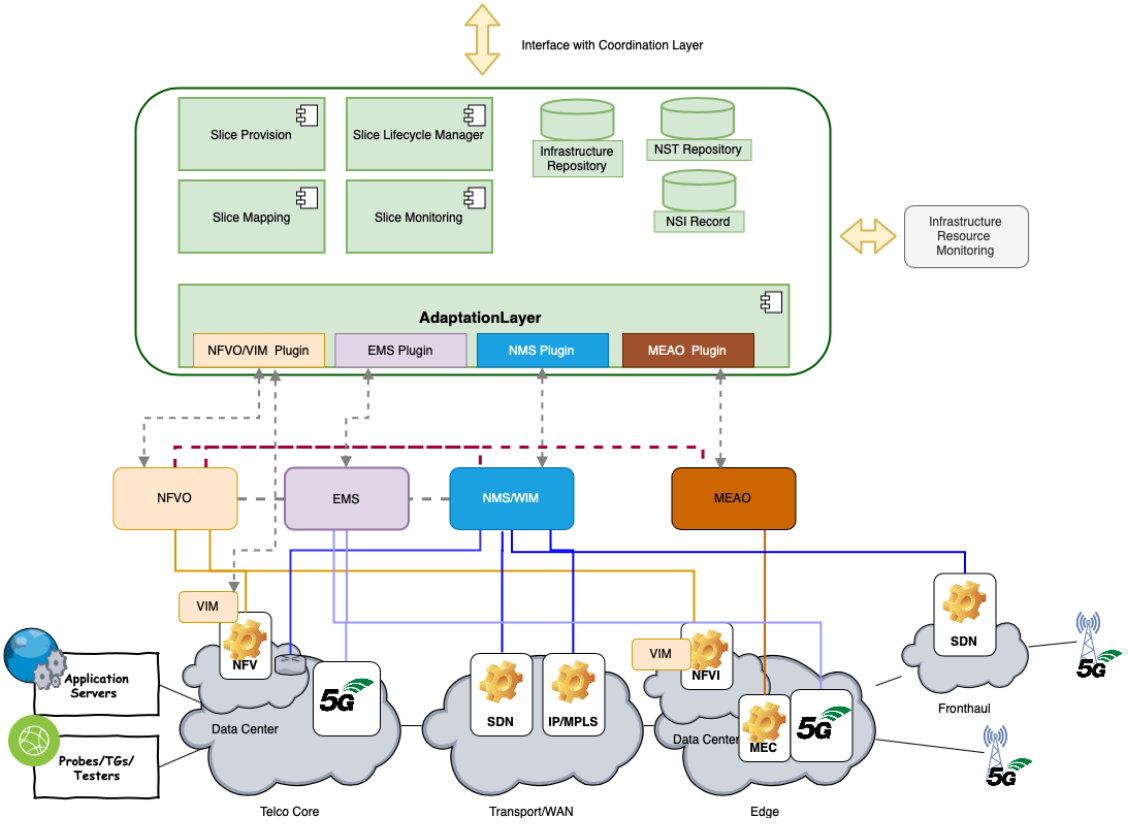

Figure 5-3: Slice Manager Architecture

5.2.1.3 Composition and sharing of end-to-end network slices for vertical service arbitration

The delivery and management of vertical services is tightly coupled with the orchestration of the network slices hosting these services. A joint lifecycle management approach, which considers the combination of vertical service elements and their mobile communications, allows to coordinate the allocation of network and computing resources along the whole chain, from the radio access interconnecting the UEs up to the distributed servers where the virtual applications are running. In 5G architectures, an E2E network slice is thus considered as the composition of virtual functions constituting the access and core networks, which enable the mobile connectivity, with additional virtual applications instantiated at the edge and/or cloud domains and implementing the vertical-oriented logic of the service, while interconnection is provided at the transport network level. In this scenario, the management of the virtualized networking elements related to access, core and transport domains, typically performed through a Network Slice Management Function (NSMF), must be driven and complemented by the orchestration of the virtual application functions, taking into account their profiles in terms of QoS, isolation and security requirements, resource consumptions, dynamicity and service interdependencies.

Following this concept, the Vertical Slicer is an architectural element introduced in the 5G architecture proposed in [5-47] as an extended Network Slice Management Function that integrates vertical service management functionalities. It acts as coordinator for the lifecycle management of all virtual entities composing the E2E network slice. Such entities are organized in network slice subnets that are instantiated on-demand, optionally across multiple domains, and automatically sized, configured, customized and scaled on the basis of the vertical service requirements and dynamicity.

In this context, the Vertical Slicer introduces two features that, on the one hand, facilitate the verticals in the process of deploying their services in a 5G infrastructure and, on the other hand,

allow to optimize the resource utilization on the basis of the service demands applying service-driven sharing strategies at the network slice level.

The vertical-oriented definition of a service, which drives its deployment in a 5G environment, exploits the concept of vertical service blueprints. A service blueprint exposes a simplified and abstracted view of the service, mostly expressed from the vertical's perspective, identifying its components, their interconnectivity, metrics and configuration parameters. The blueprint minimizes the networking and 5G technology details, usually difficult to manage for a vertical, but offers enough flexibility to declare application-level customizations and configurations that are then automatically translated into network slice parameters. The translation process, implemented internally at the Vertical Slicer level, hides the complexity of the network slice structure. Verticals can define their service in terms of application components only, providing just high-level connectivity requirements of the mobile traffic, e.g., expressed through pre-defined service categories, or selecting a slice type and related parameters. Starting from this abstraction, the system composes the E2E network slice, identifying its networking and application components, as well as the associated slice profile. These inputs are then used to drive the orchestration of the network services associated to each slice subnet, which can be deployed in different domains, and the configuration of the radio access resources.

The service-driven optimization of the slice resources is based on the coupling between vertical service and slice management, which allows to manage the slices' lifecycle on the basis of the evolution of the associated vertical services. Modifications at the vertical service level, which can be triggered manually or through closed-loop automations on the basis of application performances, are reflected on the network slices adjusting dynamically their dimension and their resources. Network slice sharing strategies are adopted to share common virtual functions or slice subnets among different service instances, in compliance with their isolation requirements and QoS requirements. An arbitration function at the Vertical Slicer handles the concurrency of co-existing vertical services, within shared or different slices, according to the service level agreements established with the tenants. In case of scarce resources, services with lower priority are automatically moved to alternative slices to potentially share existing components, scaled down or even terminated, according to the active policies.

5.2.2 E2E Slice Management

Table 5-2: Architectural solutions for end-to-end slice management

Architectural solution	5G PPP Project	Additional Reference
Orchestration hierarchy	5G-CARMEN	[5-82] [5-83]
E2E slice management and orchestration approach focused on scalability	MonB5G	[5-30]
Service slicing	FUDGE-5G	[5-79]

5.2.2.1 Orchestration hierarchy

The architecture in [5-82] and [5-83] extends the 5G cellular system with orchestrated distributed network edge resources in support of connected cars, which leverage infrastructure services from topologically close service instances. Whereas various past solutions were based on E2E orchestration, taking network domain orchestrations in the central offices, the transport network, as well as the RAN into account, the proposed solution focuses on the management and orchestration of decentralized automotive services, which are provided at network edge resources.

Service continuity for such agile customer from the automotive industry is a key objective, which requires the coupling or tighter integration of so far independently treated systems for 5G mobile communication, Multi-Access Edge Computing (MEC) and NFV MANO. The following summarizes the architectural keys and the main enablers for the orchestration of distributed edge resources and the support of full edge resources control in the view of treating the network edge as an integral part of an E2E sliced system.

System Overview of 5G Edge Orchestration System

In the context of E2E management of cooperative, connected and automated mobility (CCAM) services in federated environments, this solution proposes a multi-domain, multi-tenant and hierarchical orchestration system that leverages, extends and integrates the ETSI NFV-MANO system and ETSI MEC system. One of the goals of the orchestrated platform for CCAM is to facilitate cross-border service continuity. This challenge goes beyond the simple roaming or handover between different operators, in the sense that it also includes the migration of applications and services from one (MEC) cloud to another, in order to keep providing the roaming vehicle with the expected Service Level. Since latency is one of the key requirements of CCAM services, especially those demanding L4 autonomous driving, the network slices over which the CCAM services are delivered are deployed and managed at the edge sites, closer to the vehicles. Figure 5-4 shows a high-level functional architecture of the 5G Edge Network Orchestration Platform for CCAM with the relevant functional blocks and reference points.

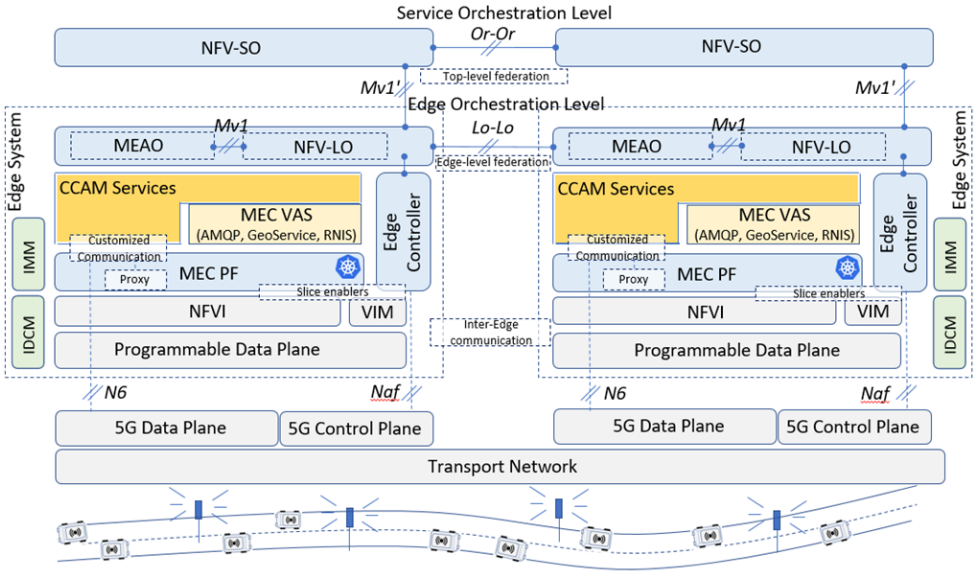

Figure 5-4: Functional architecture and key references points for 5G edge network orchestration

As shown in the figure, the orchestration framework has two tiers of orchestration layer, where the top layer NFV Service Orchestrator (NFV-SO) has a 1:N relationship with edge level orchestrators. The edge level orchestration system is composed of the NFV local orchestrator (NFV-LO) and MEC Application Orchestrator (MEAO). The NFV-LO and MEAO collaborate with each other over the Mv1 reference point as per the ETSI GS MEC 003 specification [5-23]. The edge orchestration system (NFV-LO and MEAO) is responsible for the Life Cycle Management (LCM) of the network slices within its domain. A domain of an edge orchestration system is characterised by a MEC site that characterizes an NFV Infrastructure (NFVI) providing compute, network, storage resources (i.e., MEC servers) on which network slices are instantiated upon. An Edge Controller is developed for the LCM of the NFVI resources within a MEC site. There is a 1:N relationship between the Edge Orchestration System and the Edge Controllers.

For the E2E management of network slices that span across multiple edge domains, even crossing administrative and country domains, the 5G edge network orchestration platform realizes federation interfaces over the multiple reference points. These are the Or-Or reference point between the NFV-SOs belonging to different domains, and the Lo-Lo reference point between the NFV-LOs belonging to different administrative domains. An interface for the inter-edge communication is also realized which will be explained later. The Or-Or reference point is based on the ETSI GS NFV-IFA 030 specification [5-22], while the Lo-Lo reference point inherits from the Or-Or reference point but its scope is limited to establishing direct federation between the edge orchestration domains to directly inter-coordinate the LCM of multi-site network edge slices bypassing the NFV-SO. In other words, the NFV-SO as being the top-level orchestrator has full administrative control of the edge orchestration system but it can delegate management tasks to the edge orchestration system via a novel concept of Management Level Agreement (MLA) that is negotiated between the NFV-SO and the NFV-LO over the Mv1' reference point. The MV1' reference point is also inherited from the Mv1 reference point between the NFV-LO and the MEAO mentioned above. For well-coordinated management of multi-site network edge slices, the MLA is also negotiated between the NFV-LOs over the Lo-Lo reference point, after the scope of the MLA has been agreed between the NFV-SOs of the respective domains over the Or-Or reference point.

5.2.2.2 E2E slice management and orchestration approach focused on scalability

The orchestration and management architecture proposed in [5-30] aims to provide a new framework for the concurrent provisioning of high numbers of network slices as envisioned in 5G and beyond. The primary goal of this approach is to achieve scalable and automated management of network slices in multiple orchestration domains. The framework adopts the management system decomposition proposed by ITU-T [5-24] and uses the MAPE (Monitor-Analyze-Plan-Execute) paradigm [5-25] as the basis, implemented through AI-driven operations. The framework allows for the creation of a "management slice" that can be used for run-time management of multiple slice instances of the same template *(Management as a Service - MaaS)*. The OSS/BSS of each orchestration domain focuses on the lifecycle management (LCM) of slices and resource management, but it is agnostic to slices. Each slice can be seen as a service with its own management platform, called embedded or In-Slice Management (ISM). The ISM is part of a slice and is implemented as a set of VNFs; therefore, the resources scaling mechanism can contribute to its performance and new management services can be dynamically deployed/updated during the slice lifetime. The approach provides isolation of management planes of slices (not provided by ETSI NFV MANO [5-27] nor 3GPP). The ISM of each slice (i.e., slice OSS/BSS) may act as a service orchestrator. AI can be applied at multiple levels of the architecture hierarchy, having their relevant entities of Monitoring System (MS), Analytic Engine (AE) and Decision Engine (DE). The sets of interacting MSs, AEs and DEs are instantiated at the OSS/BSS level (for E2E slice management and orchestration in orchestration domain (for slice admission control, allocation of resources to slices and domain FCAPS), global, cross-slice, and cross-domain optimizations), inside the virtualized infrastructure, within slices (responsible for each slice FCAPS management), or as a part of each node/function (autonomic Element Manager) and thus enable FCAPS management in a distributed and automated manner. Due to the embedded management, the cooperation is based on a minimized exchange of information between the management system components. It typically uses KPIs to achieve the goal. All subsystems use MS/AE/DE triplets to perform specific, control loop-based optimization and communicate over the intent-based interfaces.

The details of the framework are presented in Figure 5-5. The **MonB5G Portal** is used by Slice Tenants, Slice Management Providers and Infrastructure Providers to request slice LCM. It

exposes capabilities and partakes in negotiations related to the contract's business dimension. The **Inter-Domain Manager and Orchestrator (IDMO)** is involved in slice preparation and deployment phases. Eventually modified slice template includes mechanisms for slice stitching to obtain the E2E slice and proper modification of the E2E slice management plane. If the infrastructure has multiple owners, IDMO may decide how to split the E2E slice template dynamically to a new one, which supports inter-domain interaction of slice components located in different orchestration domains. The **Domain Manager and Orchestrator (DMO)** is responsible for the orchestration of slices in its domain, manages the domain resources and is agnostic to slices. The DMO can be seen as a combination of resource-oriented OSS/BSS and a MANO orchestrator. The **Infrastructure Domain Manager (IDM)** enables programmable infrastructure management by the Infrastructure Provider, who can use the MonB5G Portal to deploy additional management functions (IOMFs). The slices are self-managed, and the slice template includes a slice management plane called **Slice MonB5G Layer (SML)** and its main part called **Slice Functional Layer (SFL).** A generic structure of a self-managed, single domain slice (SML/SFL) is shown in Figure 5-6. The SFL part is composed of virtual functions dedicated solely to slice functions, but it can also use Domain Shared Functions (DSFs), which are grouped to form shared slice. The use of DSFs provides a reduced footprint of slices and decreased slice deployment time. SFL consists of AI-driven Element Managers (node MS/AE/DE) called Embedded Element Managers (EEMs).

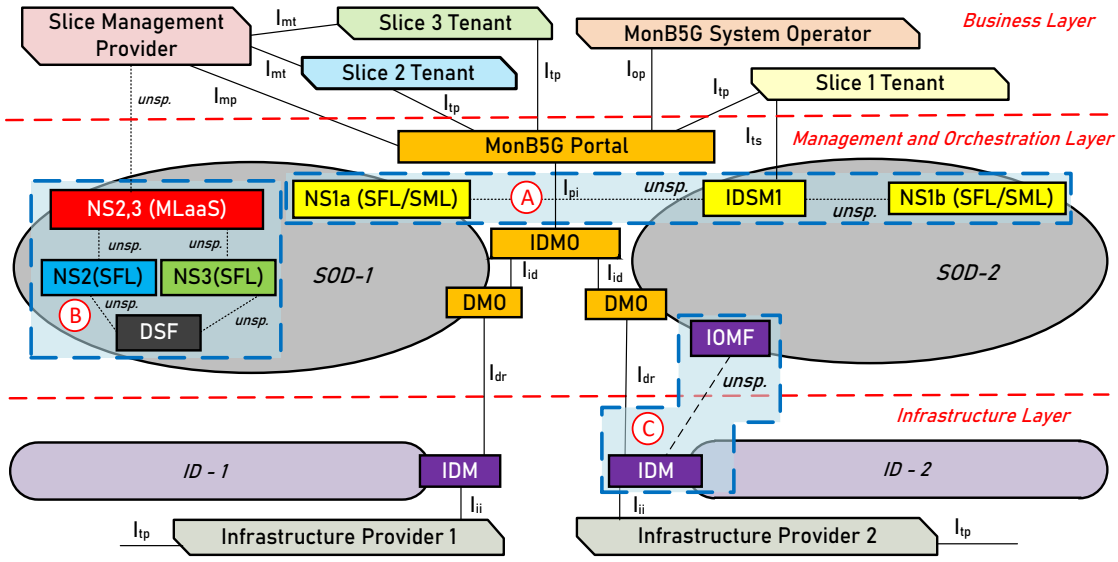

Figure 5-5: Scalable E2E slice management and orchestration framework with different options of slice deployment: A – multi-domain slice; B – slices that use MaaS and shared functions, C – orchestrated management functions of Infrastructure Provider

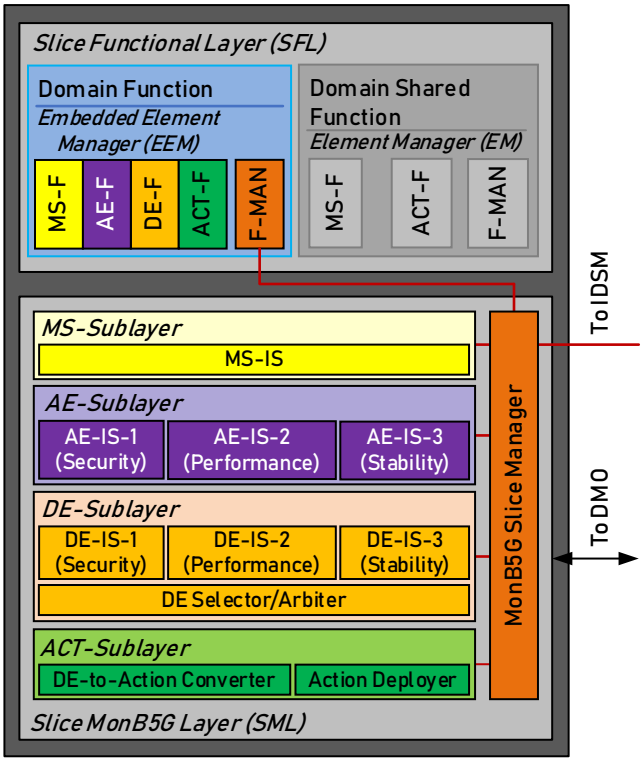

Figure 5-6: Generic structure of the SML/SFL slice

The ACT component is responsible for converting high-level DE output into a set of low-level primitives. EEMs are the links between the SFL and SML parts of a slice. The SML part is split into MS, AE and DE sublayers. The MS provides generic, reusable monitoring, whereas AEs and DEs cooperate to achieve a specified data-driven proactive decision. Specifically, AE analyses the data obtained from MS for a specific purpose (e.g., security attack identification, fault detection, performance prediction). The analysed data is then fed to the related DEs to take appropriate decisions later on converted by ACT to elementary actions. There are multiple goals to be optimized; therefore, multiple AEs and DEs can be a part of SML. To resolve unavoidable conflicts between DEs, the DE Selector/Arbiter is a part of the DE sublayer. The DEs of SML may decide about SML and SFL functionality update by sending orchestration requests (resource scaling, template update). Moreover, the SML provides direct, intent-based management to the Slice Tenant. When a slice spans multiple SODs, the Inter-Domain Slice Manager (IDSM) entity (deployed as VNF) is responsible for the E2E slice management. It interacts with SMLs of all domain slices that compose the E2E slice. The addition of SML to SFL undoubtedly increases slice footprint, implying also longer slice deployment time. MonB5G proposes using the Management as a Service (MaaS/PaaS) paradigm to solve the problem. In this case, SML is an independent slice capable of managing multiple SFL instances of the same template. The MaaS platform (called MonB5G Layer as a Service MLaaS) can be operated by a Slice Management Provider's business entity. This case for a single SOD is marked as Option B in Figure 5-5, where SFLs of the MLaaS-managed slices also use services provided by DSF for reduction of SFL footprint. The Option A of the figure concerns deployment of a self-managed multi-domain slice, and Option C shows infrastructure management-oriented functions (IOMF) deployment.

5.2.2.3 Service Slicing

The architecture in [5-79] builds upon the concept of a SBA for both control and user plane functions. As a result, 5G Core and vertical applications are considered as enterprise services which are managed by an underlying SBA platform that implements service routing, lifecycle management and control, monitoring and service slicing. Furthermore, the platform assumes an

underlying NFV- and SDN-enabled infrastructure with a unified access domain for UEs to communicate with the cellular telecommunication system. In this context, *slicing* is the task of resource isolation and QoS enforcement with *E2E* perspective including all possible resource domains across the control and user plane, i.e., access domain, 5GC CP and UP, and DNs. The resulting *Service Slicing* vision demands slicing operations at run-time in a programmable and service-centric fashion. It becomes apparent that each of these domains have their own set of properties and objectives that have to be sliced, thus creating a multi-dimensional challenge. The realisation and demonstration of established concepts around the creation of 5GLAN Virtual Groups, RAN slicing and cloud slicing. Additionally, the architecture provides an SBA-driven approach for slicing 5GC control plane functions that has been already made public in its concept in the eSBA group of NGMN [5-31]. This - so called - *Service Slicing* approach offers programmable APIs for enterprise services to communicate preferences for the slicing operations across the aforementioned slicing domains. Linking the independent domains together into an E2E fashion in order to form a logical "slice" is the key challenge and is an ongoing architectural task within the project.

Further to the Service Slicing capabilities**,** the proposed platform operates as a VNF-based platform within a pre-defined and configured wholesale slice within an existing infrastructure respecting existing APIs and technologies around ETSI NFV MANO (e.g., OpenStack, OpenShift) and SDN (e.g., OpenFlow and/or existing controllers such as Floodlight, OpenDayLight or ONOS). The provisioning of the platform is utilising a Platform-as-a-Service toolchain, called Agnostic platfoRm DEploymeNt orchesTrator (ARDENT) [5-32], allowing the automation of the provisioning and management of the SBA platform across multiple sites.

5.2.3 Integration of transport networks

Table 5-3: Architectural solutions for integration of transport networks

Architectural solution	5G PPP Project	Additional Reference
Integration with WAN Infrastructure Manager	TeraFlow	[5-33]
Network management aspects for integrating transport and radio management for THz fronthaul links	Teraway	[5-41]

5.2.3.1 Integration with WAN Infrastructure Manager

Together with NFV, Software Defined Networking (SDN) is a key enabler for the telecommunication industry transformation. SDN provides the necessary network transformation bringing network functions and APIs, easing the convergence of the telecom and the IT industries [5-33] [5-34].

SDN has been demonstrated as an enabler for NFV architectures, integrating network services and associated resources. [5-35] distinguishes between SDN resources and SDN controllers. SDN resources might be located in the NFV architecture as: a) physical switch or router; b) virtual switch or router; c) e-switch, software based SDN enabled switch in a server NIC; and d) switch or router as a VNF. Moreover, an SDN controller can be located in different positions: 1) merged with the Virtualised Infrastructure Manager functionality; 2) virtualised as a VNF; 3) part of the NFVI and is not a VNF; 4) part of the OSS/BSS; and 5) being a PNF.

This flexibility provides a clear benefit for NFV architecture to include SDN enablers. Particularly, the inter-connection of NFV infrastructure points-of-presence (NFVI-PoP) through WAN

Infrastructure Manager (WIM) and the request fort Multi-Site Connectivity Services has also been widely studied [5-36]. The necessary data models and protocols are defined in [5-37].

ETSI OpenSource MANO (OSM) includes, since release 5, the necessary data models for inter-domain connectivity services request. To this end, L2VPN are requested to a WIM in order to provide the necessary connectivity [5-39]. Several research projects in OSM Ecosystem have contributed in this approach, for instance as presented in [5-38].

5.2.3.2 Network management aspects for integrating transport and radio management for THz fronthaul links

With the constant evolution of the technology and the introduction of new generations [5-40], networks become more complex, and therefore harder to control and manage. The shift toward architectures based on SDN and NFV is therefore paramount to endow networks with "intelligence", so to become more autonomous, dynamic, modularizable, resilient and cost-efficient. Centralizing the control plane enables global optimized routing decisions and makes the network flow programmable to fit specific requirements, also helping simplifying operation of multi-vendor and multi-technology networks through appropriate architectures and standard information, data models, and interfaces. SDN can enable then a programmable transport network, which is able to create multiple and isolated transport slices, where transport resources may then be allocated dynamically, interconnecting physical and virtualized network functions distributed geographically.

Therefore, operators are transforming their transport networks moving to SDN-enabled architectures. Multi-operator initiatives are also in place to align vision, architectures and use cases, generating traction and development in the industry [5-80]. SDN implementation in live networks has already started in many networks, and stringent requirements in terms of integration in the full SDN ecosystem and support of standard models and interfaces are being derived for any transport solution under consideration for deployment. Not only because all the technical benefits, but also due to the relevance that the SDN architecture has as an enabler of slicing, key to develop new service and business models linked to differentiation of service performance and quality targets. The proposed architecture, show in Figure 5-7, will automatically manage fixed and radio-based transport connectivity. The transport controller shown in Figure 5-7 includes the SDN controllers for managing fixed switch element and the THz radio element. Both the switch and radio element controllers will provide end to end network resource management.

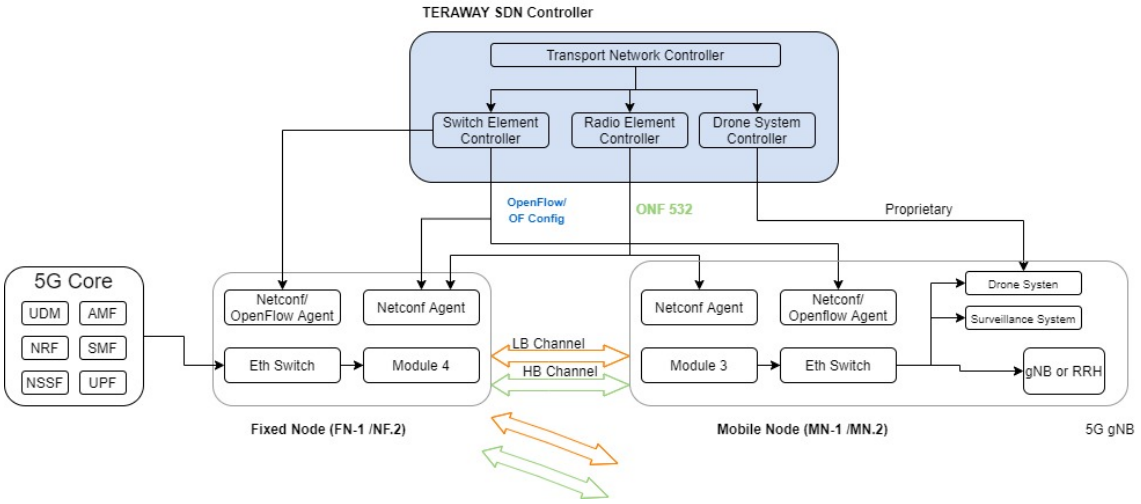

Figure 5-7: Automated network management architecture

The Transport controller in Figure 5-7 will utilize either Netconf or OpenFlow protocol for managing the fixed Ethernet switches. The Transport controller will utilize Netconf with ONF TR 532 data model for managing the radio module 3 and 4 that will establish the THz link, The radio modules will deploy different Low Bandwidth (LB) and High Bandwidth (HB) capacity to deliver high-capacity radio link.

However, the integration of THz links as part of E2E transport requires a set of modules that allow the access to radio resources as shown in Figure 5-8. The THz radio modules described in Figure 5-8 integrate a Netconf agent that will be managed from the Netconf agent in the Transport controller shown in Figure 5-7. In the radio modules the Netconf agent will interact directly with the radio Base Band Unit for changing carrier frequency or modulation to improve capacity and reliability of the radio communication channels. The Netconf agent in both radio modules will also connect radio link quality values (i.e., SNR) to be reported to the transport controller to evaluate the quality of the communication channels and take some corrective actions.

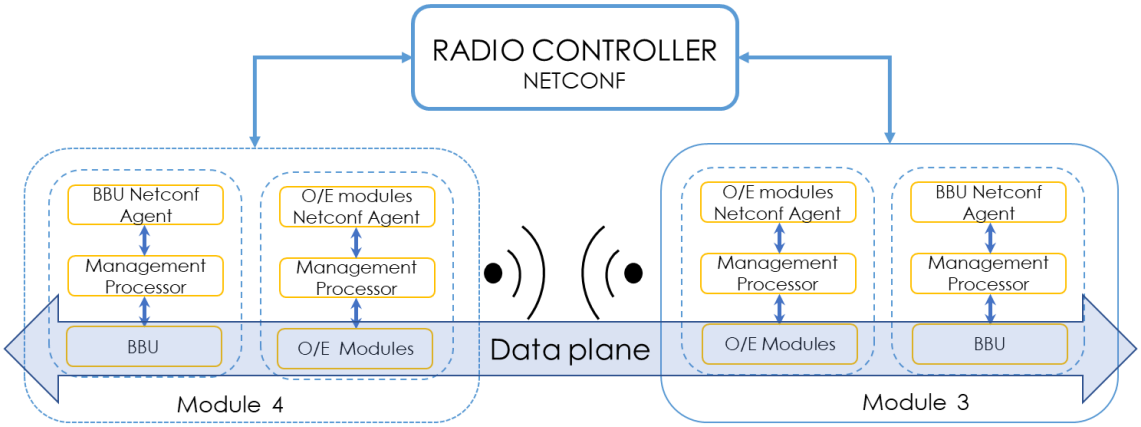

Figure 5-8: Radio module for automated network management

5.3 Service and Network Automation

The so called “zero touch” service and network management is inherently related to increased levels of automation. The involvement of humans in the service and network management processes has been gradually reduced thus moving from the traditional full open-loop paradigm (full human involvement and participation in management decisions) towards fully automated closed-control loops. The latter is greatly supported by the parallel adoption of advancements in AI/ML. Framed within the above, the first part (sect. 5.3.1) of this section presents two solutions for automating SLA assurance namely, an AI-driven closed-loop control architecture for vertical service SLA management (sect. 5.3.1.1) and an ML-based SLA assurance scheme based on flexible orchestration of various slices and virtual / physical functions (sect. 5.3.1.2). The adoption of AIML in enhancing variant use cases of automated service and network management is further elaborated with more details and examples in the second part of this section (sect. 5.3.2). AI-based orchestration through the proper deployment and usage of analytics functions is presented in sect. 5.3.2.1. More details on the AI/ML integration in the context of SLA vertical management is given in sect 5.3.2.2. An AI/ML-based architecture for autonomous profiling and E2E service provisioning and monitoring is presented in sect. 5.3.2.3. Last but not least, sect. 5.3.2.4 provides examples of ML Training and Deployment Pipelines in dynamic environments, where location information and its change play a significant role.

5.3.1 Automated SLA Assurance

Table 5-4: Architectural solutions for Automated SLA Assurance

Architectural solution	5G PPP Project	Additional Reference
AI-driven closed-loop control of vertical service SLA management	5Growth	[5-44], [5-47], [5-48], [5-49]
ML-based SLA assurance through flexible orchestration	5G SOLUTIONS	[5-81]

5.3.1.1 AI-driven closed-loop control of vertical service SLA management

Automation is a key aspect to build full E2E autonomous networks. To this aim, ETSI has defined a Zero-touch and Service management (ZSM) framework that aims to have all operational processes and tasks executed automatically. This can happen through the new architecture design of closed-loop automation and embedding intelligence with data-driven AI/ML algorithms, which are the key enablers for self-managing capabilities, with lower operational costs, accelerated time-to-value, and reduced risk of human error.

Aligned with the design concept of the ETSI ZSM closed-loop automation framework, a closed-loop architecture design for vertical service lifecycle management is proposed ([5-47], [5-48]). This closed-loop includes the process of collecting monitoring data from the services and networks, performing real-time data analytics for identifying events to handle, and taking proper decisions for optimization and re-configuration of the system, such as auto-scaling, self-healing and fault-tolerance, anomaly detection and automated troubleshooting, automated authentication and traffic management.

Figure 5-9 explains the concept of this closed-loop design integrated with the stack proposed in [5-47], which is composed of three core building blocks, namely Vertical Slicer (5Gr-VS), Service Orchestrator (5Gr-SO), and Resource Layer (5Gr-RL). The stack presents the service MANO platform, which interacts with the Vertical-oriented Monitoring System (5Gr-VoMS) and the AI/ML Platform (5Gr-AIMLP). The 5Gr-VoMS integrates application-level monitoring probes and provides enhanced monitoring to support innovative mechanisms related to reliability (via self-healing and auto-scaling), control-loop stability, and analytical features (such as, forecasting and anomaly detection), and also to fully support data streaming as an enabler for the efficient analysis of large data sets, required by AI/ML techniques. The 5Gr-AIMLP provides AI/ML as a service to support the different layers to run AI/ML algorithms for their decision-making processes. It handles online or offline training of selected AI models using either data coming from the 5Gr-VoMS or external data. The decision-making entity (also called as agent) is ultimately the entity that executes the model.

These building blocks interact with each other, creating a closed-loop control of the system. The details of the workflow are introduced in [5-48] and have been demonstrated in [5-49]. The basic logic for usual forecasting and classification problems is described in the following:

- The 5Gr-AIMLP exposes a catalogue of AI/ML models that can be tuned/chained to compose more complex models.
- The 5Gr-AIMLP requests the 5Gr-VoMS for orchestration of monitoring probes and retrieves on demand context information (e.g., current number of users) and performance metrics (e.g., CPU consumption), to train a model or compute its reward.
- The 5Growth platform related layer (e.g., 5Gr-SO) configures all needed data pipeline components to run the optimized model, which is passed down to the agent for online execution by exploiting performance metrics coming from 5Gr-VoMS.

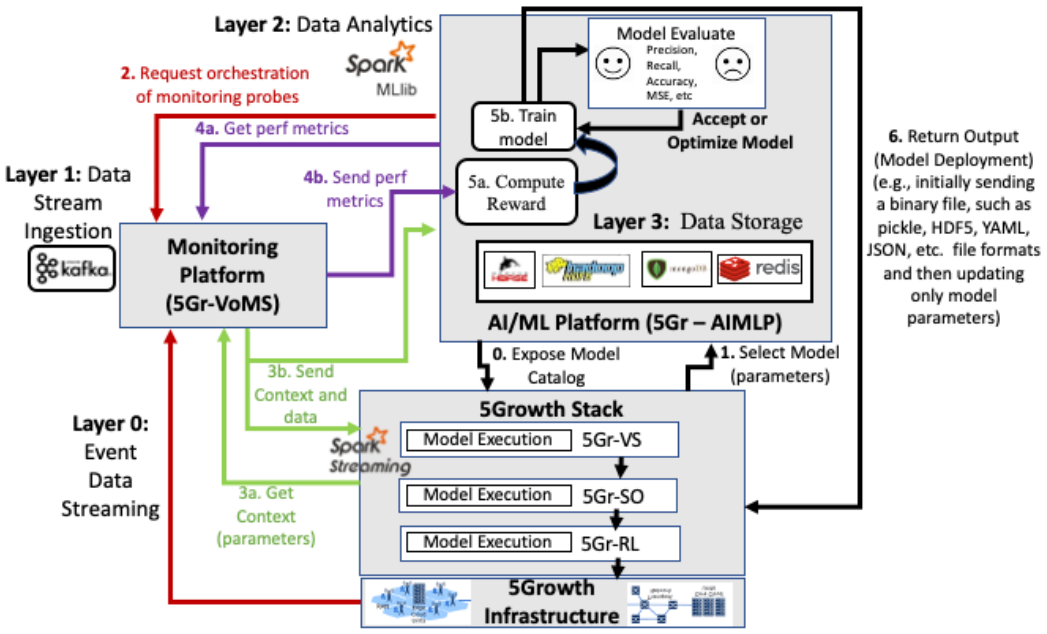

Figure 5-9: Closed-loop Automation [5-47]

5.3.1.2 ML-based SLA assurance through flexible orchestration

The complexity of 5G networks is well understood, with a variety of elements adding to this complexity, including the orchestration of various slices and virtual / physical functions, constantly changing network conditions, etc. Systems have evolved over the years from reactive to more proactive solutions, with a goal of ensuring uninterrupted service at defined SLA requirements. Automatic solutions to support SLA assurance in the 5G network can be supported by ML/AI methods.

One specific example to be investigated is the implementation of closed-loop automation to support a 5G video streaming service in a cross-domain environment using ML performance prediction algorithms [5-81]. ML methods such as cross-domain correlations and KPI prediction form the learning basis of the data analysis. These methods are incorporated into a Zero Touch Automation block, which in turn can send recommendations to the cross-domain orchestrator. This mechanism and its associated architecture are represented in Figure 5-10.

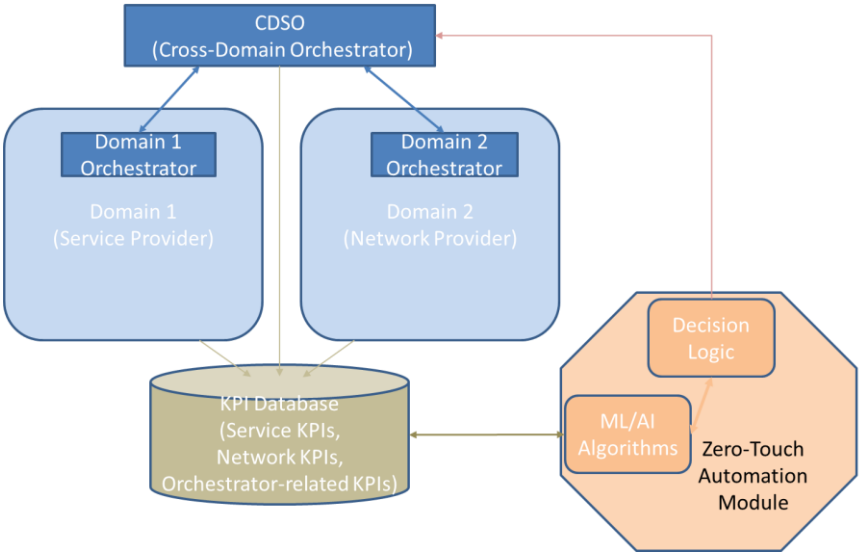

Figure 5-10: High-level architecture with multiple domain orchestration and closed-loop Zero-touch Automation in [5-81]

In this specific example, ML methods such as cross-domain KPI correlations, as well as prediction methods will be used. For example, methods such as Pearson, Kendall, Spearman are used to detect correlations between network and service KPIs. This can give indications on which network KPIs will influence service KPIs related to the SLAs, or can indicate undesired changes between the two domains in the case when the correlation changes over time. Similarly, regression-based prediction enables predicting service KPIs based on network KPIs. In addition to this, time-series prediction methods are employed to proactively decide to change orchestration parameters, in case network KPIs that influence service quality are predicted to go towards values that would mean that the SLA can no longer be guaranteed. This decision is then passed to the cross-domain orchestrator (Nokia's CDSO in this case), which will communicate new parameters to the respective domain orchestrator(s).

5.3.2 AIML Adoption

Table 5-5: Architectural solutions for AIML Adoption

Architectural solution	5G PPP Project	Additional Reference
AI-based Orchestration	5G-TOURS	[5-50] – [5-53]
AIML integration in the context of vertical service SLA management	5Growth	[5-44], [5-45], [5-48], [5-49]
Autonomous profiling and E2E service provisioning and monitoring using AIML	5G-VICTORI	[5-54] – [5-60]
AIML-based M&O exploiting localization	LOCUS	[5-61] – [5-63]

Current work in the standardization of 5G Networks assumed a significant use of AI mechanisms in service and network management and orchestration. The need to introduce AI arose from the fact that, on the one hand, new virtualisation and slicing technologies open up the possibility of efficient delivery of vertical services with a given level of quality on a shared infrastructure, and, on the other hand, lead to high complexity of the entire system, which increases the requirements

for resource management modules, especially the ability to predict changes in the behaviour of the entire system.

In such situations AI, with its feature to learn from the past behaviour of the system and its ability to predict future behaviour, is an ideal tool to support decision-making processes. The use of AI modules, of course, raises several questions, for instance how to integrate these modules with the existing software infrastructure, how to select specific algorithms and evaluate their effectiveness, and how to assess the resources needed for specific functions.

5.3.2.1 AI-based orchestration

Among many other use cases, AI and ML techniques allow for the smart management and orchestration of resources, especially the ones related to the telco cloud.

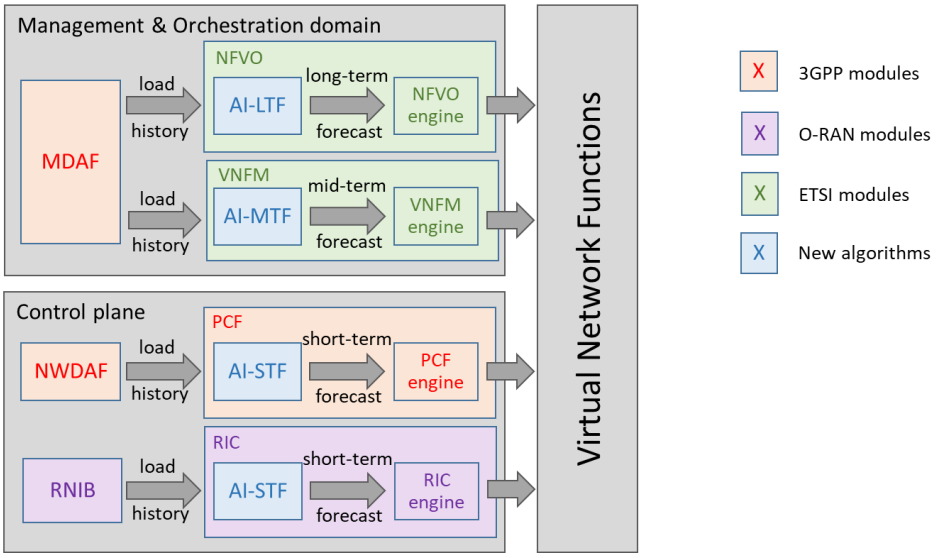

Figure 5-11: Major SDO blocks related with Data Analytics and proposals for enhancements

Figure 5-11 depicts the network data analytics framework as proposed by major architectural SDOs. In the Management and Orchestration domain, the MDAF module is responsible for the so-called Management Data Analytics Service (MDAS) [5-67] for all network slice instances, sub-instances and network functions hosted within the network infrastructure. This involves centralized collection of network data for subsequent publishing to other network management and orchestration modules. In the proposed framework, we specifically employ this service to collect mobile data traffic loads generated in the radio access domain by the individual slices.

As a result, the MDAF allows building historical databases of the network demands for each base station and slice. These may then be exposed [5-50] to the AI-based prediction algorithms for (i) long-term forecasting (AI-LTF), and (ii) mid-term forecasting (AI-MTF).

Management aspects for the c-plane

On the control plane, the Network Data Analytics Function (NWDAF) module is responsible for collecting data on the load level of a NF or a network slice [5-51], playing a very similar role to that of the MDAF in the management domain. These data may be fed to an AI-based short-term forecasting algorithm (AI-STF), which predicts the future traffic load [5-50]. The forecast is leveraged by the Policy Control Function (PCF) module, which provides a unified policy framework to govern the network behaviour. PCF can use the forecast provided by AI-STF to optimize its policies, such as: (i) the QoS parameters (for those services that can be provided at different QoS levels); (ii) the access and mobility policies; or (iii) the UE Route Selection Policy

(URSP). In contrast to the previous modules, these updates are performed at rather fast timescales, down to hundreds of ms.

While the NWDAF module has been designed for the network core, a similar approach can be applied to the RAN. Although 3GPP has not yet proposed modules equivalent to NWDAF in the RAN, other initiatives such as the O-RAN alliance have taken this path. In the ORAN architecture [5-52], the Radio Network Information Base (RNIB) collects load information of flows or flow aggregates at the RAN level, the RAN Intelligent Controller (RIC) enables near real-time control of RAN elements/resources, and the RAN resource orchestrator handles the overall resources at the base station level. In this case, the AI-STF forecasts can be leveraged by the RIC to perform the optimization of the radio resources at a fine time granularity (in the order of hundreds of ms) and by the RAN resource orchestration to update the resource and bandwidth allocation at larger timescales (up to the order of minutes).

AI-based algorithms discussion and design

The above framework introduces three new AI-based algorithms: AI-LTF, AI-MTF and AI-STF [5-50]. These algorithms follow the same design guidelines, aiming at providing network capacity forecasts. The main difference between them is that they work at different granularity in terms of traffic volume (at global, slice, or flow levels) and timescale (intervals of hours, tens of minutes, minutes or shorter). The design of these three algorithms is presented in [5-50].

We evaluated the system with three specific algorithms that populate the AI-LTF, AI-MTF and AI-STF, namely:

- AI-LTF: Long-term forecasting for VNF placement: this algorithm takes care of computing the exact placement of VNFs according to the available capacity at any point in time.
- AI-MTF: mid-term forecasting for NFVI scaling, which was implemented in one of the Proof of Concept (PoC) promoted by ETSI ENI [5-53].
- AI-STF: short term forecasting for QoS policies, which reacts at faster timing to set QoS parameters for network flows.

While the interested reader can find the full evaluation in [5-50], we selected here the results related to AI-LTF. The long-term forecasting capabilities provided by the AI-LTF algorithm are useful to make decisions about the suitable placement of the VNFs serving one or more slices. To evaluate its performance, we consider a scenario where a datacentre with processing capacity C serves the seven slices and assume that the computational demand of a given slice is proportional to the number of transmitted bytes.

In this case study, we use a decision-taking interval equal to 8 hours to account for the fact that VNF placement decisions are typically taken with a coarse time granularity of hours due to the limitation of the underlying NFV technology. We focus on an edge network datacentre and employ AI-LTF to support the VNF placement decisions taken by the NFVO module by anticipating the overall traffic load at the target datacentre. Then, the NFVO can decide at every decision interval how many slices are served by the datacentre of capacity C, and which slices shall instead be placed elsewhere.

Figure 5-12 depicts the results obtained with AI-LTF against those obtained with an Oracle algorithm that assists the NFVO with the knowledge of the real future demand (such an oracle algorithm is unfeasible in practice but provides an optimal benchmark to assess AI-LTF's performance). Figure 5-12 depicts the occupation ratio (top) and number of admitted slices (bottom) for each 8-hour orchestration period. The algorithm implemented by the AI-LTF module is compared against an optimal but unfeasible Oracle solution with perfect knowledge of the future traffic load. We observe that AI-LTF follows quite closely the oracle. The overall usage of

the deployed infrastructure remains high at all times. The algorithm only moves more slices than needed away from the datacentre on very limited occasions. In rare cases, it places more slices than it should in the datacentre, leading to an overload situation that results in computational outages for the served slices; however, even when this happens, the actual overload levels are negligible. These results confirm that AI-LTF is a promising solution to assist effective VNF placement decisions.

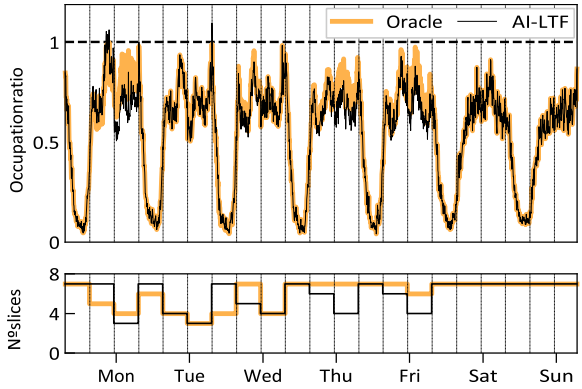

Figure 5-12: VNF placement of slices at one target datacentre

5.3.2.2 AIML integration in the context of vertical service SLA management

The interaction of the AIML Platform (AIMLP) with the rest of the building blocks of the architecture towards SLA compliance has been explained in Section 5.3.1.1 (AI-driven closed-loop control of vertical service SLA management). This section focuses on the internal architecture and functionality of the AIMLP.

The AIMLP realizes the concept of AI/ML as a Service (AIMLaaS), thus addressing the need for AI/ML models for fully automated service management, network orchestration, and resource control within the 5Growth architecture. Specifically, the AIMLP is a centralized and optimized environment for efficient training, storage, and serving of AI/ML models that may be needed for any decision-making process at any layer of the 5Growth stack (e.g., for slice arbitration at the 5Gr-VS, for automated NFV-NS scaling at the 5Gr-SO, or for automated path restoration at the 5Gr-RL). The architecture and the fundamental workflow of the platform are depicted in Figure 5-13, along with the entities with which the main interactions take place.

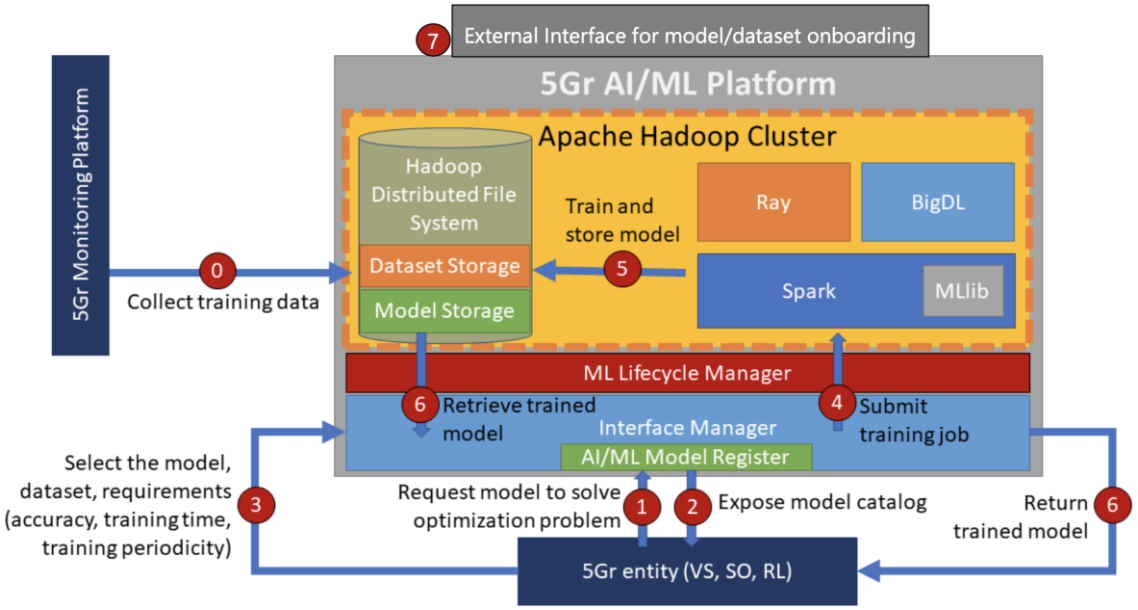

Figure 5-13: Structure and workflow of the AIML platform [5-44]

Such entities are defined in [5-44] Vertical-oriented Monitoring System (5Gr-VoMS) and a generic entity of the 5Growth architecture requiring a trained model (e.g., the 5Gr-Vertical Slicer or 5Gr-Service Orchestrator), hereinafter simply referred to as 5Gr-entity. The 5Gr-VoMS provides raw monitoring data that are used for taking operational decisions once the model is running in the 5Gr-entity and are also collected at the AIMLP to build training datasets, which can be subsequently used for training purposes. The 5Gr-entity also interacts with the AIMLP, in particular with the Interface Manager, to request and receive AI/ML models trained on the latest dataset available.

The 5Gr-AIMLP includes the following main components:

- **Model Registry**, which records the models uploaded to the platform, their metadata, and pointers to the stored models and associated files;
- **Lifecycle Manager**, which is in charge of the models lifecycle. Upon the uploading of a new model, it adds the corresponding entry to the Model Registry and, if it is a yet-to-be-trained model, it triggers the training process using the appropriate AI/ML framework. After a model is trained, the Lifecycle Manager monitors its status: it can trigger a new training job either periodically, or whenever new data are available from the monitoring platform;
- **Interface Manager**, which processes the requests for AIML models coming from the architectural stack and forwards them to the proper block inside the computing cluster;
- **Computing cluster**, which is based on Apache Hadoop[5] and leverages Yet-Another-Resource-Negotiator (YARN) for the computing resources management, and the Hadoop Distributed File System (HDFS) for the storage of datasets and models. The YARN cluster nodes have access to different AI/ML frameworks, according to the requested model type. Spark[6] is used to train classic supervised and unsupervised models, BigDL[7]

[5] https://hadoop.apache.org/

[6] https://spark.apache.org/

[7] https://bigdl-project.github.io/

is used for Deep Neural Networks, and Ray[8] can be used for Reinforcement Learning models.

Finally, we underline that, through the web interface (marked as 7 in Figure 5-13), an authorized external user can also onboard onto the AIML platform off-line trained ML models, as well as ML models and the corresponding datasets, to be trained within the platform itself. For further information, the reader is referred to [5-48] and [5-49].

5.3.2.3 Autonomous profiling and E2E service provisioning and monitoring using AIML

Currently, a considerable effort has been applied towards the adaptation of ZSM to provide complete E2E automation of network as well as NFV orchestration. With the upsurge of ML methods, there has been a push in the telecom industries to adapt these techniques to reduce human intervention and optimise the network and computing resource consumption for the next-generation zero-touch NFV orchestrators. To achieve the ZSM goals, these next generation of intelligent NFV orchestrators need deep knowledge about the performance of Network Services (NSs) and Virtual Network Functions (VNFs) to assign optimised configuration of resources to them in order to meet the performance goals, SLAs, and autonomously orchestrate them across multiple edges. This chapter describes the profiling method defined in [5-54] , called NAP (Novel Autonomous Profiling) [5-54], which will be used to autonomously monitor, profile, and generate performance profiles of the NSs across multiple domains. Besides, the prediction models generated by the NAP method will be used in the profiling component of 5G-VIOS (see Chapter 6 5G-VIOS High-Level Architecture) to instantiate NSs with the optimum amount of resource configurations required to meet the given KPIs and SLAs.

Introduction:

Historically, the act of acquiring deep knowledge about a computer-centric system is known as Profiling. The NFV systems that have profiling capabilities use the monitoring metrics to create mathematical or computational models for the performance of NSs, known as profiles.

The outcome of executing the NFV profiling measurements can be categorised as:

1. Predicting the feasible *metrics* or *performance KPIs* under a given configuration of resources.
2. Predicting *configuration of resources* for achieving the stated performance KPIs specified in the use case SLAs.

The majority of the state-of-the art profiling articles provide methods to predict performance metrics under given resources (First category introduced above) [5-55] - [5-59]. In contrast, less work focus on the second category to predict the appropriate configuration of resources [5-57], [5-59]. In addition, the latter works do not consider all resources simultaneously, for instance, CPU, Memory and Network. However, when deploying an inter-domain NS comprising multiple VNFs hosted at domains, various resources such as CPU, Memory, and Network should be assigned to the involved VNFs to meet the required performance targets and SLAs specified by the UCs. Considering both categories mentioned above at the same time, the leading role of an autonomous profiling system should be to make a connection between the resource configurations, service demands, and performance targets.

[8] https://ray.io/

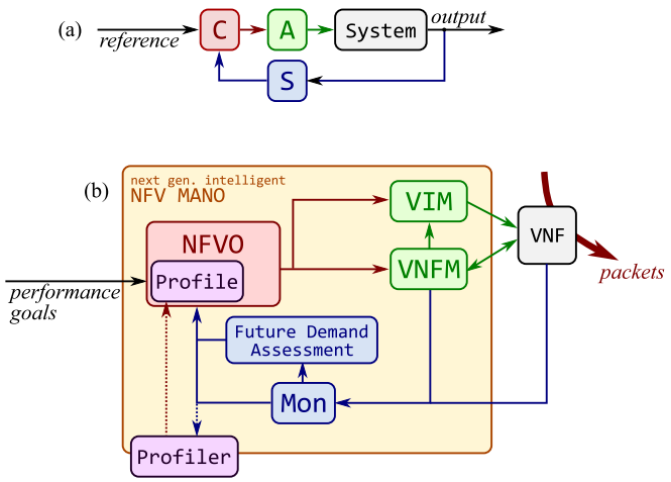

Figure 5-14: Analogy between (a) classical control loop where C indicates a controller, A indicates actuators and S indicates Sensors, and (b) next generation autonomous NFV MANO systems that feed monitoring metrics into the Profile models [5-54]

To fulfil this capability, as indicated in Figure 5-14 (b), the Profiler can get the monitoring metrics from the Monitoring tools, and by considering the given performance goals, it creates models for the performance of VNFs (Profiles). Then by utilising these profiles and ML techniques, the profiler can autonomously compute the optimum configuration of available resources to meet the performance goals and SLAs for that VNF. By having this information and utilising the NAP method [5-54], the autonomous inter-domain orchestrator can deploy the VNFs, ***Proactively,*** with an optimum amount of resource configurations and at the same time meet the KPI and performance goals. Moreover, during the life-cycle management (LCM) of the running VNFs, the profiler can monitor the utilisation of the resources at VIMs and VNFs and, based on the achieved performance metrics, can update the 5G-VIOS ***reactively*** to possibly derive LCM decisions such as scaling or migration.

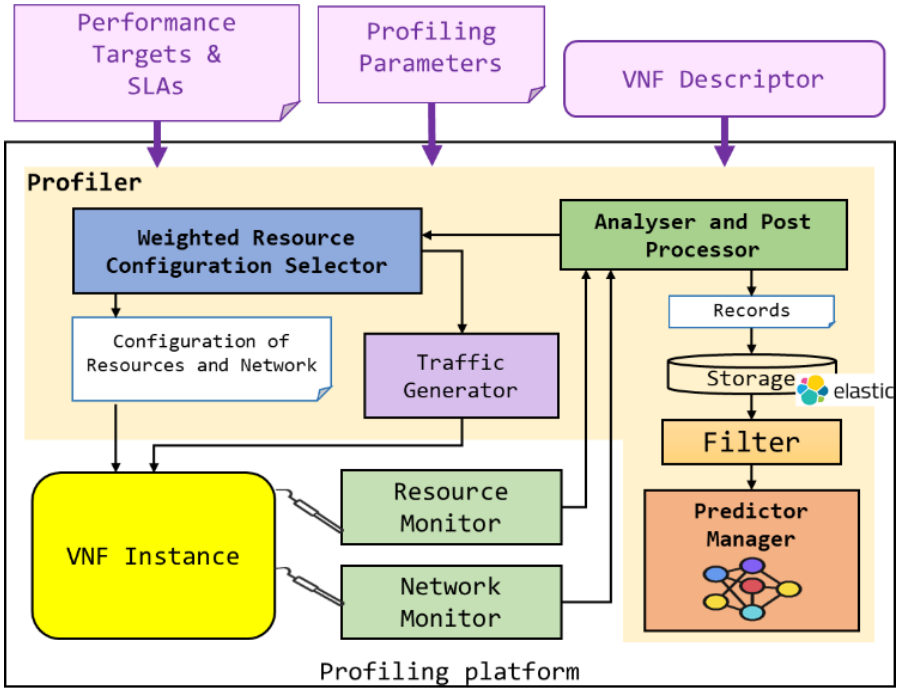

Figure 5-15: High-Level architecture of the autonomous profiling approach [5-54]

As illustrated in Figure 5-15, the **Profiler** comprises components such as the **Weighted Resource Configuration Selector**, the **Analyser and Post Processor**, and **Predictor Manager**. The Profiler receives the given Performance targets and SLAs, the list of performance parameters and the VNF descriptor, which is planned to be profiled. Then, with the help of the **Weighted Resource Configuration Selector**, it selects a configuration of resources, assigns them to the VNF, and asks the MANO to run the VNF and requests the Traffic generator to generate the traffic. Afterwards, the **Analyser and Post processor** receives the monitoring data from the monitoring tools and will analyse the metrics and find the Optimum Maximum Input Rate (Optimum MIR) the VNF can handle to meet all performance targets and SLAs. Then, it will record the analysed performance metrics referred to as the 'Performance Profiles' for this configuration of resources utilising the Elastic Search, Logstash, and Kibana (the Elastic Stack) data repository [5-60]. As the profiling time is limited and it is not feasible to profile a VNF with all possible sets of configurations of resources in a limited time, the profiler (**Weighted Resource Configuration Selector)** will assign weights to the resources and will only test and record a small subset of the possible configuration of resources that impact the Optimum MIR more than the others. As a case study, we tested the correlation between: (a) CPU, (b) Link Capacity, and (c) Memory, and Optimum MIR per two types VNFs; SNORT and vFW. As illustrated in Figure 5-15, CPU and Link Capacity have a higher impact on the load the SNORT can handle. In comparison, the Link Capacity has the most significant impact on the load that vFW can support while meeting the given performance targets. This shows the accuracy of the proposed model and the necessity of computing the weights of various resources to profile an NS. The interested reader can refer to [5-54] for comprehensive details on how the profiler will compute the weights of resources and how it will weighted randomly selects a small subset of the configuration of resources utilising corresponding Algorithms.

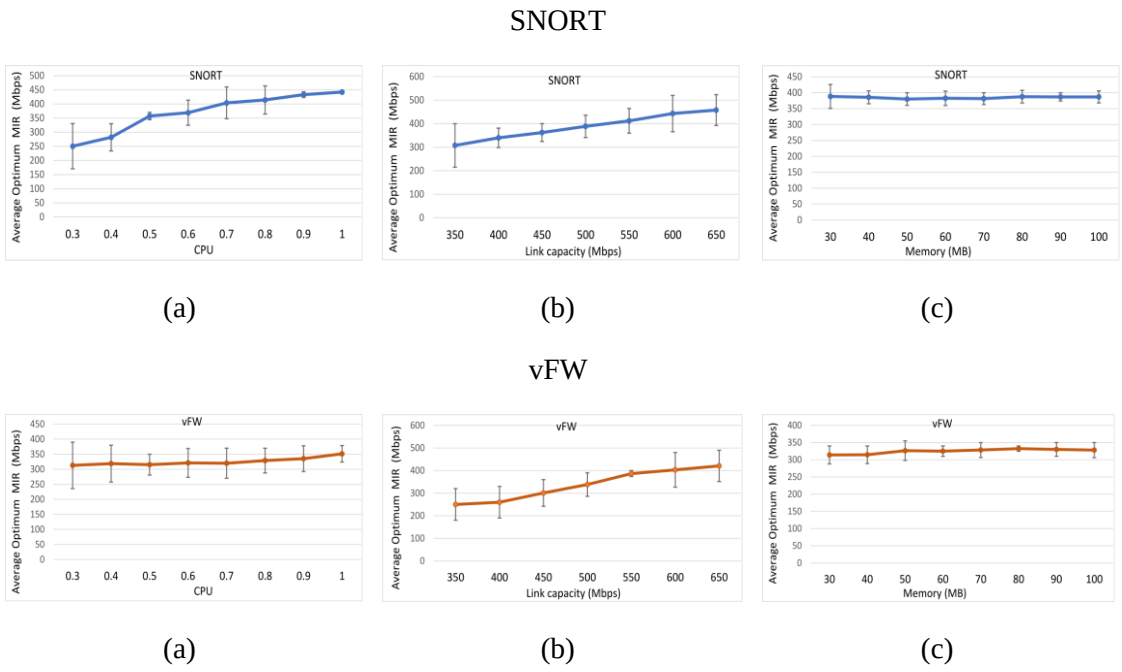

Figure 5-16: The Correlation between (a) CPU, (b) Link Capacity, (c) Memory, and the Optimum MIR per SNORT and vFW, respectively [5-54]

Following Figure 5-16 and utilising our proposed NAP method [5-54], the **Predictor Manager** creates and trains prediction models to predict specific quantities based on past measurements and the *tested* configuration of resources described above. It has the following roles:

1. It creates a model to accurately predict the Optimum MIR for the previously untested configuration of resources while meeting the performance targets.
2. It calculates the absolute amount of resources required to meet both the given performance goals, SLAs, and the Optimum MIR in the target environment.

The Predictor Manager employs the following ML-based techniques to predict the performance profiles mentioned in the corresponding roles. The reader is referred to [5-54] for a full evaluation of the models and on the comprehensive results.

a. Multiple Input-Multiple-Output General Regression Neural Networks (MIMO-GRNN).
b. Random Forest.
c. Multi-Layer Perceptron.

5.3.2.4 Training and Deployment Pipelines in dynamic environments with changing location

This section presents examples of ML training and deployment pipelines which are impacted by and exploit changing localization information. Various location-driven Use Cases (UCs) such as the ones described in [5-61], [5-62] and [5-63], demonstrate the applicability of both offline and online modeling streams that fully exploit localization information as a crucial dataset for serving the purposes of important traffic and user mobility related use cases, which are crucial for the effective planning and operation of networks and services

1. *Training ML/DL models One-off (Offline/batch training) and Inference (Predictions) on the fly*

In this approach a pre-trained ML model (i.e., a model both trained and evaluated offline using a pre-determined dataset) is used.

Example 1: Network demand forecasting (Knowledge building for network management, described in detail in [5-62]). Figure 5-17 below exemplifies the case of offline training and inference on the fly for this use case.

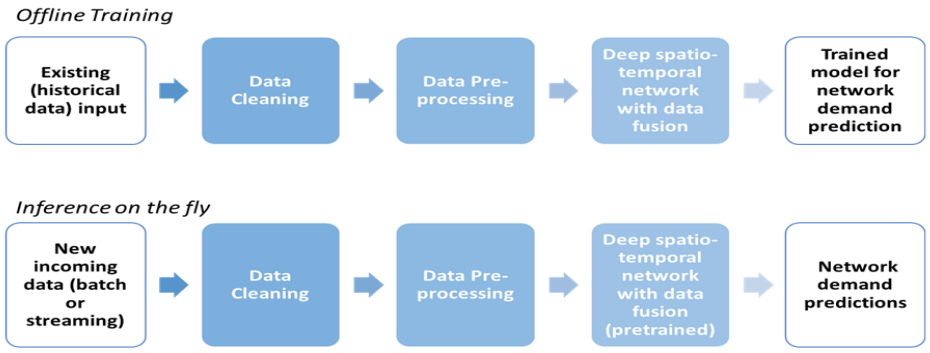

Figure 5-17: Network demand forecasting ML pipeline

Offline Training: Existing datasets after cleaning and pre-processing are used to train a DL model to estimate the network demand in terms of maximum uplink and downlink throughput. The outcome of this pipeline is a trained DL model for network demand prediction.

Inference on the fly: The new data after cleaning and pre-processing is used as test data for predictions (inference) by the pre-trained DL model. The outcomes of this pipeline are the predictions for network demand (max uplink and downlink throughput).

Example 2: Learning group mobility characteristics using wireless fingerprints (Crowd mobility analytics using mobile sensing and auxiliary sensors, as described in [5-61]). Similarly, for example 2, the ML pipelines are presented in Figure 5-18.

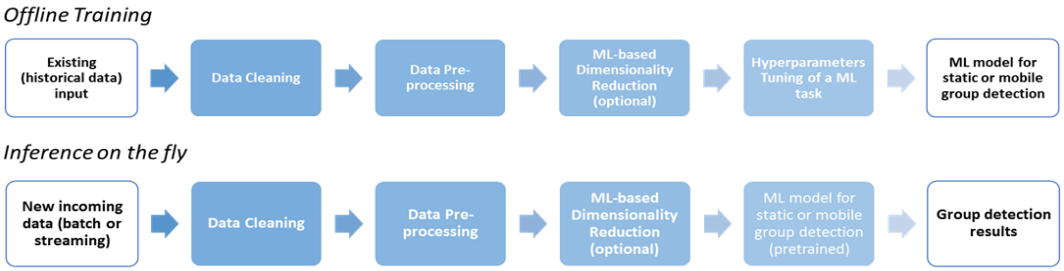

Figure 5-18: ML pipeline for learning group mobility characteristics using wireless fingerprints

Offline Training: Existing datasets after cleaning and pre-processing are used to train ML models to detect groups in the crowd movements. ML-based dimensionality reduction and hyperparameters tuning of a ML task can be included as optional stages before training. The outcome of this pipeline is a pretrained ML model for the group detection in crowds.

Inference on the fly: The inference pipeline uses a similar set of functions like the training pipeline except that the dimensionality reduction process (if applicable) is predetermined and in the final stage the pre-trained ML model is applied instead of training a new ML model.

2. *Real-time/Online Training and Inference*

In the online learning (also called as incremental learning) the ML models are trained in real-time and tested (inference) on the fly with the new data. A related example follows.

Example 3: Pipeline Transportation optimization based on identification of traffic profiles:

In the respective use case [5-61] and [5-62], the analytics request translates into a series of sequential processing jobs (shown in Figure 5-19) that will ultimately produce the ongoing traffic profile updates mechanism. These internal functional blocks are related to data input, data pre-processing in the microservice container environment, invocation of the specific ML jobs for the path identification and persistence of their respective output into a specified geospatial schema [5-63], aggregation of the velocities and statistical profiling of each UE device found in the underlying area. This analytics service is a stateful service that will be performed in a repetitive manner in order to update each identified path traffic profile. Updates found on the total traffic profiles of the areas can then be filtered to propagate the appropriate responses on the service's subscriber via an API gateway [5-63].

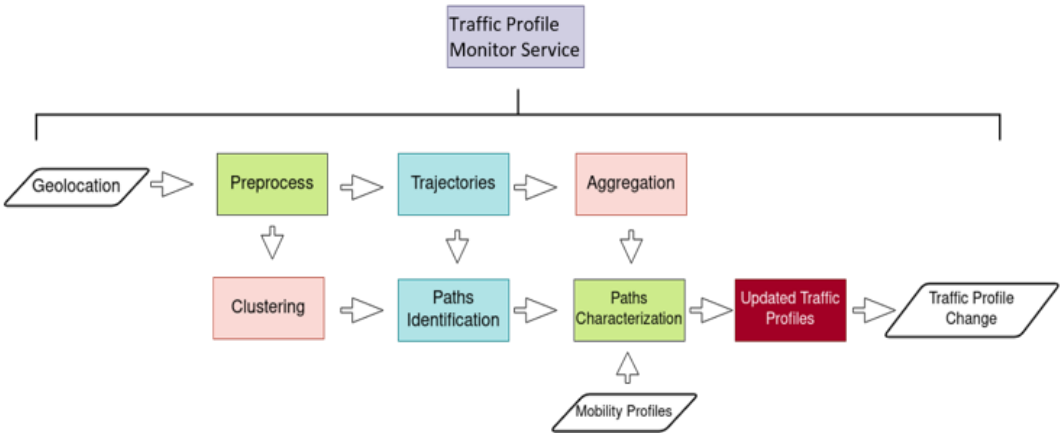

Figure 5-19: Pipeline for Traffic Profile Monitor Service

5.4 Cloudification

The variety of vertical applications and services that current and future networks are expected to serve require flexibility in the way such services are deployed. The move towards SBAs and microservices, and the increasing importance of function deployment at the resource-constrained edge that require lightweight deployments, make cloudification relevant in a 5G context. This section presents a cloudification architectural overview starting with a generic discussion on the integration of cloud native and container-based approaches (Section 5.4.1), following with how they are managed and orchestrated at the edge (Section 5.4.2 and Section 5.4.3), and finally, specific considerations in the use of containers for the deployment of 5G Cores and vertical applications (Section 5.4.4). Table 5-6 presents a mapping of the features explained and projects that deal with them, as well as additional references for the interested reader.

Table 5-6: Cloudification features

Cloudification feature	5G PPP Project	Additional Reference
Standards-based cloudification	5G-VINNI	[5-13] [5-16]
M&O of containers in ETSI MEC	5G-CARMEN	[5-83]
Service Function Virtualization	FUDGE-5G	[5-79]
Automated deployment of containerized 5G Core network	5G-HEART	[5-64] [5-65]

5.4.1 Standards and architecture for 5G Cloudification

It has become apparent that VNF orchestration is being enhanced by the use of Cloud-based Network Functions (CNF) often implemented using Containers [5-16]. Considering an architecture where Kubernetes is used as the orchestration engine for CNFs, there is the potential need for a dual mode NFVI, to enable VNF and CNF orchestration to co-exist. This raises a number of new challenges for MANO, discussed extensively in ETSI GS NFV-EVE 004 [5-73]. The architecture based its integration of CNFs and Kubernetes on principles taken from Standards. There are clear requirements related to Container Management and Orchestration, highlighted in the ETSI NFV specifications, which have been adopted to guarantee an ETSI NFV Compliance:

- ETSI GS NFV-IFA 010: “Management and Orchestration; Functional requirements specification” [5-74]
- ETSI GS NFV-IFA 036: “Specification of requirements for the management and orchestration of container cluster nodes” [5-75]
- ETSI GS NFV-IFA 040: “Requirements for service interfaces and object model for OS container management and orchestration specification” [5-76]

Additional high-level requirements are detailed in [5-16], to be taken into consideration for including CNF capabilities in a Network Slice:

- Requirements on CISM/CIR (Container Infrastructure Service Management/Container Image Registry) exposed service interfaces
- Requirements on M&O of virtualised containers
- CISM exposure of services to NFVO, these services being:
    - OS container workload management
    - OS container compute management
    - OS container storage management
    - OS container network management

- OS container configuration management.

Container-based implementation is now being demonstrated in various 5G PPP projects (e.g., [5-18]).

The above standards enable the orchestration of VNFs and CNFs to the edge resources following the same functional architecture as for centralised VNFs. However, in terms of deployment, the right trade-off between centralization and distribution needs to be analysed. In fact, there are two extremes for Edge Cloud deployment that frame the spectrum of options - these being centralized and distributed. Reference [5-16] considers the impact of the different levels of functionality and orchestration capability that can be deployed in each scenario and varying options in between. Figure 5-20 shows five possible levels of variance between a 'Fully centralised' and 'fully distributed' model.

Where Edge Cloud is centralised, this offers support for eMBB services from a relatively low number of physical sites. As the edge cloud becomes more distributed, the need for more infrastructure and more physical edge locations increases. However, where an application demands low latency or some degree of application processing to be performed very close to the device, a distributed model becomes essential for the effective operation of the application. The operator must balance between the require SLA of the application and the business case impact of supporting greater or fewer physical edge instances.

This in turn has an impact on the relative levels of functional capability that should be supported in each location, as shown in Figure 5-20.

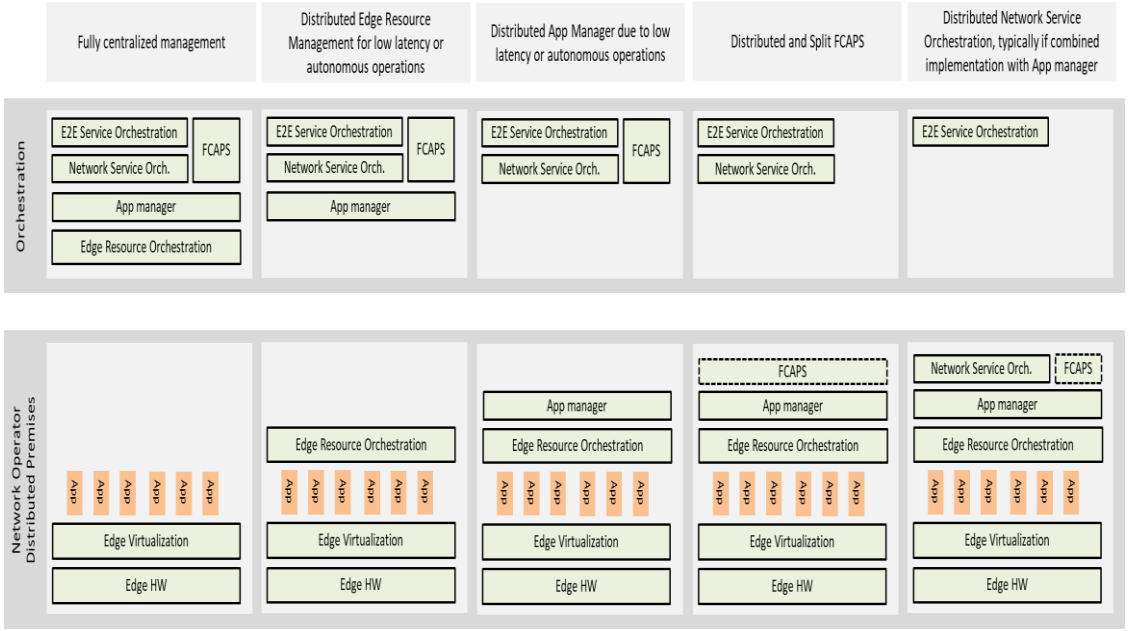

Figure 5-20: Edge cloud deployment options

A number of Edge Cloud models have been deployed ([5-13], [5-18]), also described in the Radio and Edge chapter of this white paper, and different implementation options for Edge Orchestration layers have also been discussed, as per Figure 5-20. Note that within the figure, the App Manager, Edge Resource Orchestration, Edge Virtualization and Edge Hardware could be owned and operated by the Network Operator, a 3rd Party application provider or a Public Cloud Provider, with all options potentially co-existing within a single network or even a single site.

5.4.2 Containers and ETSI MEC

This section presents the management and orchestration architecture for an edge cloud when applied to an ETSI MEC-based edge that executes automotive use cases.

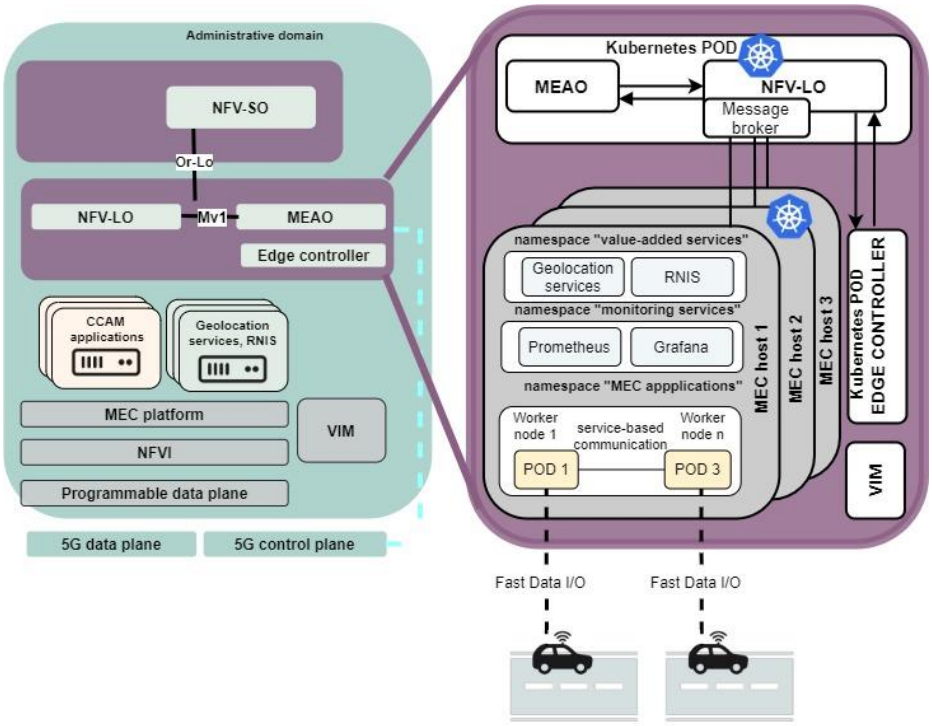

Figure 5-21: Cloud-native design overview of the 5G Edge Orchestration Platform in an ETSI MEC context [5-82]

The design of the 5G edge orchestration platform follows the cloud native principles, which means that all functional elements are implemented as container-based pieces of software rendering a highly modular design. The modularity enables a mix and match of different open source software solutions. For instance, the NFV-SO is based on existing ETSI's Open Source MANO (OSM). On the other hand, interfaces between orchestration components (i.e., Or-Or, Lo-Lo, Or-Lo, Mv1, and NFV-LO - Edge Controller, as presented in Figure 5-21) are implemented following the SBA. These interfaces use REST-based communication. Furthermore, the Kubernetes (k8s) platform was leveraged for the purpose of developing architecture elements. As depicted in Figure 5-21, the MEAO & NFV-LO components of the Edge Orchestration System are implemented as separate containers within a k8s Pod, thereby managing the MEC applications and services via a message broker. Similarly, the MEC applications and services are implemented as container applications in different k8s Pods within each MEC host. The on-boarding procedure practically entails the preparation of Docker images for the MEC applications and services on all required edges. Furthermore, the containerized applications consume MEC Value-added Services (VASs) (e.g., geolocation services, Radio Network Information Service (RNIS), etc.) to enhance their operation. Each Pod with an instance of a CCAM service application can be equipped with one or multiple customized network interfaces, such as for service-based communication and data sharing with other service instances, or for fast data plane I/O and associated low-latency communication with other application instances or service clients. For enabling edge network slices, the MEC applications and services are grouped in different namespaces to ensure isolation for performance reasons. Moreover, a monitoring service comprising Prometheus and Grafana are configured in a separate monitoring namespace for collecting real-time metrics and usage statistics for all MEC hosts belonging to the edge domain and to be consumed by the orchestration

entities. For the management and orchestration of the MEC applications/service an Edge Controller is configured a separate namespace running as k8s Pod.

The NFV Service Orchestrator (SO) can select orchestrated edge resources according to a deployment strategy and enforce the instantiation of an image of the requested CAM service at the selected edge through an NFV Local Orchestrator (NFV-LO). For a large-scale deployment, the NFV-SO can request multiple edge resources to deploy such service.

The NFV-LO and the MEAO treat the service deployment per its description in a Network Slice Template and admit the enforcement of the service through an Edge Controller function. The Edge Controller handles multiple distributed servers in one or multiple edge clouds, which are denoted as worker nodes that provide the local hardware resources for the deployment of service instances. The federation interfaces are sketched at the NFV-SO and the NFV-LO level to accomplish roaming and cross-border scenarios. The additional roles of the Edge Controller include: *i*) slice management, *ii*) connectivity management, *iii*) network programming for traffic steering, as well as *iv*) interfacing with the 5G Core network for receiving client mobility related event notifications, which may require re-configuration of services and traffic steering policies within or between local edge clouds. In case more mobile clients access edge services from a certain location, the orchestration system and the Edge Controller need to provide and re-configure the associated local edge resources accordingly. To provide a mobile access to the topologically closest edge service, and to distribute the load properly between all edge resources utilized for a service, the transfer of a client's session state might be needed, from a service instance on one edge to an instance on another edge. Whereas the Edge Controller is in charge of monitoring and controlling the edge worker node underneath, arrangement, deployment and management of service instances beyond the scope of an Edge Controller is left to the orchestration layers, to which the Edge Controller exposes an Open API.

5.4.3 Service Function Virtualization

The cloudification of the telco landscape is ongoing at a tremendous pace and there have been significant changes done to key blocks of the system architecture. For instance, starting with Release 14 in 3GPP a paradigm shift was induced adopting cloud principles, which resulted in the definition of a SBA for the 5G system. In essence, the majority of 5G Core (5GC) Network Functions (NFs) embed service-based interfaces (SBI) and the communication pattern has been upgraded to the stateless application protocol HTTP/2 SBI-enabled NFs. This enabled the realisation of these 5GC NFs as microservices following the 12-factor app methodology [5-77] allowing the adoption of cloud concepts to meet demand, to increase availability and reliability as well as flexibility. This cloudification of the 5GC poses the question on introducing standardised cloud native methodologies to provision microservices through well-defined APIs. While ETSI MANO released their first take on a reference architecture for microservices [5-76], the standard landscape on descriptor definitions, programmable and open APIs enabling the provisioning and lifecycle management are rather scattered with limited applicability to the need of the telco world, which has a rather strong notion of geographical or topological-driven decisions when it comes to the distribution and instantiation of 5GC NF instances across the network. Based on this observation, the usage of Kubernetes as the de-facto implementation for microservice orchestration may have limited application in some contexts, as it may neither support fine-grained (down to the service instance level) location-aware lifecycle management or a (across locations) federated policy-driven SLA assurance approach. In these cases, there is an attempt to take on this challenge and propose an evolution of NFV, called Service Function Virtualisation (SFV). It follows an information model, which is derived from Service Function Chaining (SFC) in its terminology. This model, illustrated in Figure 5-22, is categorised into orchestration, lifecycle management, routing and packaging.

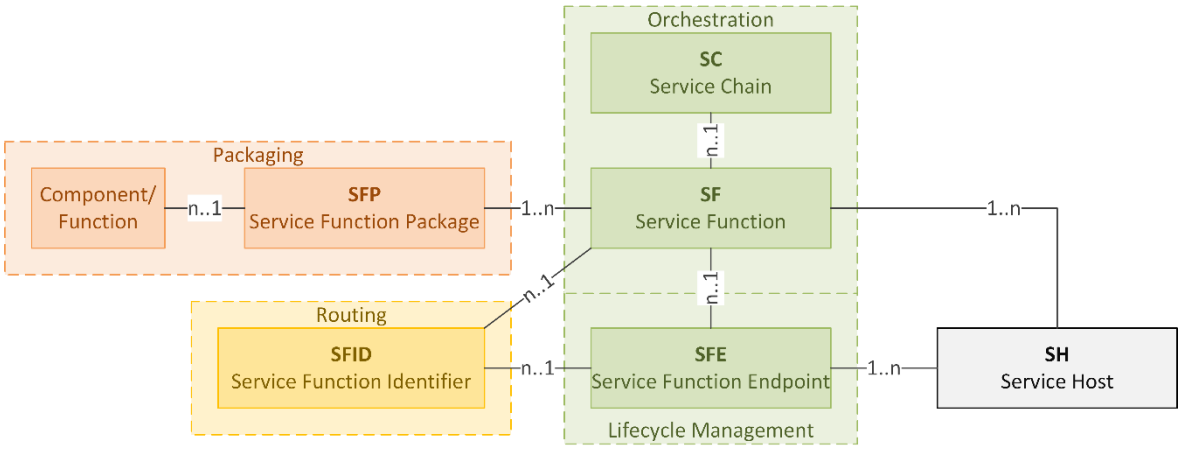

Figure 5-22: SFV information model

5.4.3.1 Orchestration and Lifecycle Management

The service that is being orchestrated is declared as a **Service Chain** (SC), which is essentially an arbitrary but – within the tenant's orchestration slice – unique name, allowing for its identification. Each service chain then has one or more **Service Functions** (SFs) that represent the actual decomposed application the service chain embodies. Each SF is then represented by a unique **Service Function Identifier** (SFID) (e.g., fully qualified domain name (FQDN)) and linked against the routing layer for registration of the identifier (more information in the paragraph below about routing). SFs are then orchestrated as instances of SFs, called **Service Function Endpoints** (SFEs). Note, the SFV information model also allows the assignment of an SFID against a subset of SFEs representing the same SF with the subset in the range of *{1..n-1}* with *n* being all SFEs of the same SF.

SFEs are orchestrated into a specific state across **Service Host** (SH), which represent compute devices capable of hosting the SFE. For instance, an SH can be a larger VNF that maxes out the compute, networking and storage properties provided by the infrastructure provider on a compute node or any other host such as UEs. The lifecycle states offered by SFV are:

- NON_PLACED: The packaged service function is logically accounted on the cluster but does not consume any physical computing resources (vCPU, memory, storage).
- PLACED: The packaged service function is placed on the cluster and is logically accounted against the available resources. Thus, physically it only consumes storage but no vCPUs or memory.
- BOOTED: The service function is placed and started on the cluster but has not been registered against the platform and therefore is not reachable by any service. However, it allows the bootstrapping of all SF internal components.
- CONNECTED: This state registers the service function identifier (FQDN) against the platform and is reachable by any service under the given identifier.

With the information model presented above, an extended set of SF scaling scenarios are enabled through the ability of location-aware orchestration with the inclusion of the Service Host into the information model. SFV supports typical vertical (change properties such as number of vCPUs),

horizontal (increase number of instances) and global scaling scenarios (increase number of locations where the service is offered).

5.4.3.2 Routing

The routing of packets among SFEs is decoupled from the orchestration layer and is independent from which routing technology is being used (IP, NbR, etc). However, it is expected that the routing layer offers features.

At orchestration time, the SFIDs for each SF are communicated to the routing layer through a registration interface. The routing layer then determines at run time which SFE to choose for any occurring request at an ingress point to the data plane.

5.4.3.3 Packaging

Packaging up an SF into a Service Function Package (SFP) essentially results in an image for a particular hypervisor (e.g. KVM or Xen), virtualisation technologies (e.g., LXC, Docker, rkt, Kata or UniKernel) or native system (APK for Android, IPA for Apple, EXE for Windows or deb for Debian-based systems) which can be imported and spawn up. While an SFP can host more than one function/component, cloud-native deployments strongly demand the creation of microservices to allow an orchestration down to function-level, if desired. If more than one function is packaged into an SFP the SFVO can only orchestrate SFs and lifecycle manage SFEs, but not the components inside an SFE.

5.4.4 Automated deployment of a containerized 5G Core Network

The proposed containerized 5G core network is related to industry initiatives such as [5-64] [5-65]. This experimental setup is based on open source software and it is orchestrated using Kubernetes and Helm. The setup is split between 2 separate Kubernetes clusters, one of the clusters (on the left in Figure 5-23), is common to different projects, while the cluster on the right is specific for each project.

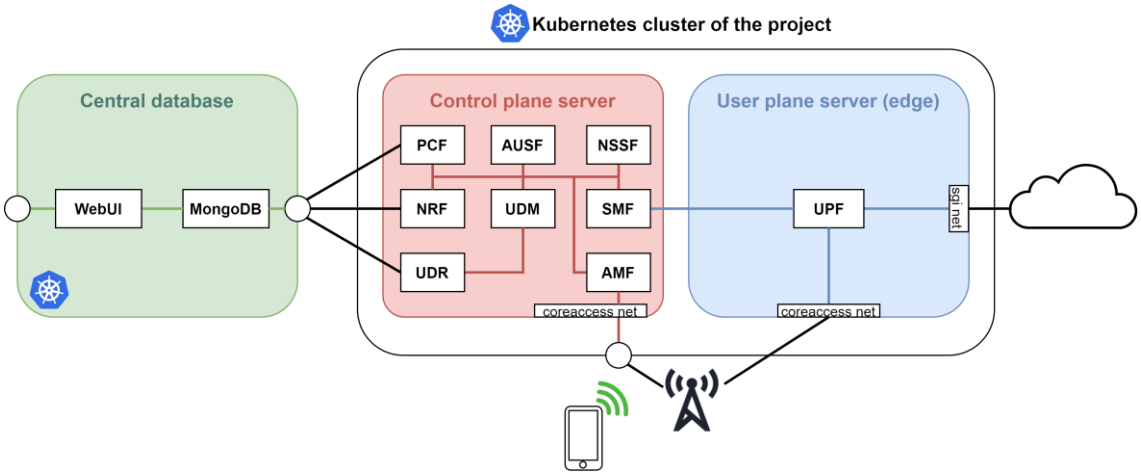

Figure 5-23: Containerized core network approach

The left-hand cluster (i.e., “Central database”) is a single node cluster and contains 2 pods, one of them contains a web user interface (WebUI) and is exposed to the outside using a NodePort service. The other pod is an off-the-shelf MongoDB pod containing 2 replicas exposed externally using another NodePort service. The shared database makes it possible to control all the subscriptions in different projects from a single place. The UDR is not placed together with the central database and it is placed instead in the cluster of the project. The reason for this is that in this core design, the UDR uses SBI to communicate with the UDM, so it is easier to handle it as

part of the internal Kubernetes services. On top of that, other functions like the PCF and the NRF bypass the UDR and access the MongoDB instance directly, so MongoDB needs to be exposed in either case.

The right hand cluster (i.e. "Project cluster") is a 2- (or more) node cluster. In its minimal setup, there is a control plane node responsible for 5G control plane tasks and doubles as the Kubernetes master. The other nodes are responsible for user plane tasks and can be placed next to the control plane node or in edge servers to enable MEC. The internal networks (SBI between control plane functions and N4 between the SMF and the UPF) are handled by simple Kubernetes services. The PCF, NRF and UDR can reach the MongoDB in the central database by accessing the NodePort in the central database. For the remaining interfaces Multus is used to create secondary interfaces. The AMF gets a secondary interface with a fixed IP address in the core access network which is accessible for the gNB, and it is used for NGAP/N2. The UPF gets 2 secondary interfaces, one in the core access network (this doesn't need a fixed IP address) for GTP-U/N3 and another in the SGI network for the N6 interface and functions as the default route for all the traffic coming from the UEs.

The configuration of the Kubernetes cluster, the configuration of the gNB and registering UEs in the database remain as manual processes. Conversely, the configuration of the 5G core network is automated using Helm charts. This allows the user to configure the secondary interfaces, the external database, supported slices and more from a single file, and deploy the whole core with a single command.

5.5 Monitoring and Data Management

Flexible and scalable monitoring systems are fundamental enablers for the automated orchestration of 5G networks, enabling the collection, distribution and storage of metrics and KPIs that feed the management and orchestration logic. This section presents the frameworks proposed by some 5G PPP projects, focusing on specific aspects of monitoring in 5G networks. The software-based monitoring solution presented in Section 5.5.1 addresses the dynamic nature of 5G infrastructures, introducing a flexible monitoring framework that instantiates and re-configures analysers and measurement probes during the network operation. The Vertical-oriented monitoring system described in Section 5.5.2 focuses on the monitoring of network KPIs, application metrics and logs for vertical service instances deployed in the 5G network, as input for their SLA management. Finally, Section 5.5.3 presents a data aggregation framework for the unified collection, distribution, storage, analysis and visualization of monitoring data generated from heterogeneous data sources. Table 5-7 summarizes the monitoring and data management aspects analysed in this section and their mapping with the 5G PPP projects where they have been investigated.

Table 5-7: Monitoring and data management features

Monitoring feature	5G PPP Project	Additional Reference
Integrated software-based monitoring framework for 5G networks	5G-HEART	[5-42], [5-43]
Vertical-oriented monitoring	5Growth	[5-44], [5-45]
Monitoring data aggregation	5Growth	[5-46]

5.5.1 Integrated software-based monitoring framework for 5G networks

A flexibly re-configurable monitoring framework is needed for dynamic software-based network architectures. In order to guarantee visibility into the network during and after architectural changes performed on the fly to adapt the system to the temporally changing requirements, the monitoring framework must be able to adapt as well. For this purpose, a passive monitoring approach based on distributed software probes measuring the traffic in selected locations within the network architecture, and a centralised analysis component processing the collected measurement data and managing the measurement probes, can be used. This approach is well suited for integration to a constantly changing monitoring environment such as a 5G network, where the software-based VNF and service function chains are dynamically activated, re-configured and deactivated during different phases of the network slice life cycle. Based on the monitoring needs of the different types of network slices and services running on top of these slices, a varying amount of software probes can be placed to different virtualised network functions and interfaces to achieve the desired monitoring granularity.

As mentioned above, the monitoring framework comprises of two different types of software components, i.e., measurement probes and analysers. The analyser component is responsible for gathering, analysing and visualising the results, but it is not part of the measurement path and requires only network connection to one of the deployed measurements probes. It is also possible to use the analyser component only for the gathering of the measurement data from the probes and forward it to external databases for further analysis and visualisation. The measurement probes are installed and run in the network functions or nodes that serve as endpoints of the measured network path. The data traffic passes through the probes, which perform passive packet-by-packet measurements and log the results in the form of quantitative network KPI or QoS metrics.

By changing the placement of the analyser components and measurement probes, the monitoring framework can be optimised to capture the performance of a single user or service running in the network or to provide an overview of the performance of the whole network or a network segment. As both the analyser and measurement probe components are fully software-based, the measurement framework can be reconfigured at any time during network operation. Moreover, by preinstalling measurement probes to the deployed network functions, they can be activated, e.g., based on the high-level monitoring results and user for automatic troubleshooting when E2E network performance issues are detected. Some examples of analyser and measurement probe placement for the monitoring of vertical trial services can be found from [5-42] and [5-43].

When separate analyser and measurement probe instances are configured for the downlink and uplink directions of the monitored network path, accurate one-way delays can be included in the set of captured network KPIs. In such configuration, there is an additional requirement for accurate time synchronisation between all analyser and measurement probe components for time stamping purpose. For 5G network latencies, there are basically two commonly available synchronisation methods providing the required accuracy, i.e., precision time protocol (PTP) or global positioning system (GPS) –based time. Within in single network domain, a common PTP server machine providing the reference time to all network functions with low delay and jitter is a possible approach. For a measurement paths spanning over multiple network domains, a GPS-based synchronisation approach is usually the only viable option.

5.5.2 Vertical oriented monitoring

The Vertical-oriented Monitoring System (VoMS), integrated with the management and orchestration stack, enables the monitoring of the performance of vertical services deployed in

5G infrastructures. These performance data can be used as input for different kinds of orchestration decisions that combine network KPIs with service-level metrics. The VoMS is a conglomerate of the software components and logical processes, combined under a single architecture, that serves the purpose to observe and gather logs and metrics from the vertical application's workloads.

The VoMS is responsible for the following functionalities:

- Collecting VNF logs and metrics;
- Holding, tracking and providing metrics and logs to other orchestration components;
- Measuring KPIs.

The VoMS architecture and its interaction with the other orchestration components is shown in Figure 5-24, showing a potential implementation in terms of software building blocks.

The **Monitoring Manager**, integrated in the overall Service Orchestrator, triggers activation and configuration of monitoring jobs during the service lifecycle. In particular, it is the component in charge of translating requests for high-level monitoring jobs referred to NFV service instances into low-level requests related to the monitoring of resource-level parameters, identifying the particular metrics to be collected by the VoMS.

In the example reported in the picture, the alerts generated from the VoMS feed the **SLA Manager**, which handles the procedures for SLA assurance at the service orchestration level (e.g., triggering automated scaling actions to deal with underperforming conditions). However, the data collected by the VoMS can be consumed by a variety of additional orchestration entities, including AI/ML platforms, forecasting platforms, etc. The SLA Manager keeps track of KPIs or real-time measurements mirroring the load of the resources and interacts with the VoMS following a subscription-notification paradigm, to promptly react to any alert associated with the target monitoring data.

The VoMS architecture consists of three functional blocks: the Config Manager, the Metrics block and the Logs block. The **Config Manager** is responsible for coordinating the configuration of the various VoMS components when new monitoring jobs are dynamically activated or modified during the lifecycle of vertical services and related network slices. In particular, the Config Manager triggers the installation and configuration of monitoring probes in the remote Virtual Machines (VMs) running the vertical service applications or the virtual network functions to be monitored. The **Metrics block** and the **Logs block** are responsible for the collection, storage, visualization and processing of metrics and logs respectively, including the generation of alerts.

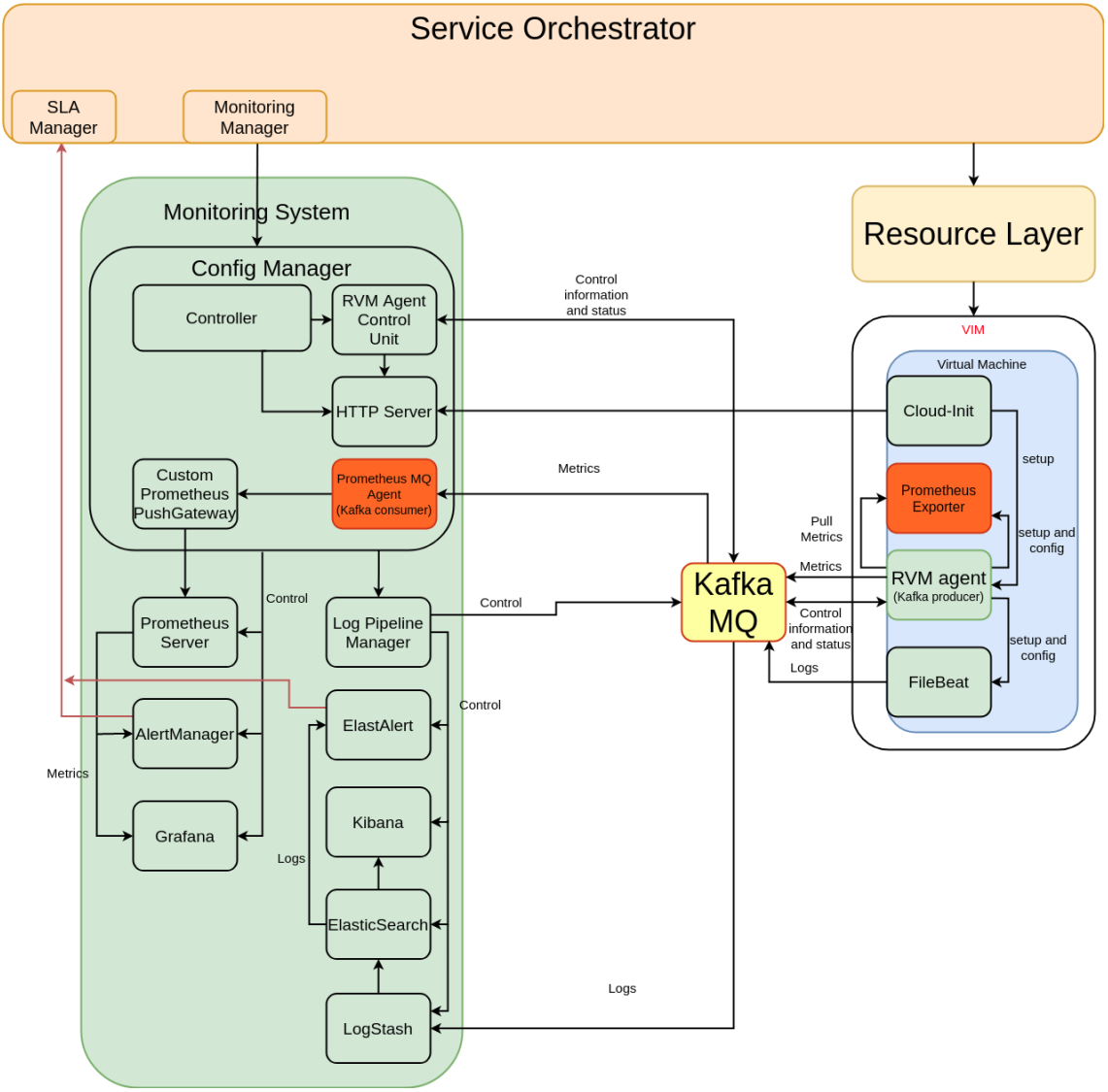

Figure 5-24: Vertical-oriented Monitoring System Architecture

The exchange of control information as well as the distribution of metrics and logs is managed through a message broker, which consists of a Kafka broker (Kafka MQ component) in the VoMS reference implementation represented in the figure. The collection of metrics from the various service VMs is mediated through Remote VM (RVM) agents running at the each remote VM, where they can execute bash and python scripts to change VNF configuration and install extra software. RVM agents are used to install and configure monitoring probes dynamically and they enable pushing VM metrics to the VoMS through the message broker.

In the reference implementation depicted in Figure 5-24, the Metrics block is based on Prometheus and Grafana. It collects the metrics from the Kafka message broker and stores them into a Time Series Database (TSDB), where they can be efficiently queries from external entities. This block implements basic data processing, offering features for data aggregation, alerts generation, deduplication, grouping and routing. The Logs block, based on Elasticsearch, Logstash and Kibana, offers the functionalities to collect and store the logs, implementing search and analytics tasks generating alerts on anomalies, spikes, or other patterns of interest from the log data. In this implementation, the VoMS can provide metrics and logs to other systems by using native Prometheus and Elasticsearch interfaces or through the Kafka topics, which may be also used for other systems as a source of metrics data from the VoMS.

5.5.3 Data Aggregation

While the introduction of closed-loop mechanisms is not such a radical change in network management, the use of data-driven techniques (analytics, AI…) brings new ways of deriving further insights from behavioural data and improving network management and orchestration, and towards increasing network self-awareness. The most delicate aspects to make data-driven network management a reality are not related to the analytics algorithms or AI models being applied, but to matters related to the network itself, especially with monitoring data flows, their structure, availability and trustworthiness, i.e. the application of an appropriate *data engineering* approach to monitoring data.

Figure 5-25 shows a high-level overview of the different modules in a general data engineering platform. It mainly consists of six modules, as described below. Note that the interconnections between each of these modules are shown loosely and there may be several interfaces connecting those modules depending on the use case.

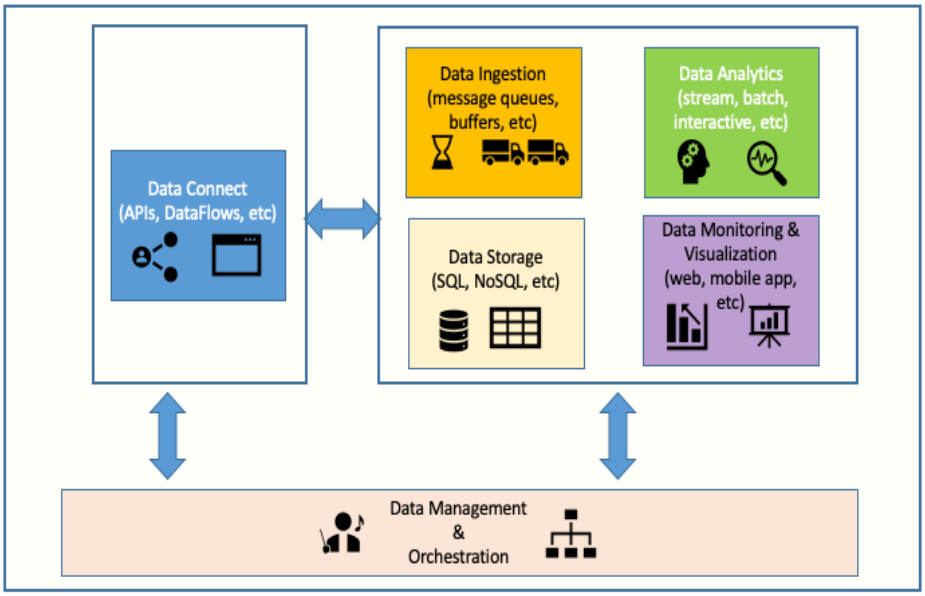

Figure 5-25: Data engineering platform

Data Connector: Exposes the API to receive data from data sources and is used to feed data into common temporary storage.

Data Ingestion: Acts as a distributed publish-subscribe messaging system, enabling ingestion of data into the platform. It manages data (transformation and enrichment), a messaging system (asynchronous and in real-time) and prevents potential pipeline choking.

Data Processing and Analytics: Analyzes data in batch, interactive, streaming, or real time mode. It enables query capabilities over big data elements (e.g., Hadoop cluster), databases and general storage.

Data Storage: Data can be stored in graph databases, in-memory and analytics databases or distributed storage systems.

Data Visualization and Monitoring: Data are visualized in 1D, 2D and 3D for temporal and spatial analysis, monitoring pipelines, dashboards, alerts and notifications.

Data Management, Orchestration and Scheduling: Some of the features that are handled by this module are ensuring resource management, defining and scheduling workflows, tasks and services across the platform, and orchestrating virtualized resources lifecycle.

The above generic pipeline, when applied to a particular OAM framework, will process some specific data sources of interest. Furthermore, data consumers of the monitored information may be diverse as well, consisting, for instance, of orchestration stack entities or network management applications monitoring network operation.

Network infrastructures constitute a paradigmatic example of complex entities that encompass a potential high number of monitoring data sources along with their properties. In this respect, data aggregation mechanisms can provide consistent and manageable information for further processing. Thus, these mechanisms become a crucial component, in particular, in scenarios wherein a full E2E control is intended for the services running on top of the network infrastructure.

Data sources may present different means to access data. For instance, some data sources rely on push methods, hence data is passively received from them, whereas others are based on polling mechanisms at a particular pace. Similarly, data sources may provide data in different formats, ranging from raw to strictly structured formats based on standard models. Data is transported according to a great variety of mechanisms, entailing different access control, confidentiality, and integrity methods. Moreover, timing constraints shall be considered on both the data collection and their subsequent processing.

Given such heterogeneity, designing suitable solutions openly applicable and reusable in different scenarios becomes a challenging task. Adapting data in an efficient way, while keeping the metadata that characterizes it, requires a semantic data framework that infrastructure providers and vertical service consumers can leverage. This framework would allow a flexible usage of produced data, hence enabling organizations to run different types of analytics from visualizations to big data processing, real-time analysis, and machine learning solutions.

Regarding the definition of metadata, the ETSI ISG CIM (Context Information Management) standard is introduced. CIM considers the exchange of data and metadata across systems to be a crucial enabler for smart applications, allowing them to better collect information from different origins, combine and filter the information, and eventually, create derivative information or make decisions. For this purpose, CIM defines the NGSI-LD protocol, a new data exchange protocol to address data provenance, data quality and access control [5-66].

Figure 5-26 depicts a CIM-based architecture comprised of Context Sources and Context Consumers that exchange information through the Context Broker by leveraging the NGSI-LD API. The CIM standard introduces the NGSI-LD information model as the means for describing the structure of context information. The NGSI-LD information model leverages property graphs and linked data by extending the JSON-LD format. Context information is any relevant information about entities, their properties, and their relationships with other entities. Entities may be representations of real-world objects such as physical servers or may also describe abstract concepts such as a network function. Therefore, NGSI-LD information models provide a theoretical basis about the characteristics of the systems they represent.

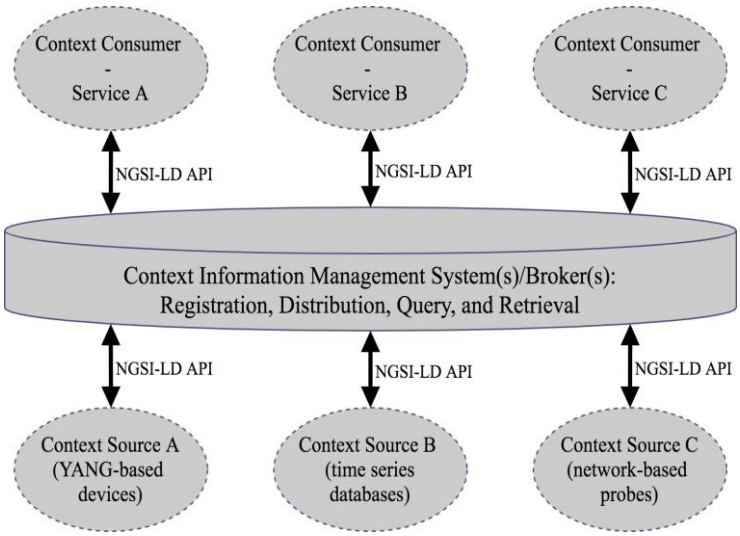

Figure 5-26: CIM-based architecture

The IoT domain has been the main focus for the application of the CIM framework so far. But given its support for binding context sources and consumers, the CIM framework can incorporate new information models that address the network monitoring domain. Specifically, relying primarily on YANG models due to the current trend towards network telemetry, albeit other modelling mechanisms are being considered as well. Namely, SNMP MIBs, as the historical network monitoring standard; time series databases such as Prometheus, which facilitate the collection and query of metrics; and standard JSON encoding, due to the widespread usage of REST APIs.

5.6 Evolution of MANO Design Principles

Current network management solutions, even those envisioned for early 5G rollouts, are still burdened with the problems of past generations (e.g., vendor lock-in, long development cycles, telco stack often delivered into large operational structures which are functionally siloed). These problems prohibit from a flexible and fast evolutions of services and networks for the operators, taking into account the operational complexity that late 5G and B5G technology will bring in their networks. This complexity resides in the need to manage and orchestrate a wide variety of services across all network segments, with an E2E perspective. The specificities of these segments, with different pace of technology evolution each and with solutions from different vendors, unveils significant integration issues for operators. This is exacerbated as the number of hosted services increases, some of them with very different KPIs. The above reasoning requires operators to transform their current OSS, adopting novel management approaches that allow addressing these integration and scalability challenges. This section presents a number of new trends on the evolution of the MANO design, including distributed management autonomy, service based management architecture and SF virtualization.

Table 5-8: Evolved MANO Design features

New MANO feature	5G PPP Project	Additional Reference
Distributed Management Autonomy	5G-CARMEN	[5-83]
Service Based Management Architecture	5G-CLARITY	[5-67], [5-68], [5-69], [5-72]
Service Function Virtualization	FUDGE-5G	[5-79]

5.6.1 Distributed Management Autonomy

One of the system features of the 5G edge orchestration platform as described in Section 5.2.2 is the support of distributed management and orchestration capabilities by enabling two hierarchical orchestration domains, the higher orchestration layer managed by the NFV Service Orchestrator (NFV-SO) and the Edge Orchestration System controlled by the NFV Local Orchestrator (NFV-LO). However, one of the issues in such an environment is the decision on the distribution of the various MANO operations between NFV-SO and NFV-LO. The delegation of management autonomy becomes more challenging and necessary, when the NFV-SO and NFV-LO may belong to different administrative domains, and in cases of the NFV-LO belonging to different tenants. For cross-domain operations, the scope of management autonomy is also negotiated between the NFV-SOs, and by extension between the NFV-LOs, of respective domains.

In this context, the novel concept of Management Level Agreement (MLA), introduced in [5-78], is being utilised. The MLA is negotiated between the NFV-SO and NFV-LO that determines the operational and functional bounds of NFV-LO with respect to executing LCM actions on active network edge slices and associated resources. In other words, the MLA determines the functional/operational autonomy of the NFV-LO in terms of executing LCM actions on the relevant virtual service instances and related resources, which has been delegated by NFV-SO(s). It is possible for an NFV-SO to negotiate different MLAs with different NFV-LO instances that fall under its administrative control. It should be noted that as a higher-level orchestrator, the NFV-SO has full management and administrative control of the services and resources within its administrative domain, and the NFV-SO delegates full or partial set of its features, capabilities and services to NFV-LO via the MLA. This gives the NFV-LO the autonomy to exercise management and orchestration functions over respective service instances and associated resource with minimum reliance on NFV-SO. However, the NFV-SO will execute those LCM actions that have not been delegated towards NFV-LO. Having full administrative rights over the NFV-LO instance(s), the NFV-SO monitors the NFV-LO(s) for MLA compliance and provides services, features and capabilities to them that are outside the negotiated MLA bounds. Under specific situations, it may also override the NFV-LO(s) certain decision on actions. Some examples of the permissions negotiated during MLA negotiations are:

- Permission to perform scaling operation. A separate permission may be sought for each type of a scale operation such as scale-up, scale-down, scale-out, scale-in. In this regard, the appropriate scaling policy is also exchanged.
- Permission to perform migrate operation on specified VNF(C) instances. In this regard, the appropriate migration policy is also exchanged.
- Permission to perform update operation on specified VNF(C) instances. In this regard the relevant software packages are provided.
- Permission to perform auto-healing operation. In this regard, the appropriate healing policy is also exchanged.

In this sense, the MLA parameters between the NFV-SO and NFV-LO are being negotiated over the ETSI MEC defined Mv1' reference point, and relevant interface(s) are required to enable the negotiation and establishment of MLA rules. In a multi domain scenario, the NFV-SO of federating domains will negotiate MLA over the Or-Or reference point and by extension, over the Lo-Lo reference point between the peering NFV-LOs in different domains. An exemplary list of parameters that are exchanged as part of the MLA negotiation is given in [5-78], while the 5G CARMEN deliverable D4.2 [5-83] specifies the data structure and the messaging protocol of MLA negotiation over the relevant reference points.

The MLA is a data structure listing a set of administrative rules applying to a reference Network Service (NS), in the context of a reference NFV Local Orchestrator (NFV-LO) controlled by a

reference NFV Service Orchestrator (NFV-SO), as depicted in Figure 5-4. The rules are related to the permission given over operations performed on NS components or NS-related components outside the local domain. The first set of permissions managed by MLA and negotiated over the *Mv1'* reference point in between NFV-SO and an instance of a NFV-LO is related to the local delegation of LCM tasks by the NFV-SO to be performed by the NFV-LOs on the NS components. The second set of permissions instead addresses the permissions of usage of interfaces defined over the Lo-Lo reference point between the peering NFV-LOs. A JSON schema of the MLA descriptor can be found in [5-83].

5.6.2 Service Based Management Architecture

The Service Based Management Architecture (SBMA) is an emerging novel architecture style that allows migrating from functional blocks exposing telecom-style protocol interfaces (e.g., Network Managers / Element Managers providing 3GPP Itf-N interfaces [5-84]) to management services exposing APIs based on web-based technology. This change of paradigm facilitates a rapid evolution of management and orchestration capabilities in compliance with the innovation of the underlying network, by simply adding or updating APIs using libraries and other enablers (e.g., development tools, specification tools, code generators, security mechanisms) which are broadly available. This approach allows service innovation with minimal integration effort. Different SDOs have already captured the benefits of having a SBMA in their specifications. For example, 3GPP SA5 [5-67] and ETSI ISG ZSM [5-68] define their architectural frameworks based on SBMA. Even ETSI ISG NFV, which originally chose an interface-centric approach for the design of the NFV MANO framework, has decided to migrate towards a SBMA from NFV Release 4 on [5-69].

The SBMA concept is defined around the management service construction. A management service is a standalone service that offers a set of management capabilities for innovation and communication purposes within a well-defined environment. The scope of this environment typically covers a *single management aspect* (e.g., provisioning, performance assurance, fault supervision) on *a single network entity* (e.g., slice, network service, etc.). Every management service is provided by a *management service producer* and can be consumed by one or multiple *management service customers.* The capabilities of a given management service are accessed by management service via a standard service interface, which conveys the following two artifacts:

- **A group of management operations** (e.g., create, read, update, delete, subscribe/unsubscribe) **and/or notifications**, providing primitives to view and manipulate objects according to the management aspects the management service is designed for. These primitives are network-agnostic, in the sense they do not include information about the semantics of the management objects. The implementation of these primitives is typically based on RESTful HTTP-based APIs, although other protocols (e.g., RESTCONF) can also be used
- **An information model**, specifying which network entity is managed using the management service. This information model describes the semantics of the class representing that network entity. This semantics (relationships, constraints) allows associating objects with instances of that network entity. Information model definitions, typically specified using protocol-agnostic language like UML, are mapped into data model definition used for implementation. Yet Another Markup Language (YAML) or YANG are examples of data modelling languages that can be used to that end.

To make analogy to SBA, where the concepts of "NF" and "NF" are used (NF means network function), the SBMA also makes use of "MF" and "MF service" (MF means Management Function). A "MF service" represents a management service that is exposed by a MF (playing the

role of management service producer) to authorized MFs (playing the role of management service consumer) though a service-based interface. An MF can expose one or more services to other MFs. Similarly, a MF can consume one or more services from other MFs. Figure 5-27 illustrates this scenario, providing a simplified view of the internal composition of a MF. As it can be seen, a MF is composed of one or MF services (see Figure 5-27 a), each offering a group of model-driven primitives (i.e., management operations and/or notifications pinned to a specific data model) through a service based interface (see Figure 5-27 b).

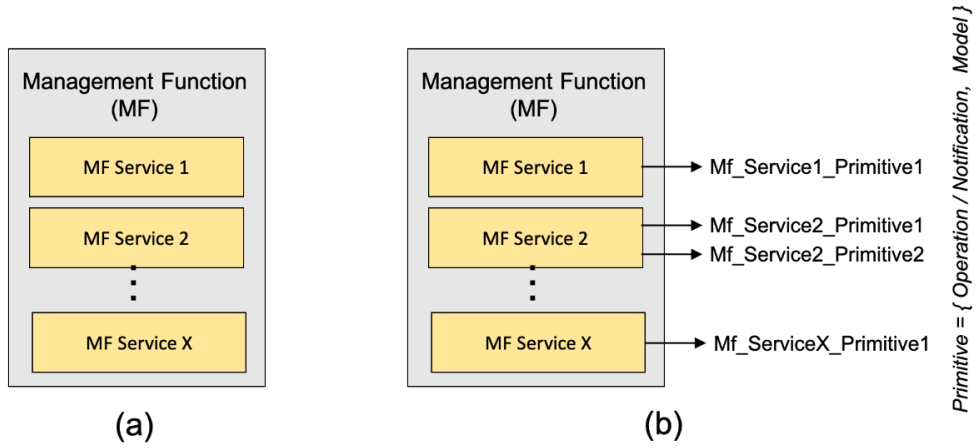

Figure 5-27: MF and MF service concepts

The introduction of SBMA brings two additional characteristics compared to interface-based management system, as captured in Figure 5-28. On the one hand, **dynamic service registration and discovery**, relying on a registry where services available in a MF are registered and can be discovered by other services in the same or different MFs. On the other hand, **the use of a persistent data storage service**, which enables having a common data layer for the entire OSS, thereby allowing for stateless MFs.

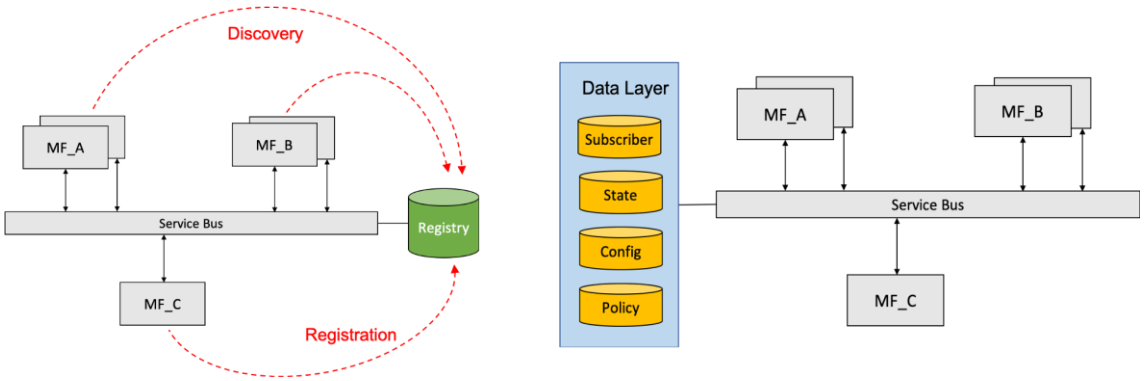

Figure 5-28: Features in a SBMA: dynamic service registration and discovery (left) and persistent data storage (right)

Based on the above rationale, Figure 5-29 illustrates an archetypal SBMA. As it can be seen, it is formed of a set of management services which are federated together based on the definition of three novel entities:

- **One or more MFs**: A MF is a management entity playing the roles of management service producer and/or management service consumer. A SBMA consists of different MFs, each typically producing/consuming management services that are used to manipulate instances of the same network entity. NFV Orchestrator (NFVO) and Network Slice Management Function (NSMF) are examples of different MFs. The former

is focused on the deployment and operation of instances of NFV services, while the latter deals with instances of slices.

- **One repository**, which is a data-store that provides a single integrated catalogue and inventory for the entire SBMA.
- The **service bus**, which allows interoperation and communication between the MFs taking part in the SBMA, including their interaction with the repository. The functionalities of this software bus (e.g., service registration and discovery, application-layer message routing, fast failover management, message transformation capabilities) are equivalent to the one described for the SBA. Indeed, the application/transport layer protocols (HTTP2/TCP) and serialization protocol (JSON) remain the same. Though standards does not mandate specific technology solutions for service bus, message broker has become a de-facto solution, with implementations based on RabbitMQ [5-70], ZeroMQ [5-71] or NATS [5-72].

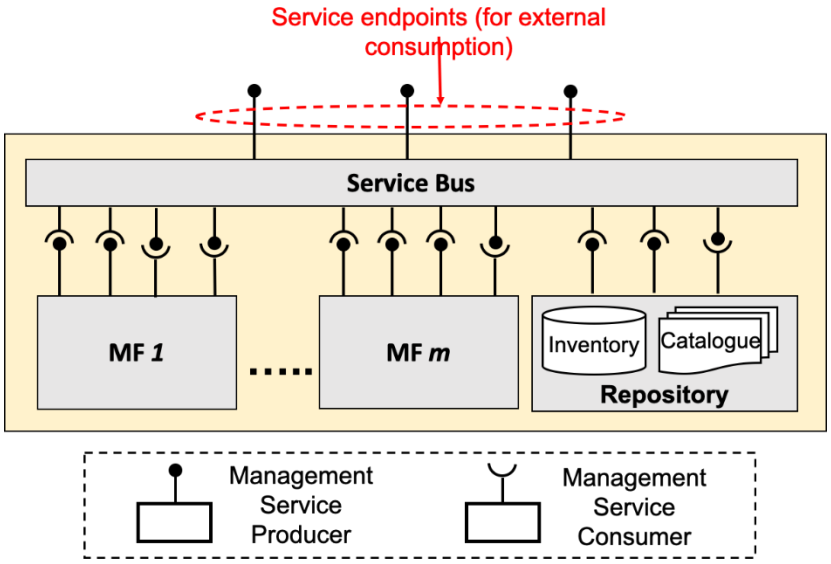

Figure 5-29: Blueprint of a baseline SBMA

Operators may build their OSS based on this SBMA blueprint. To provide management consistency in their managed networks (5G infrastructure resources and functions from multiple vendors, spanning across different network segments and integrating a wide variety of technologies), operators can define different management domains out of this SBMA, following the principle of separation of concerns. The scope of every concerns, and thus of every management domain, is up to the operator's criterion, as ETSI ZSM states in [5-68]. This gives the operator the freedom to define the number and types of management domains building up the SBMA. For example, the operator could decide to have one management domain for every network segment, for every vendor, or for every technology.

In the case the operators choose the first option, the SBMA would consist of five management domains:

- AN management domain (c.f. 3GPP SA5 and O-RAN)
- CN management domain (c.f. 3GPP SA5)
- TN management domain (c.f. IETF)
- NFV management domain (c.f. ETSI ISG NFV)
- E2E service management domain (3GPP SA5 and TMForum OpenAPIs)

Each is architected as captured in Figure 5-29 and all connected by means of a cross-domain integration fabric (c.f. ETSI ISG ZSM).

5.6.3 Service Function Virtualization

Another evolution of the MANO feature focuses on the integration and trialling of an SBA platform which is fully softwarised and allows the provisioning/orchestration of its service routing, lifecycle management and control service monitoring and service slicing as VNFs into an NFV and SDN-enabled infrastructure. Thus, towards the infrastructure it is assumed that the existence of a programmable APIs allows the provisioning in a rather automated and unified fashion. The evolved SBA platform [5-79] positions itself as an enabler for cloud native enterprise services offering service routing, lifecycle management and control, and service monitoring as part of the platform over which the enterprise services are being provisioned. The architecture principles are described as an evolution of NFV entitled **Service Function Virtualisation (SFV)**. In comparison to other CNF-focused frameworks, e.g., Kubernetes, SFV has a different information model and descriptors for describing the enterprise service targeting the provisioning over a telco system with multiple locations and an underlying transport network implementation service routing across the entire transport network. Figure 5-30 illustrates the components of SFV enabling the provisioning and lifecycle control of instances within a service chain.

The paradigm shift on the transitioning from VNFs to CNFs for enterprise services (e.g., 5GC and vertical applications), does not only allow the adoption of well-proven web technologies for the realisation of an application (aka microservice software architecture), but it also enables a unified cloud native orchestration of a service. The proposed system architecture comprises an orchestration layer focusing on the orchestration and lifecycle management of 5GC NFs and vertical applications. Figure 5-30 zooms into the orchestration layer and illustrates the individual components and their interfaces using UML syntax highlighting endpoints (client) and service endpoints (server). As can be seen, the Vertical Application Orchestrator (VAO) is logically located above SFV. This is mainly due to the objective to unify advances of the FUDGE-5G system where the orchestration layer itself is agnostic to the microservice that is being orchestrated and lifecycle managed, i.e., 5GC vs vertical application. Both services are a composition of service functions that form a service chain following advances of Service Function Chaining (SFC). As SFC is concerned about the routing and its configuration among service functions of a service chain inside the routing fabric, [5-79] describes the required evolution of NFV for microservices as SFV. It is worth noting that SFV follows the ETSI MANO reference model and can be seen as a counterpart to the recently published ETSI IFA 040 specification [ETS20] aiming for a reference model for CNFs.

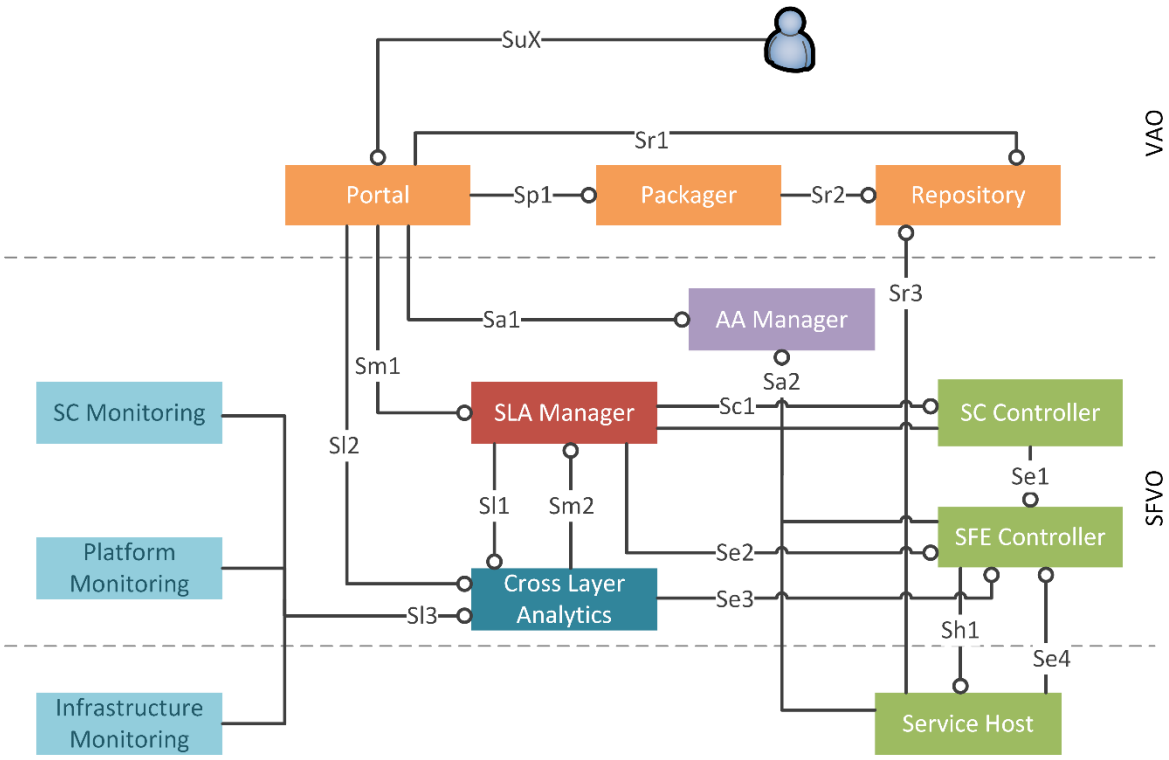

Figure 5-30: Component architecture of the eSBA orchestration layer [5-79]

Figure 5-30 provides the names of all service-based interfaces a component offers following the same naming convention, i.e., *S* for Service followed by a *lower-case letter* identifying the component that provides the interface and an *integer number* unique to the component

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6 Cross-Domain Aspects

6.1 Introduction

One of the ambitions of 5G is to perform end-to-end management of network services and resources across different infrastructures of an administrative domain, e.g., core, metro, access as well as across different administrative domains. A 5G platform should essentially be able to address any domain boundaries and ensure that it can provide the required end-to-end Quality of Service (QoS) for all services across administrative domains or network technology segments. Additional challenges that need to be addressed by 5G solutions in multi-domain environments include seamless service delivery to mobile users with particular emphasis in high-speed mobility environments where agile mobility patterns are relevant.

Standardization bodies such as IETF and ETSI have created standards and guidelines while open source communities have been formed, including Open Source MANO (OSM), Open Baton, SONATA and ONAP, with the aim to address relevant issues. However, 5G platforms expected to support multi-domain services are limited to date to best effort connectivity that do not satisfy service specific requirements in an end-to-end fashion. A number of 5G PPP activities that are aiming to address the associated challenges taking relevant architecture and design considerations are presented in this chapter.

6.1.1 Multi-domain Orchestration Architecture

Functionally an important tool to address some of the challenges described above is to enable collaboration and coordination among administrative domains and network technology segments, with the aim to facilitate automatic and fast deployment and orchestration of any service. In this context, several 5G-PPP project activities are addressing the crucial topic of multi-domain orchestration from different perspectives. Specifically, this is achieved through:

i) the development of a common platform that solves the inter-facility orchestration problem. This platform can be used to interconnect multiple sites, compose and on-board services across multiple facilities.
ii) the extension of the services offered per domain by aggregating the service catalogue and resources from other administrative domain.

Architectural solution	5G PPP Project	Additional Reference
Cross-Facility Orchestration	5G-VICTORI	[6-1]
Cross-Facility Orchestration	5G-VINNNI	[6-2], [6-3], [6-4]
Multi- and Inter-domain Interactions: Resource and Services Federation	5Growth	[6-5], [6-6]

6.1.1.1 Cross-Facility Orchestration (5G-VICTORI, 5G-VINNI)

As part of the 5G-PPP activities, a solution supporting cross-facility orchestration is developed referred to as the [6-1] Operation System (5G-VIOS) that is able to broker Network Services (NSs) across multiple domains and facilities [6-1].

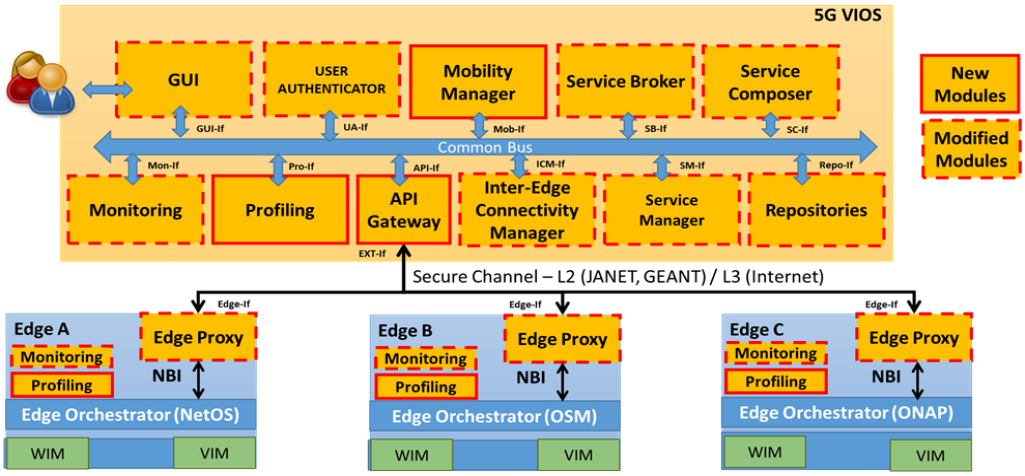

Figure 6-1 5G-VIOS High Level Architecture [6-1]

This platform, depicted in Figure 6-1, enables management of slices, resources and orchestration of services across these facilities. 5G-VIOS provides NS deployment across different sites, dynamic layer-2 (L2) or layer-3 (L3) cross-site service interconnections, inter-site service composition and on-boarding, E2E slice monitoring and management for the deployed E2E services. The design of 5G-VIOS considers the status of the individual MANO platform at each facility and reflects the facility extensions to a common multi-site orchestration platform. This builds on top of the orchestration solutions of each facility, to provide E2E services across the different sites. The cross-domain orchestrator implements suitable drivers to communicate with the Northbound Interfaces (NBIs) of the site orchestrators, while also provisioning and orchestrating the necessary L3 or L2 dynamic connectivity across the data plane of the sites. This solution will be used to extend and/or combine trials to be demonstrated at each site.

Definition of domains

Each domain can be interpreted in two ways:

- As a **technology domain,** which will require orchestration of resources across multiple technology domains, e.g., RAN, Core Network (CN), Multi-access Edge Compute (MEC), Wireless & Optical transport network, etc., in a single geographical domain and operator. As there are multiple resource management and orchestration frameworks for resource virtualisation and automated provisioning of resources and services, it is necessary to unify management and orchestration of different technology domains to realise E2E software defined infrastructures suitable to host 5G services.
- As an **operator/administrative domain**, which means orchestrating resources and/or services according to operator policies using domain orchestrators belonging to multiple administrative domains. In order to realise E2E orchestration, interaction between multiple infrastructure providers must be addressed at different levels, including resource management and orchestration, service management and orchestration and inter-operator Service Level Agreement (SLA) fulfilment.

Multi-domain orchestration architectures

Some initial discussion on multi-domain orchestration has been provided in [6-5]. Multi-Domain Orchestration (MDO) may be implemented according to two primary concepts, either as a federation, whereby each NFVO talks with a peer NFVO to orchestrate the resources under a shared pool. These MDOs are using the east-west interfaces, specifically the Or-Or reference point, as defined in the ETSI GS NFV-IFA 030, or the So-So reference point introduced by [6-

21]. This reference point enables NFVOs from different administrative domains to communicate with each other and orchestrate network services and resources.

On the other hand, in hierarchical brokering there is a central point that brokers the services across the different domains according to the requirements from the service and availability of the resources. It is also responsible for setting up any required inter-domain connectivity policies. A number of research projects follow this approach [6-1], [6-23] and [6-24]. Having a trusted third party to interface and broker the services across multiple domains (cf. section 5 of [6-11] and see Figure 2-2 in Chapter 2 for an example), increases the scalability of the solution as each NFVO only needs to interface with a single entity (the brokering platform) and not with multiple systems, for service orchestration. The broker does not have full control over the underlying infrastructure, which still remains under the control of the individual NFVO but can have a full view of the exposed services across all connected domains. The broker communicates with the underlying NFVOs on the north/south interface using the Os-Ma-Nfvo reference point defined in ETSI GS NFV-IFA 030.

Other research activities also address the problem of multi-site interconnection with the goal to enable a range of service and network orchestration interactions, as well as targeting more traditional interconnection at the control and media plane. The basis of interconnection in this context is described in [6-2], and enables differentiated QoS, Assured Service Quality (ASQ) and Value Added Connectivity (VAC), building on principles from [6-3], [6-4], and taking MPLS and BGP as underlying principles as per IETF RFC 4364 [6-37]. As an alternative early implementation, best effort internet is considered as a default.

Once the different platform sites are interconnected, interoperability for network services can be deployed and operated across sites. Where VAC is supported, the individual connectivity services and traffic flow state information will be handled at the RAN and 5G Core level but not in the transport, backbone and interconnection segments which only handles the traffic at the aggregated levels. These traffic aggregates will most likely be handled at different hierarchical aggregate levels, according to NSP traffic engineering policies.

Interconnectivity will typically be realized via inter-provider APIs indirectly accessing these MANO capabilities, according to the specific APIs provided and the security policies in the provider domains, as illustrated in Figure 6-2. The specifications of these inter-provider APIs are still at an early stage by the industry forums and specification defining organizations. Options are considered and described in [6-2] and [6-22].

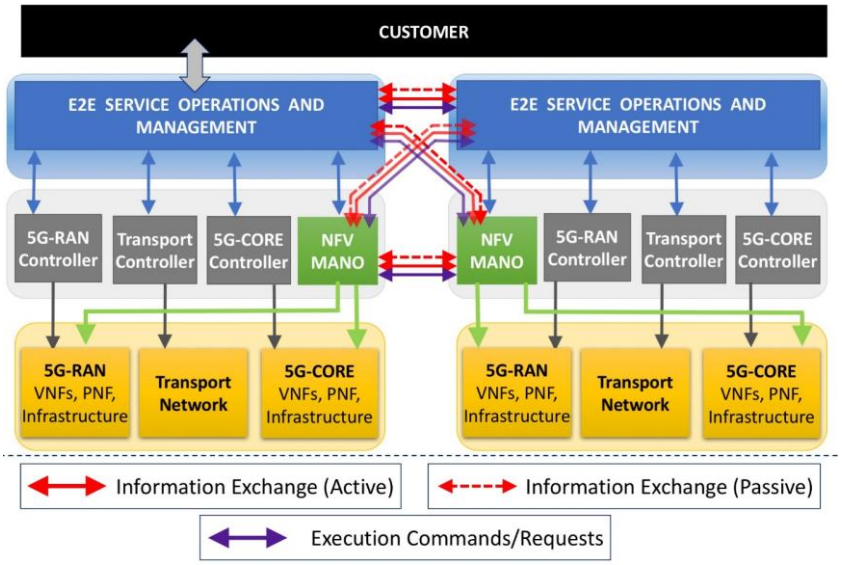

Figure 6-2: Interfaces needed for Sites Interoperability

6.1.1.2 Multi- and Inter-domain Interactions: Resource and Services Federation

By supporting multi-domain interactions with peering or hierarchical domains, service providers can extend their offering by aggregating the service catalogue and resources from other administrative domains. Such interactions occur at the service level (i.e., service federation or hierarchical multi-domain service support) or at the resource level (i.e., resource federation). Regarding the former interaction, different types of services can be handled: communication services, network slices, or NFV network services. The first two are handled between the Vertical Slicer [6-35] and the corresponding building block embedding the Communication Service Management Function (CSMF) and Network Service Management Function (NSMF) functionalities defined by 3GPP, and the latter is handled between peering service orchestrators.

As for resource federation, it is handled at the service layer, between peering service orchestrators. Such interactions are depicted in Figure 6-3 as solid lines. Other interactions can also be envisioned, such as the ones in dashed lines. Notice that the term federation is used when referring to non-hierarchical interactions, i.e., between two entities offering the same functionality in both providers. Furthermore, federation implies multi-domain, but multi-domain does not imply federation (e.g., hierarchical relationship).

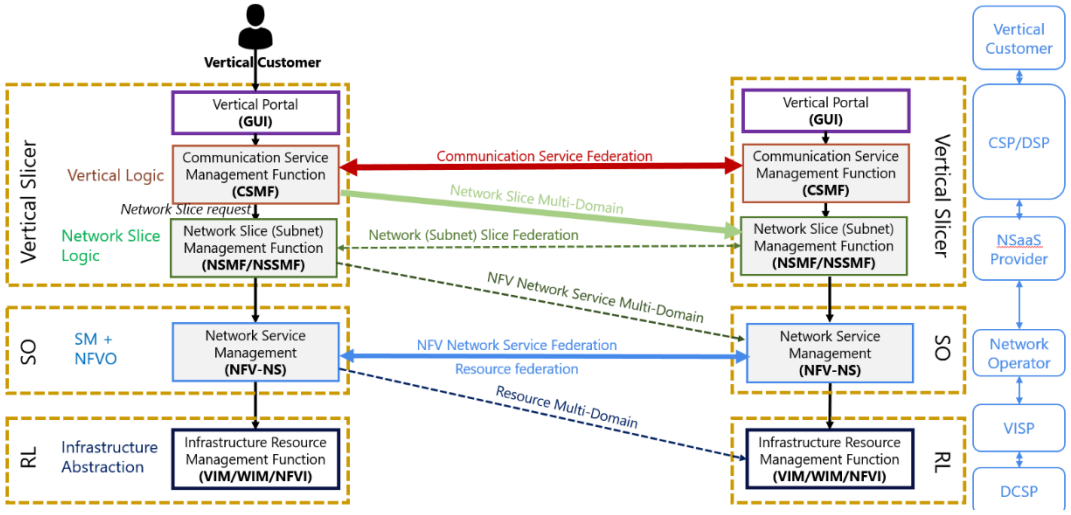

Figure 6-3: Multi- and Inter-domain Interactions

Table 6-1 presents the interfaces / APIs considered by 5Growth to implement each of the multi- and inter-domain interactions [6-36]. Table 6-1 presents the interfaces / APIs considered by 5Growth to implement each of the multi- and inter-domain interactions [6-36].

Table 6-1 Interfaces-compliance for each Multi- and Inter-Domain Interaction [6-36]

Multi- and Inter-domain Interactions	5Growth API-compliance
Communication Service Federation	REST API made available by the peer domain
Network Slice Multi-Domain	3GPP TS 28.531
Network (Subnet) Slice Federation	3GPP TS 28.531
NFV Network Service Multi-Domain	ETSI GS NFV-IFA 013 / ETSI GS NFV-SOL 005
NFV Network Service Federation	ETSI GS NFV-IFA 013 / ETSI GS NFV-SOL 005
Resource Multi-Domain	ETSI NFV IFA 005

The diverse nature of services and technologies naturally leads to multi- and inter-domain scenarios, where each domain has its own orchestration deployment that must be coordinated with that of other domains towards an end-to-end (E2E) service offering. This is a key aspect towards the support and adoption of 5G private networks, also known as 5G Non-Public Networks (NPN) , and their integration with the Public Network (PN) of the Mobile Network Operator (MNO), commonly referred as Public Network Integration with NPN (PNI-NPN).

6.1.2 Inter-domain management for Vertical Services

Architectural solution	5G PPP Project	Additional Reference
Network Service Life Cycle Management across domains	5G-VICTORI	[6-5]
Vertical Service Decomposition across domains	5GROWTH	[6-6]

6.1.2.1 Network Service Life Cycle Management across domains

Within a multi-domain environment and assuming a hierarchical brokering MDO, the service orchestration and Life Cycle Management (LCM) is broken down into three main phases, the service composition, the service initialisation and the service deployment. A high level data flow

is illustrated in Figure 6-4, with the data flows from the service broker (SBR), the service manager (SMA) and API Gateway (AGA) components for the cross-facility orchestration platform 5G-VIOS described in section 6.2.1.1 [6-5] (shown in Figure 6-1).

Life Cycle Management - Phase 1: service composition

The first step for this is to compose the end-to-end network service. The vertical user can interact with the brokering service to select the required Network Services (NSs) among the available NSs and on which domains the user prefers to run these NSs. The Service Composer (shown in Figure 6-1) requests the corresponding Network Service Descriptor (NSDs) from the Repository and the optimal resource configuration from the Profiling in order to compose the inter-domain end-to-end NS (iNS). Noted that the details on how the Profiling component computes the optimum configuration of resources required to meet various use-case KPIs and SLAs are provided in Chapter 5 of this White Paper.

Life Cycle Management - Phase 2: service initialisation

The second phase of LCM addresses service initialisation. After the service composition phase the composed iNSs are pushed through the broker to the corresponding domain NFV orchestrator (NFV-O). Each NFV-O checks the resources required by the iNS for its domain and responds back to the broker service acknowledging that. If the resources are not available and the NS cannot be fulfilled then a new iNS needs to be composed using other domains or different resources.

Life Cycle Management - Phase 3: service deployment

The third phase in the LCM includes the deployment of the iNS on the corresponding domains. The composed acknowledged iNS is now deployed on the corresponding domains and the flows are configured. The data planes across the different domains are set-up on the newly deployed end-points. At the same time, the Monitoring component initiates the processes to monitor the compute and network resources and associated KPIs for that NS that are stored for future use by the Profiling or directly the vertical user.

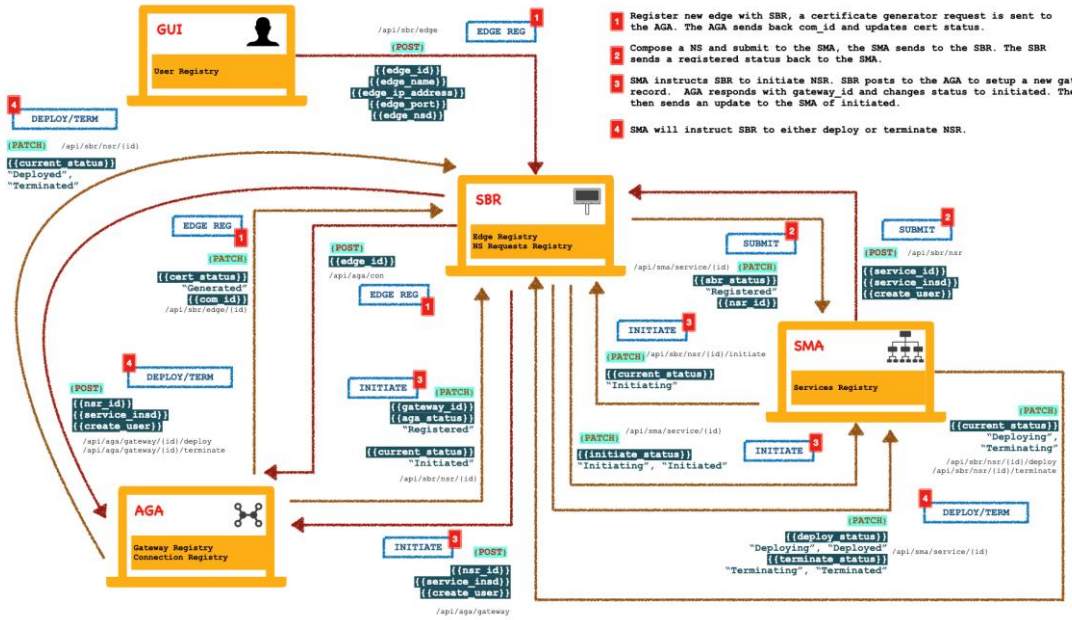

Figure 6-4: 5G-VIOS Service Broker Data Flow

6.1.2.2 Vertical Service Decomposition across domains

With the multitude of administrative and technological domains that are envisioned to offer and support the deployment of E2E vertical services, the question arises on how vertical services are decomposed, requested, provided, and stitched across all the different domains [6-6].

On one hand (Figure 6-5), the vertical can perform a manual service decomposition by its own, requesting each Vertical (sub)-Service the corresponding part of the whole Vertical Service. It requires the vertical to identify what is going to be deployed on each administrative and technological domain, and to handle the burden of interacting with as many orchestration deployment platforms as required, including the establishment of peer or federation agreements. However, much of the complexity must be handled by the vertical itself, requiring know-how that might be out of its domain knowledge.

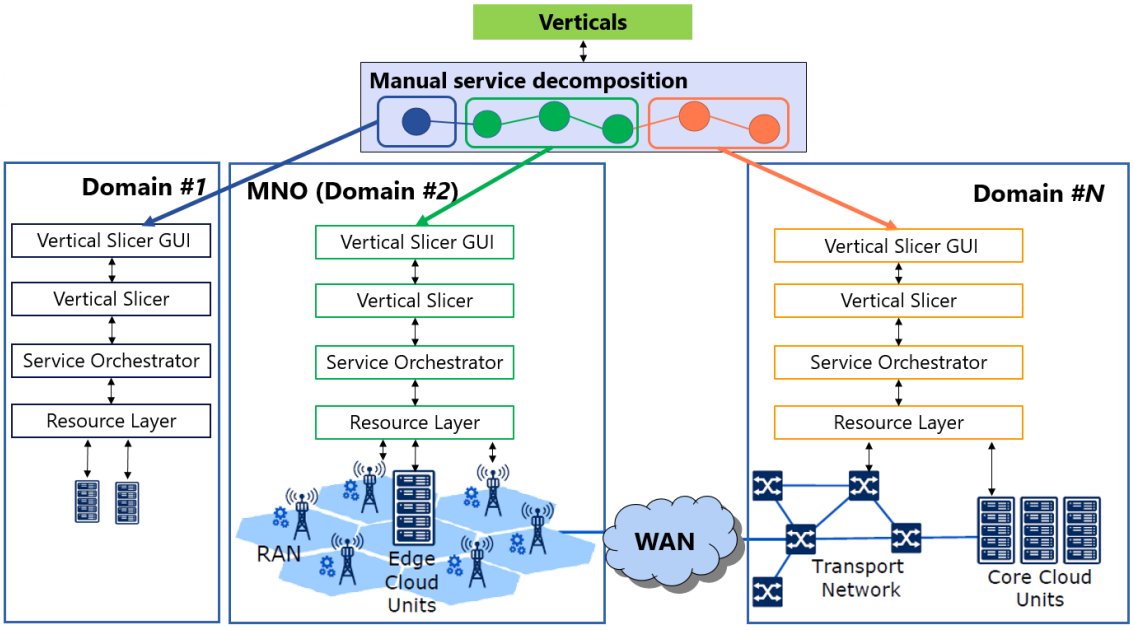

Figure 6-5: Manual Vertical Service Decomposition

On the other hand, as seen in Figure 6-6 and Figure 6-7, the vertical can delegate such task to an underlying orchestration deployment platform, which handles the vertical service decomposition and its E2E deployment on behalf of the vertical. This approach simplifies the whole process for the vertical, as the underlying platform might already have peer or federation agreements with other administrative and technological domains (e.g., MNO domain). However, it requires each orchestration deployment platform to expose well-defined / standardized programmatically interfaces (i.e., Application Programming Interfaces – APIs) so that the components on-boarding and lifecycle management of E2E Vertical Services is automated. As such, the underlying orchestration deployment platform can also automate the decomposition of the vertical service, by carefully assess the vertical service's requirements and KPIs, the capabilities and availability of resources in peer or hierarchical domains, cost, SLAs, among others.

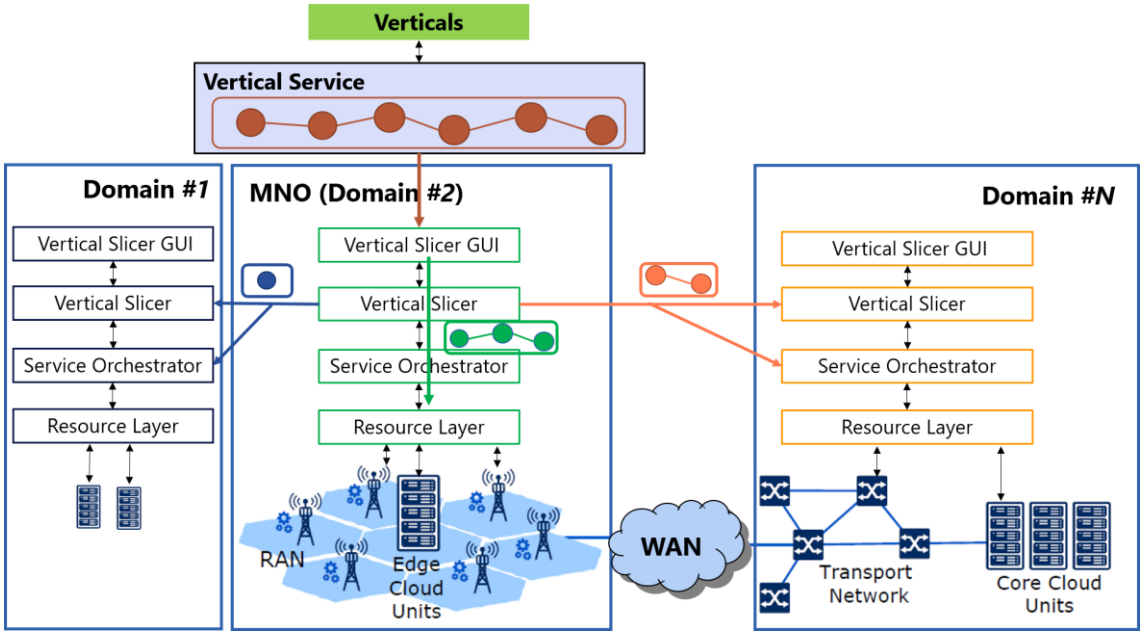

Figure 6-6: Delegated Vertical Service Decomposition (Vertical Slicer Level)

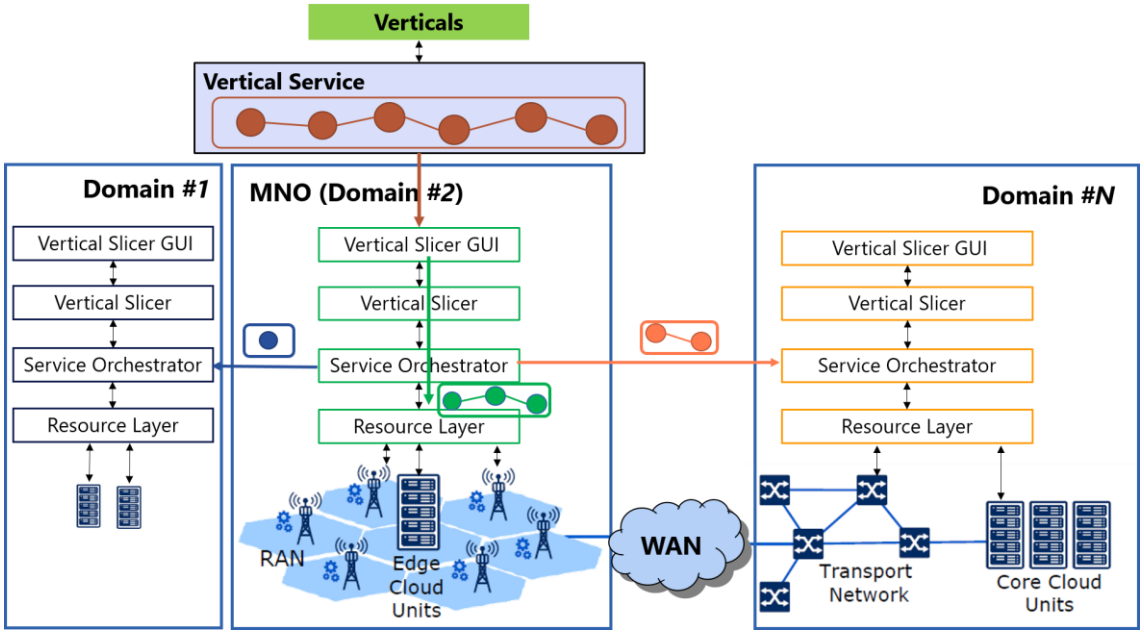

Figure 6-7: Delegated Vertical Service Decomposition (Services Orchestrator Level)

While the former gives total flexibility and control to the vertical, the latter simplifies the job for the vertical at the cost of taking over control out of the vertical.

6.2 Mobility Management in cross-domain environments

An important problem that needs to be addressed in cross domain environments is mobility management to ensure seamless service delivery as end-users and devices are moving across different administrative domains. This can be particularly challenging in cases where the end user movement can follow very agile mobility patterns and the speed of mobility is high, as is the case in automotive/vehicle environments. So, relevant architectural considerations, functional and protocol-based solutions are critical in addressing the associated challenges. Several 5G PPP

activities addressing mobility management in cross-domain environments are currently in progress.

Architectural solution	5G PPP Project	Additional Reference
Cross-border service/session continuity	5G-CARMEN	[6-7], [6-8]
Cross-border handover (Inter-PLMN handover)	5G CroCo	[6-9]
Inter-PLMN Roaming Latency	5GMobix	[6-10]
Traffic Roaming	5GMobix	[6-11]

6.2.1 Cross-border service/session continuity

An evolution of the 3GPP's 5G System Architecture towards a holistic 5G Ecosystem, which extends the scope of the 5G Control Plane for mobility management with control, management and orchestration of cloud-native service instances at distributed network edge resources is targeted by [6-7][6-8] .

Whereas the deployment of distributed service instances at distributed network edge resources enables local processing of session data and data analytics, herewith offloading the network and central cloud resources and reducing the dependency of experienced service quality on the network performance, additional challenges with such deployment need to be tackled. This includes the permanent monitoring and need for re-configuration of the network in support of continued services for each connected client. This makes the automotive industry a particularly challenging customer of such 5G Ecosystem, as vehicles move with very agile and individual mobility patterns even across country borders, which results in a handover from a source MNO's domain to a target MNO's domain.

Cross-border service continuity requires, beyond others, the following key features (labelled and indexed as Fx):

- F1 - Collaboration between MNOs in support of accelerated radio network re-selection in order to minimize radio network connectivity interruptions
- F2 - Provisioning of local breakout points on the data plane of a target MNO in order to avoid home routing of data plane traffic via an anchor point in the previous MNO's network. The 3GPP 5G System architecture offers suitable interfaces between 5G Data Plane functions (N9 reference points between User plane Functions, UPF) as well as between 5G Control Plane functions (AMF, SMF) in support of service and session continuity (SSC) and mid-session relocation of a mobile device's UPF.
- F3 – Relocation of an application session context and associated states from a service instance in a source MNO's data network to a service instance in the target MNO's data network. This requires the availability as well as sufficient resources for such service instance in the target MNO's data network to import the transferred states and serve additional clients.
- F4 – Suitable treatment data plane endpoints, such as the IP address of a mobile device and its connected service instance, as well as traffic in between them. Endpoint IP address changes during cross-border movements need to be considered.
- F5 – Cross-domain data plane forwarding to reduce packet loss and to support service continuity from a target domain's service instance after a mobile device's session state/context has been transferred.

With reference to the cross-domain architecture for 5G edges orchestration [6-8], the above features are supported as follows:

Feature F1 can be supported by cross-domain interfaces on the control or management planes, as well as by a secured data sharing platform in order to share RAN data between MNOs. The 5G system architecture can leverage RAN data of other MNOs and expose information to mobile devices in order to optimize the frequency scan and network re-selection procedure.

Feature F2 requires provisioning of 5G UPFs that can serve as local breakout points in an MNO's domain to enable optimized data plane routing and mobile devices to access to local resources, which may be provided from 5G network edge resources. For cross-domain movements of mobile devices, associated MNOs can leverage the 5G system's N16 and N14 reference points on the control plane as well as the N9 interface on the data plane between UPFs to enable service and session continuity by UPF relocation even beyond the scope of a single domain.

In the view of feature F3 and F5, the proposed architecture for 5G edges orchestration supports cross-domain operations on various planes, i.e. the federated management and orchestration planes (Or-Or, Lo-Lo) as well as the data plane applying to the N6 reference point per the 5G system architecture. The orchestration planes enable the alignment of service instances deployment, LCM and connectivity between different domains. Transfer of session context for service continuity can be coordinated and supported by the orchestration plane, e.g., to provide information about a remote service instance, which is to import the transferred session context, or to refer a service instance to a local service communication proxy to perform context transfer. Furthermore, a programmable data plane is used as an overlay to the N6 reference point to connect distributed edge resources and enable traffic steering.

At service instance level, different MNO domains can leverage the orchestration planes to exchange information about how to reach and connect to a service. This can include addressing information and supports feature F4.

6.2.2 Cross-border handover (Inter-PLMN handover)

When moving between two Public Land Mobile Network (PLMNs), vehicles can experience connection interruptions that can last up to minutes until the modem finds and attaches to a new network and the data connections are restored. Several solutions exist to provide service continuity across different mobile networks, and one in particular [6-9], [6-26] has been deployed focusing on cross-border/-MNO handover, by establishing the S10 interface between Mobility Management Entities (MMEs) of different MNOs. Cross-border handover should be expected to achieve service continuity if there are no radio coverage gaps between mobile networks across different countries. Figure 6-8 shows the architecture of this solution, in which two networks, Home and Visited, support cross-MNO handover. The MMEs of the two networks are connected through the S10 interface, and the roaming interfaces S8 between Packet Data Network Gateway (P-GW) in the Home network and Serving Gateway (S-GW) in the Visited network, and S6a between the Home Subscriber Server (HSS) in the Home network and the MME in the Visited network are established. With these connections in place, a user can be handed over between the networks, as in a handover between two MMEs in the same network. Home-routed roaming is used in this architecture, which results in maintaining the same P-GW connection from the home network to a data network after the handover is completed. It should be noted that in real-world scenarios this solution can face operational challenges, particularly in exposing the required information and configurations between involved MNOs to enable the handover procedure between cells in two different networks. Furthermore, legal requirements like lawful interception might require further attention.

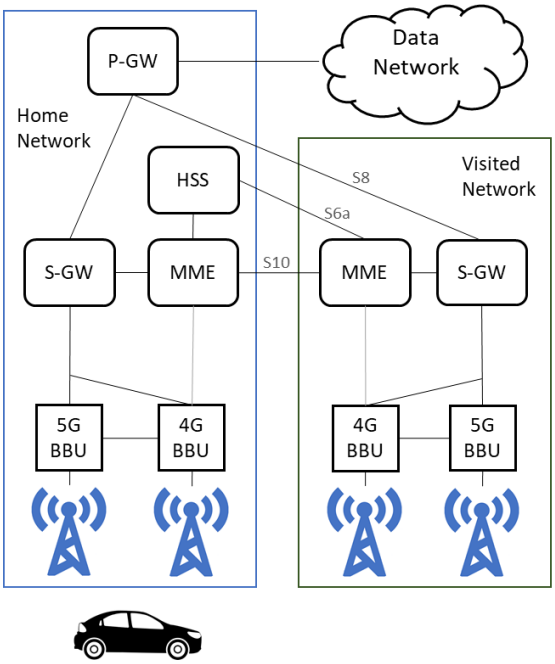

Figure 6-8: Architecture of Two Networks with Supported Cross-MNO Handover

6.2.3 Inter-PLMN Roaming Latency

In the context of the discussion above and keeping in mind that in Europe vehicles cross country borders frequently without the requirement to stop at as mobile networks are deployed on a per country basis, a connected vehicle crossing a border will be required to connect to a new cellular network. Use cases related to Connected and Coordinated Automated Mobility (CCAM) are expected to also work when crossing a country border. Most requirement documents only state the maximum end to end latency, implying this should also work when changing networks. This is also the case for the specification listed in 3GPP technical specs [6-28], [6-32]. The maximum disconnect time is given in [6-10], taking in to account that vehicles might at a specific moment lose the connection for brief moment when changing the network. This maximum disconnect time as can be very strict for some use cases, being less than 5 ms. To comply with these requirements different measures can be taken by both the mobile network and the UE inside a vehicle.

Measures at the UE focus on optimizing the search and reconnect:

- In *fast registration* approaches, the goal is to have the UE register in the new network within the allowable interruption time. To speed up the registration, the UE receives a hint on the new network to register on before it is disconnected from the initial network. The hint can be provided by an application running on the device/SIM or, in a later phase, from the network. Furthermore, to benefit from this hint, it will be necessary to prevent the UE from doing a complete scan for candidate networks, as is typical UE behaviour today. With current approaches this can already be achieved by manually controlling the connect behaviour (preventing automated searches). The application will trigger a network search before the connection is lost and steer the UE to a new network. Initial tests at the Dutch-Belgium border show that the reconnect time can become as low as 1 or 2 seconds (depending on the PLMN chosen).
- In *dual modem* setups, a connection to the new network is set up before the initial connection is lost (e.g., make before break). In current implementations, this would require two SIM cards and two modems to temporarily have parallel connections to the two networks. Also, currently an application is needed, capable of steering each UE and routing the traffic over the correct network.

Measures from the network are focused on the steering of roaming and providing a handover between bordering networks:

- Optimizing *steering of roaming* aims at selecting the best network selected for the UE and its services. The Home Public Land Mobile Network (HPLMN) is responsible to set up the roaming agreements with the Visited Public Land Mobile Network (VPLMNs) and allows the UE to make use of them. The UE should always be steered to the most optimal network, be it to utilize the specific services it requires or to benefit from the best (wholesale) roaming business model and rates. Therefore, current technologies need to evolve from denying services on non-preferred networks to steering the UE toward the preferred network.
- In *inter-PLMN handover* approaches, the well-known intra-PLMN handover is extended to work across PLMN borders. In 4G, this involves introducing an S10 interface between MMEs of the two bordering network operators. In 5G SA architectures, this translates to an N14 interface between the AMFs (potentially absorbed in the overall N32 interface between the two operators' SBA architectures in the control plane). As pointed out by earlier measurements in trials by Ericsson [6-29] and as also stated [6-9], there is no noticeable interruption because of the handover and the latency keeps well below 100 ms during such inter-PLMN handovers. Currently the N14 interface has not yet been earmarked to be used as a roaming interface. Although the inter-PLMN handover has been described since 2006 in 3GPP release 8, it has as of yet not been adopted by operators. This is probably due to the lack of demand and the complex integration that is required.

Multi-SIM solutions

Multi-SIM solutions are promising many advantages including seamless connection, improved coverage, improved bandwidth, and reduced end-to-end delay. Current solutions of multi-SIM connectivity are mostly user-oriented, i.e., UE provides functionalities of using multiple SIMs, without any support from networks. Two user-oriented multi-SIM solutions have been tested with the main goal of identifying their benefits and weaknesses [6-25]. The first solution is a multi-SIM OBU solution, which can switch over up to four 5G networks (NSA to NSA/SA modes). The criterion to switch over multiple networks is primarily based on fixed connectivity metrics such as signal strength, but the OBU allows to introduce additional different criteria. The second user-oriented solution leverages the capabilities offered by an intelligent routing device. This latter is equipped with multi-sim and multi modem capabilities and is integrated along the OBU. The intelligent router allows for seamless handover and bonding between multiple 5G bearers belonging to different mobile networks. A VPN connection allows for bearer bonding through the paired intelligent router deployed at the server site, where the CCAM applications are installed. A high-level diagram of this multi-SIM connectivity deployment is illustrated in Figure 6-9.

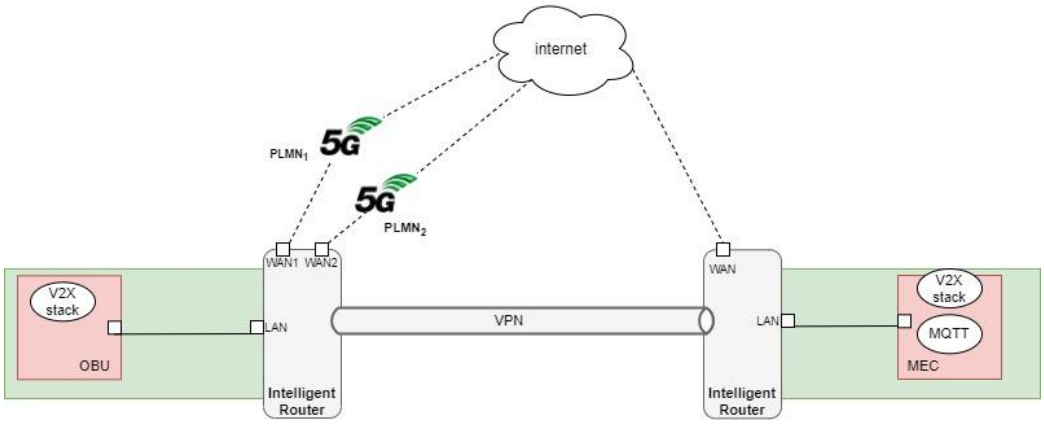

Figure 6-9: Multi-SIM 5G Connectivity solution being tested in the 5G-MOBIX project

The contemporary multi-SIM solutions, such as, those being considered in 5G-MOBIX as described in example above, are typically based on proprietary solutions, and implemented without standardised support of multi-SIM feature from the associated 3GPP systems. In that case, networks serving a particular multi-SIM device may do so with degraded performance on one or more of the connections. In response to the increased adoption of multi-SIM devices, 3GPP has included in Release 17 an ongoing work item for standardisation of enhanced support of multi-SIM devices (physical or embedded SIMs) associated with multiple 3GPP systems (scope being Evolved Packet System [EPS] or 5G System [5GS]) [6-27]. This includes study of system impacts of legacy multi-SIM device implementations and potential enhancements on aspects, such as, efficient monitoring of multiple paging channels (of each associated 3GPP system) by a multi-SIM device and coordinated departure of the multi-SIM device from one of the 3GPP systems.

6.2.4 Traffic Roaming

Even upon completion of the HO process, roaming places significant challenges relating to the routing of the traffic and associated performance. When roaming traffic is Home Routed (HR), subscribers always obtain service from their home network i.e., traffic is routed to their current location through a packet gateway at their home network. As the service is always managed through the same gateway (Packet Gateway (PGW)/UPF), service continuity, while roaming, is facilitated. However, this comes at the cost of increased latency due to the user plane traffic being routed from the visited network to the home network, typically through the GRX (GPRS Roaming Exchange)/IPX (IP exchange) networks. On the other hand, Local Break-Out (LBO) allows the optimization of the roaming traffic path through the visited network PGW/UPF, at the cost of potential service disruption since a new PDU session needs to be established at the visited network.

The selection of roaming network mode obviously depends on: 1) the latency and service continuity requirements of the services at hand i.e., sensitivity to latency and/or disruption, and 2) the actual latency or disruption delivered by each mode. The latter in turn depends on the overall topology and dimensioning of the network. From [6-10] a wide range of use cases are considered; efforts include the experimental assessment and comparison of HR and LBO solutions for inter-PLMN. The evaluation will take place both between NSA and SA architectures, offering significant insights regarding the expected benefits of the 5G Core (past of SA) in terms of routing efficiency.

Commercial Mobile Network Operators use Internetwork Packet Exchange (IPX) networks for signalling messages in order to support LTE roaming between their roaming partners. For each peer to the IPX network only a single physical connection is required. On an IPX network, the DIAMETER Edge Agent (DEA) must be deployed to support route addressing for Diameter signalling between the visited and home networks. DEA will support connection from MME i.e. S6a and PCRF S9 from the visited network towards the home network.

All roaming signalling messages are transmitted through DEA. This allows an operator network to only send or receive signalling messages to or from DEAs deployed on other operator networks. It no longer needs to learn the internal structure of other networks. In 4G/LTE roaming the UE during attach procedure will be authenticated with home HSS using S6a interface between visited MME and home HSS through the DEA in the IPX network. After the UE attach a PDP session is established and visited PCRF checks with home PCRF using S9 interface through the DEA in the IPX network.

The roaming connection is done through the DEA and operators can use flexible security policies on the DEA to protect network security, such as controlling IP address access, restricting device access, and deploying firewalls. The MME in NSA or AMF SA case needs to be configured with

the Autonomous Systems Numbers (ASN) name of the DEA to connect during roaming procedure. The roaming configuration could be based on single Database or file that includes the PLMN and the associated ASN or hostname of the DEA for accessing home HSS and home PCRF for the selected operator based on the PLMN.

5G SA roaming is required to support local breakout so needs to be implemented following the 3GPP Service Based Architecture (SBA) with the interfaces defined in the following figure where the UE will setup a new PDU session in the visited network. In the visited network the AMF will authenticate the UE accessing home UDM with N8 interface and the SMF will access UE profile from home UDM with N10 interface through SEPP.

As shown in Figure 6-10, the UE, when moving to a different operator, will be registered if roaming is enabled with the home network. This will allow the UE to setup new PDU session towards the Data Network through the visited network UPF.

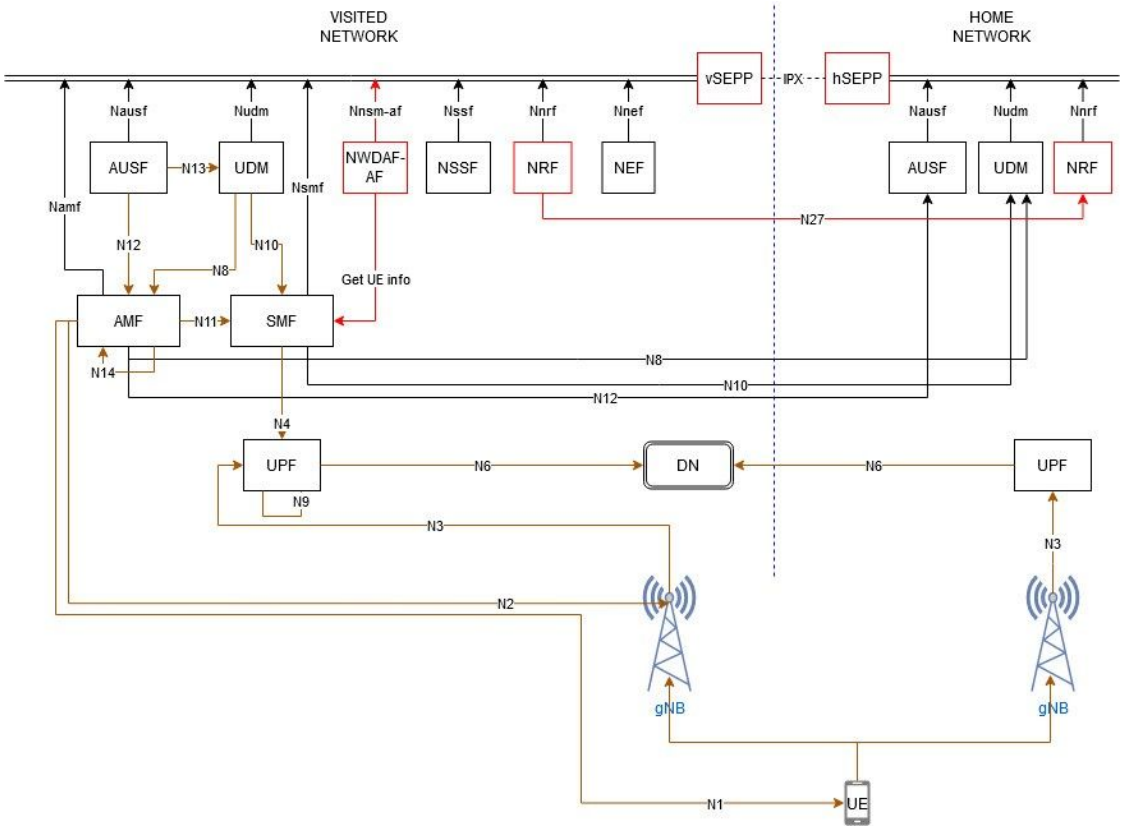

Figure 6-10: 3GPP roaming architecture

6.3 Cross-domain Service Assurance

In the context of 5G, where a number of vertical industries and their services are supported by common infrastructures, the challenge of end-to-end service assurance becomes critical. As one of the main technology enablers in this context is infrastructure virtualisation, it is clear that assurance solutions have to be designed as an integral part of the offered technology solution. This introduces the need to exploit a common infrastructure in support of the vertical services offering at the same time assurance of the network itself that is implicitly has to address a trade-off between complete isolation and flexibility. The designed assurance solutions need to provide reliable insights based on observations and conclusions drawn by complex diagnosis processes that can be supported by the technology advancements that NFV/ SDN and 5G solutions offer. This is necessary, as in order to provide service assurance for the 5G related use cases, traditional

solutions would be extremely complex to implement making them unsustainable and cost inefficient for the virtualized and multi-domain 5G environments. In this context, several activities of 5G PPP projects focus on addressing issues related with cross-domain service assurance.

Architectural solution	5G PPP Project	Additional Reference
Analytics-driven service automation	5G-VINNI	[6-2], [6-12]
QoS Prediction for application adaptation	5GCroCo	[6-9], [6-26]
5G AIOps with Operational Data Lake	5GZORRO	[6-13], [6-14]

6.3.1 Analytics-driven service automation

Service assurance is a key mechanism to guarantee the success of 5G network slicing, and so it is important to propose an architecture for service assurance in the context of network slicing.

To align with the slice orchestration architecture proposed in [6-2] a hierarchical service assurance architecture is proposed as shown in Figure 6-11.

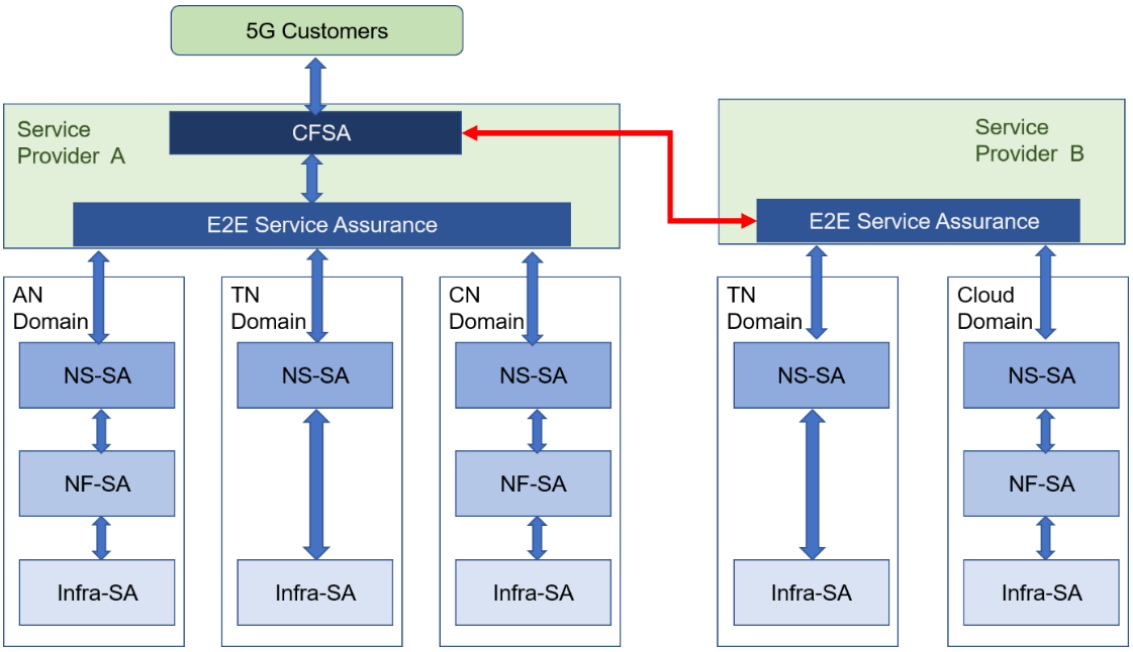

Figure 6-11: Service assurance architecture for network slicing

The bottom three layers, Infrastructure-SA, NF-SA, and NS-SA correspond to the three NFV layers defined in the ETSI MANO framework, infrastructure, Network Function (NF), and Network Service (NS), respectively. The E2E Slice Assurance (E2E-SA) is responsible for assuring the network slices provisioning for the CFS, whose assurance is achieved by the CFS Assurance (CFSA). This hierarchy reflects how a CFS is constructed recursively from simpler components.

The top layer CFSA interacts with the 5G customers and can be offered by the service provider that receives service request from the 5G customers (e.g., Service Provider A in Figure 6). 5G customers usually request communications services rather than network slices. The CFSA translates the customer's service request, e.g., service level agreement (SLA) and/or quality of experience (QoE) requirements, into the SLA suitable for individual slices that could be used by E2E-SA. If a CFS requires network slices provided by multiple service providers (e.g., service provider A and B in Figure 6-11), the CFSA decomposes the CFS-SLA into SLAs for each E2E-

SA. Furthermore, CFSA receives and aggregates service assurance related data from each E2E-SA (the red line from Service Provider B and blue line from Service Provider A) to generate an overall service assurance view for the CFS and assess if the CFS-SLA is guaranteed. This Research item is further described in [6-12].

6.3.2 QoS Prediction for application adaptation

In addition to the issues already mentioned, another important aspect in critical V2X services (e.g., safety, autonomous driving) is service adaptation to achievable performance, especially in cross-border environments. On the other side, one of the features of many V2X applications is that they can operate with different configurations, depending on the achievable performance, configurations which might be mapped to different QoS levels. This is a very useful feature, since the applications can continue to be operational if an alternative QoS profile (i.e., with a lower QoS) could be used instead of the initial QoS profile.

An application may have to adjust its configuration (e.g., increase inter-vehicle gap), according to the QoS that can be delivered. For each application-level configuration, a different QoS level (e.g., data rate, latency) may be associated. V2X application can be timely notified of expected or estimated change of QoS before the actual change occurs, allowing thus the application to gracefully adapt its behaviour and configuration to the expected achievable performance.

For instance, in the case of Tele-operated driving (ToD) use case if the requested QoS for the uplink video transmission and potentially other telemetry information is not met, the remote driver cannot perceive the situation and is unable to provide commands to the vehicle. In this case it is beneficial to command the vehicle into a safe state or reduce the QoS demand by certain countermeasures assuring requested QoS can be met by the network (e.g., change of video codec or compression, reduction of vehicle speed, safe stop, or re-routing [6-26]). Vehicle and remote driver need time to completely execute these counter measures and therefore QoS prediction is required for the imminent future. Having information about instantaneous or past QoS is not enough.

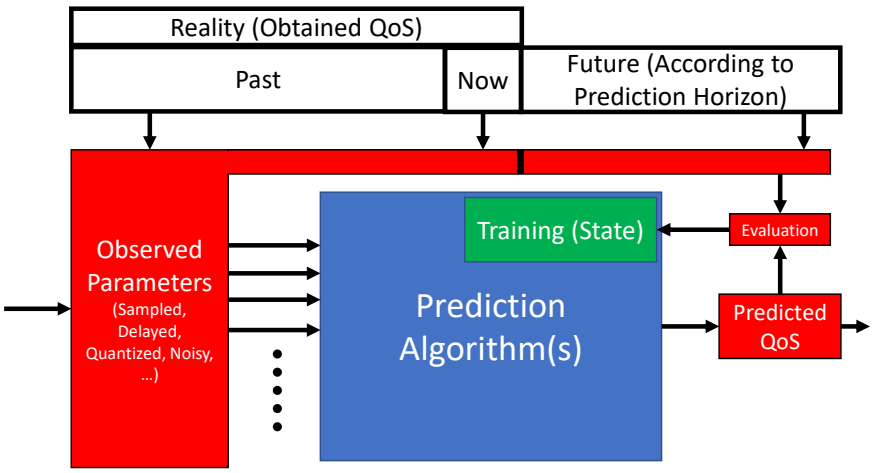

Figure 6-12: General Principle of Network QoS Prediction

Figure 6-12 shows the general principle how such prediction can be realized. The goal is to predict the QoS in the future at a different time and location. The prediction algorithm, or set of algorithms, is in the centre of this task. It takes observed parameters as input. Those do not necessarily exactly resemble the current and past network QoS due to many constraints such as sampling, quantization, delayed availability, noise, etc. Besides network parameters, further environmental ones can be collected, e.g., GNSS positions. Recently, in 3GPP Service Architecture (SA) Working Group (WG), an initial architectural solution has been introduced

about the notifications on potential QoS change in 5G communication systems. The goal is to enable 5G communication systems to provide analytics information regarding potential QoS change upon request from a V2X Application Server (AS).

[6-9] provides some examples for QoS prediction algorithms and input data are provided in they might require and how performance might change depending on input data availability and quality. Different algorithms must be further evaluated to find a compromise between access to input data and prediction performance, since access to input data might include certain effort or other issues might exist, e.g., privacy. In addition, the realisation of QoS prediction in cross-border environments (e.g., roaming and non-roaming cases) may require further investigation to make sure that existing interfaces and signalling are adequate.

6.3.3 5G AIOps with Operational Data Lake

The AIOps approach is adopted in [6-14] to achieve zero-touch automated management of network services. The approach is based on data-driven analytics and thus requires collecting and processing massive amounts of operational data of different types, formats, semantics, etc. 5GZORRO puts forward the concept of Operational Data Lake, as an engine for all the data processing as part of 5G AIOps, including both basic data processing such as data injection, formatting, and aggregation, and also advanced data processing such as model building and refining, learning, advanced inference, etc. The Operational Data Lake includes an event-driven platform that can be easily extended with new data types and data sources as well with new analytical methods and algorithms, through open APIs that allow composing custom data processing pipelines, onboard them to the Data Lake, and operate them as part of the larger platform [6-13], [6-14].

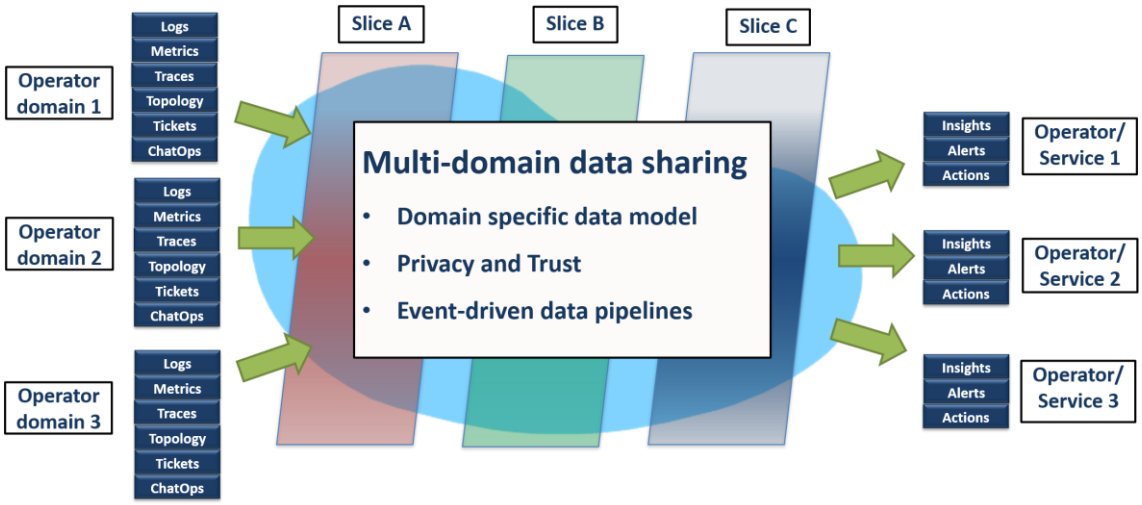

Figure 6-13: Multi-domain data sharing in Operational Data Lake

As shown in Figure 6-13, one of the major challenges we face while building the Operational Data Lake [6-15] is the multi-domain nature of the environment the Data Lake should operate in. First, we must address issues around multi-party data collection and sharing. When operational data originates from devices and services owned by different players, not always willing to share the data openly and not always using identical data models on formats to encode the data, there is a need to provide additional tooling and support to ensure analytical pipelines have access to all the data relevant for their computations, e.g. to ensure that SLA terms of the end-to-end service are satisfied, it might be required to take into account data originated from multiple domains that provide parts of this service. The strong focus of on security, privacy, and DLT based smart contracts [6-16], allows to create a zero trust environment where each player's data can be stored

safely and privately, fully protected, so it can be retrieved and operated on only by parties and for reasons the data owner has agreed to through the multi-party smart contracts [6-16]. In addition, to facilitate analytics across multiple operators and technology domains, data received from different sources must be enriched, contextualized, and sometimes translated into a unified format. For this, [6-17] introduces and implements an extensible domain specific data model for 5G, drawing inspiration from our target use cases and following industry standards, e.g. Generic Network Slice Template by GSMA.

6.4 Cross-domain slicing

The concept of network slicing is not new, however legacy technologies including 4G suffered inherent limitations in terms of flexibility, complexity and lack of automation. 5G solutions aim at offering the technology enablers that allow dynamic and flexible creation of end-to-end slices with guaranteed QoS. This will facilitate use-case-based and SLA-driven slice instantiation based on the specific use case/service requirements. These network slices will run independently and in isolation from each other spanning across different technology network segments and administrative domains. To support this vision several 5G PPP project activities are focusing on a number of relevant challenges.

Architectural solution	5G PPP Project	Additional Reference
Inter-operator slice configuration	5G-VINNI	[6-2], [6-18], [6-22]
Multi-domain Orchestration and Slice Management	5GCroCo	[6-9]

6.4.1 Inter-operator slice configuration

With the Architecture in Figure 6-2, the possibility for both hierarchical and peer-to-peer orchestration exists. Underpinning both of these options is the principle of Network Slice Federation. Hierarchical orchestration of a federated slice assumes the definition of a parent orchestrator, sitting on top of multiple child orchestrators, coordinating their workflows and providing translation of their information/data models. This introduces significant burdens in management scalability, as the number of facilities connected to this master orchestrator increases. Additionally, the scenario of having a network operator taking the broker role is unrealistic for upcoming operational networks, as it would raise concerns with the rest of operators in terms of privacy, auditability and non-repudiation. For this reason, the peering approach is preferred for federating domains.

Considering the [6-2] and [6-22] facility site components, three options can be considered for federation:

- Federation at Service Orchestration level (SO-SO): the SOs from different sites exchange information and expose their capabilities across them.
- Federation at Network Orchestration level (NFVO-NFVO): the NFVOs from different sites exchange information and expose their capabilities across them.
- Federation at different orchestration levels (SO-NFVO): the SO from one site communicates with the NFVO from another site.

In [6-2] and [6-22], there are multiple facilities each making usage of a different orchestration solution, and interoperability can only be achieved by means of standard interfaces. Table 1 gives an insight into the three federation options. As seen, there exists at least one interface to implement every federation option. For example, SOL011 [6-40] and SOL005 [6-41], which define RESTful

APIs for the implementation of Or-Or and Os-ma-nfvo interfaces, have become the standard solutions for the second and third federation options.

Table 1: Federation Options

Option	Main Features	Standard interfaces
SO-SO	Information exchanged with external SO: list of on-boarded VINNI-SBs, selected configuration of deployed slice (subnet) instances. Operations exposed for external SO invocation: slice (subnet) provisioning; slice (subnet) performance assurance; slice (subnet) fault supervision; network functions application layer conf & mgmt.	MEF LSO Interlude [6-42]
NFVO-NFVO	Information exchanged with external NFVO: list of on-boarded NSDs-VNFDs; records of deployed network service/VNF instances, with information on their resources. Operations exposed for external SO invocation: network service/VNF lifecycle mgmt; network service/VNF monitoring; network service/VNF resources mgmt.	Or-Or SOL011 [6-40]
SO-NFVO	Information exchanged with external SO: the same as for NFVO-NFVO, but without information on instances resources. Operations exposed for external SO invocation: the same as for NFVO-NFVO, but without resources mgmt. Information exchanged with external NFVO: slice (subnet) – network service mapping.	Os-Ma-nfvo SOL005 [6-41]

Considering the abovementioned cons, SO-SO is considered the most realistic solution for future commercial networks, and thus it is the one explored in [6-47]. Further definition of this is found in [6-2], [6-21] and [6-25].

[6-47] has further defined an actor-role model, discussed in [6-23], which can be extended to a multi-operator scenario. Within it, the following roles exist: (i) Communication Service Customer (CSC), to be played by customers such as ICT-19 vertical industries (ii) Communication Service Provider (CSP), to be played by 5G-VINNI Facility Sites and (iii) Network Operator (NOP), to be played by the facility sites.

Furthermore, two types of CSC were defined, the *basic CSC* that do **not** have management capabilities over the network slice/service consumed, and the *advanced CSC* that has management capabilities over the service consumed through the Communication Service Management Function (CSMF). Finally, the service provided by the facility sites is categorized into single site and multi-site services. The latter case is depicted in Figure 6-14 and it is the scenario that is relevant when it comes to *network slice federation*. Note that this model focuses mostly on the functional roles related to network slicing rather than on business roles that are extensively discussed in [6-23].

The actor role model for SO-SO federation is shown in Figure 6-15. Other federation models are considered in [6-2], [6-21], and [6-22].

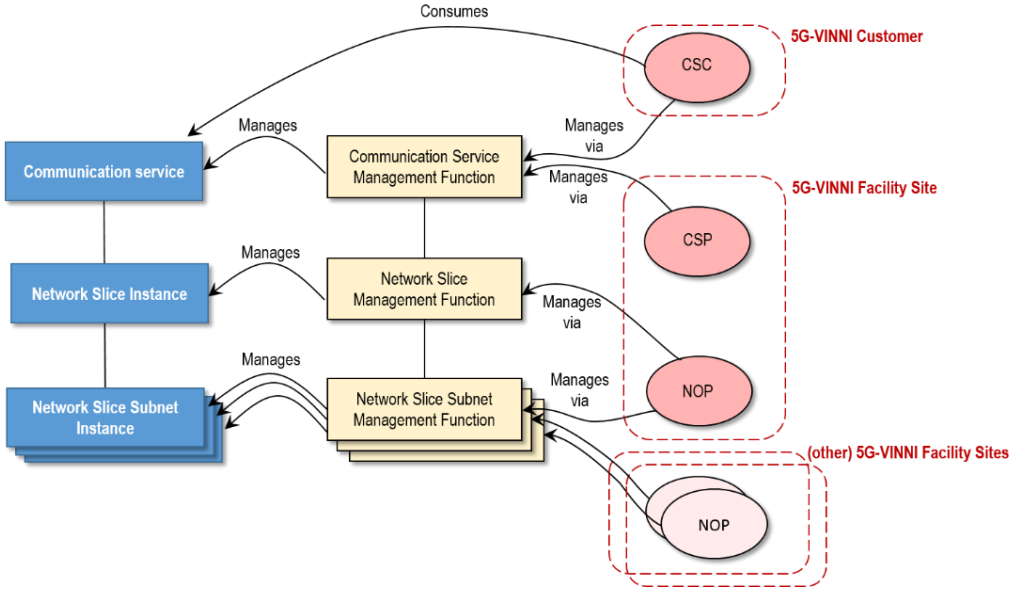

Figure 6-14: Advanced 5G-VINNI CSC, Multi-Site

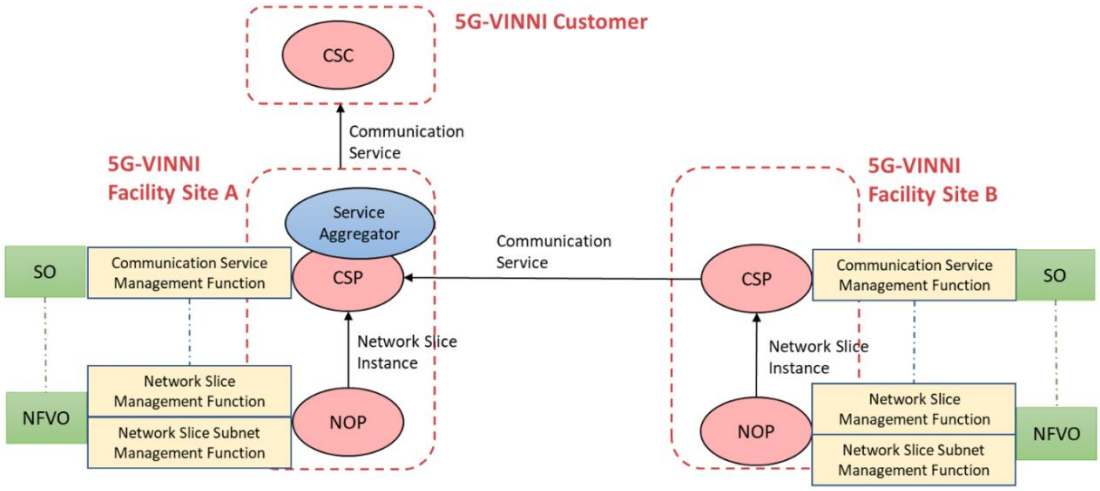

Figure 6-15: Basic 5G-VINNI CSC, SO-SO network slice federation scenario

6.4.2 Multi-domain Orchestration and Slice Management

The orchestration framework presented in [6-12] aims at providing functionalities and mechanisms for managing end-to-end Network Slices in support of automotive services deployed across different geographical, administrative and technological domains. In a multi-domain scenario, the end-to-end service must be decomposed into multiple service components that can be either placed in a centralized public Cloud or the MEC, this depending on the specific service and its network requirements, e.g., in terms of latency.

A hierarchical, centralized multi-domain orchestration layer composed of two main functional components, proposed in [6-12], is depicted in Figure 6-16: the Service Orchestrator (SO) and the Multi-domain Orchestrator (MDO). The SO is an end-to-end service orchestrator that starting from the high-level requirements of the service, determines its decomposition in functional elements (i.e., VNFs or MEC Application Servers) and virtual infrastructure requirements (e.g., network connectivity and required virtual computing resources).

This decomposition results in the generation of an end-to-end Network Slice that is built through a Network Slice Template (NST), which embeds NFV entities and MEC Applications. The SO implements also the logic for determining the sharing of sub-components among different

Network Slice instances and/or to deploy the end-to-end Network Slice across different administrative domains. The SO resides on top of the MDO that is in charge of coordinating the multi-domain service deployment using the concept of Network Slice Subnet, where each subnet is provisioned in the target domain, with explicit indications about the geographical deployment of MEC Application Servers. The MDO coordinates the lifecycle management between the end-to-end Network Slice and its slice subnets, those provided by vMNOs' Network Slice Management Functions. Moreover, the MDO handles the on-boarding, advertisement and discovery of functions across the catalogues of the different domains and the translation of descriptors and interface messages supported by the NSMFs in each domain. These adaptation functionalities are critical to overcome the fragmentation of interfaces and information models of multi-vendor orchestrators and solve interoperability issues.

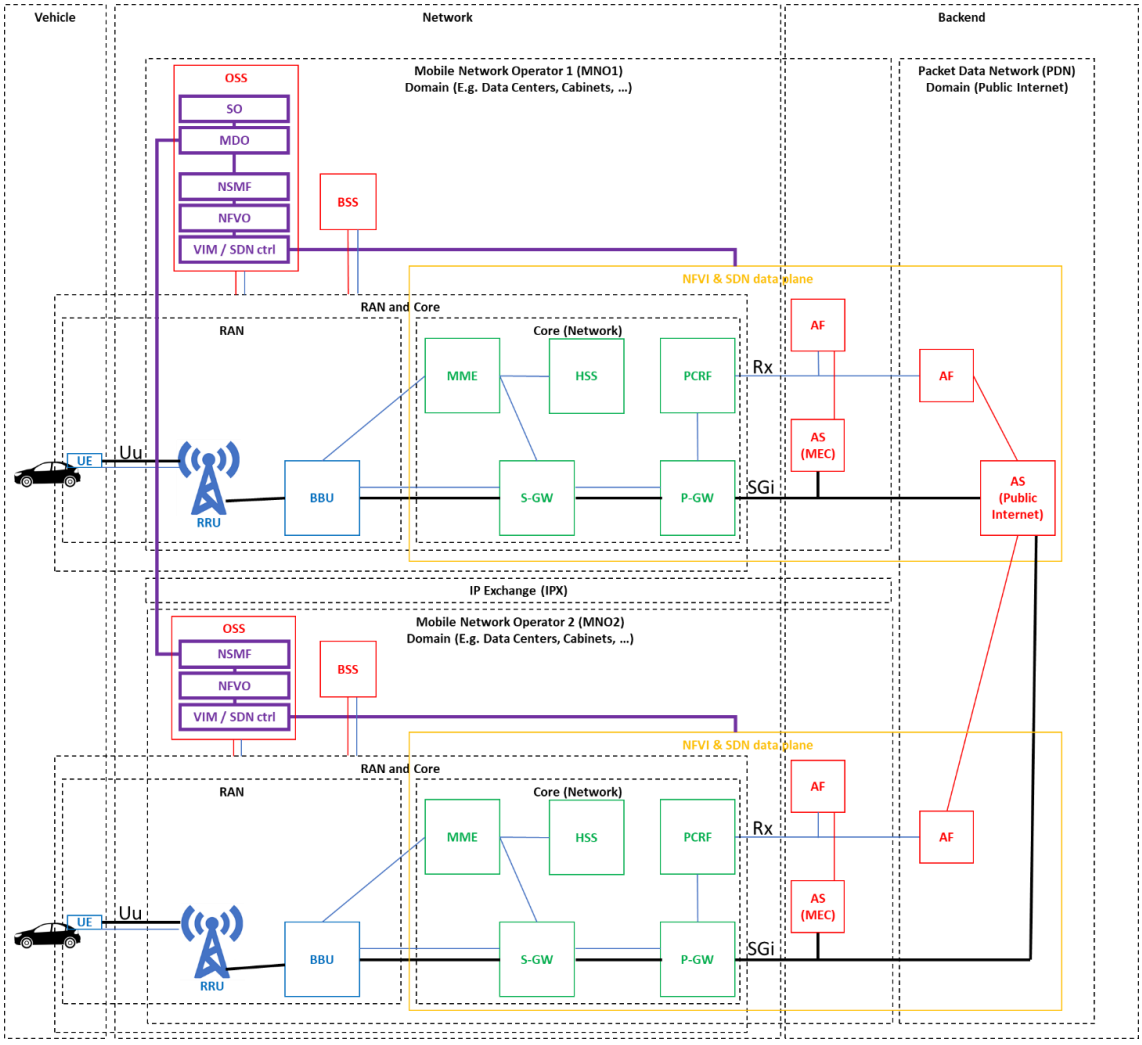

Figure 6-16: Multi-Domain Service Orchestration and Slice Management in 5GCroCo

6.5 5G Decentralized Marketplace

The ability to trade 5G resources (including radio and spectrum resources) across different domains enlarges the set of network resources and extends it to abstractions like services and slices, opening the door to a richer 5G business ecosystem [6-16].

The 5G Marketplace architecture [6-17] aims at facilitating multi-party collaboration in dynamic 5G environments where operators and service providers often need to employ 3rd party resources to satisfy a contract. To achieve this, resource providers make their resource offers available for

sharing by advertising them through the 5G Marketplace. In general terms, the proposed Marketplace enables the creation and acquisition of product offers that represent a variety of exposed telco digital assets. These offers include individual resources such as infrastructure components, VNFs and Cloud-Native Network Functions (CNFs); as well as composed bundles in the form of services and slices.

The 5G Marketplace leverages the use of DLT and Smart Contracts technologies to enable the trade of 5G resources. By leveraging a decentralized architecture, thus removing a single trusted entity, stakeholders converge on a mutual trust in the distributed state of the application. However, in addition to the foundational trust that underpins the marketplace, privacy, performance and the capability to implement the necessary business rules are fundamental enterprise requirements placed upon the supporting DLT infrastructure. Each Marketplace member will host a distributed application (DApp) that interfaces with their domain's DLT node, forming a peer-to-peer (P2P) network consortium.

A decentralized Catalogue of product offers and the subsequent trading of these resources is a key functional element of 5G Marketplace. Stakeholders only have sight of requests and all associated transactions and state on a need-to-know basis. Smart Contracts facilitate a trusted negotiation process between consumer, provider and– as needed – regulator, that aligns with agreed business rules through an eventual agreement. Subsequent management of the workflows for resource provisioning, set-up/teardown of SLA monitoring infrastructure, permissioned recording of SLA violations & licensing actions (e.g., scaleup/down), and ultimate teardown of service agreements and remuneration on completion of a contract is all automated thanks to Smart Contract execution.

5GZORRO Marketplace is ruled by Marketplace Administrators operating a decentralised Governance platform to take decisions according to a Marketplace Governance Model. A major Governance feature is the decentralized management of global (cross-domain) unique identifiers that are compliant with the emerging W3C DID Working Group [6-45].

To support the 5G Marketplace in the 5G Architecture a new set of functional elements would be required including a decentralized catalogue for 5G Resource offers and 5G Service offers, decentralized repository for legal prose statements to be used in smart contracts and the life-cycle management of smart contracts for offers and agreements between providers and consumers. See in the next sections, more details about these new 5G functionalities.

Architectural solution	5G PPP Project	Additional Reference
Resource / Service Trading	5GZORRO	[6-43]
Cross domain Identity & Permissions Management	5GZORRO	[6-17], [6-42]

6.5.1 Resource / Service Trading

The 5G Marketplace enables the trading of 5G resources (including Radio Spectrum resources) and services across different domains by using DLT Smart Contracts. Major Marketplace features are decentralized catalogues for 5G Resource offers and 5G Service offers, decentralized repository for legal prose statements to be used in smart contracts and the life-cycle management of smart contracts for offers and agreements between providers and consumers.

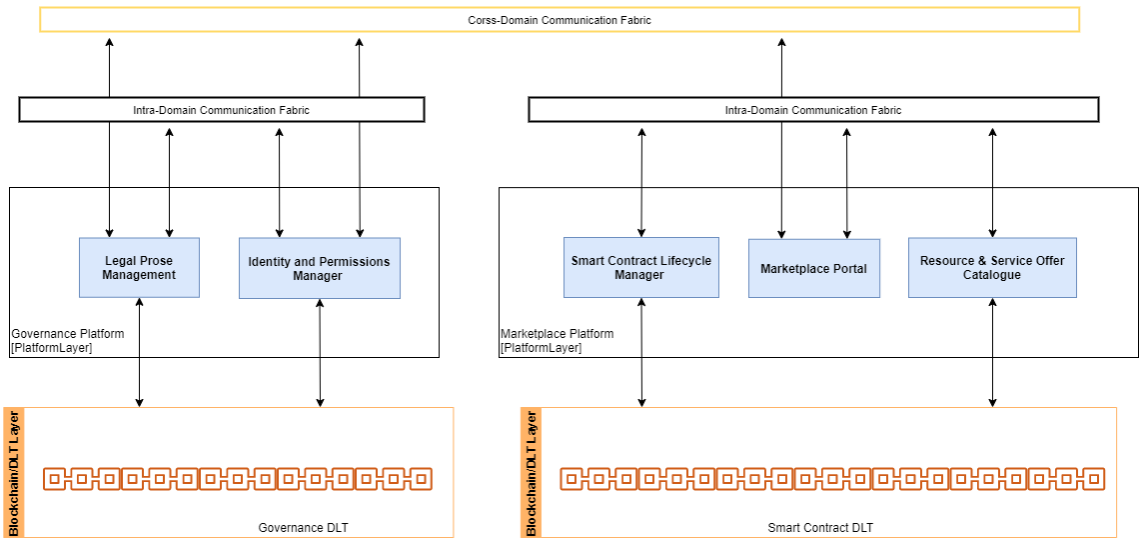

Figure 6-17: Marketplace Platform Architecture

- **Marketplace Portal**: Storefront for offer composition, searching and selection to enable a business-compliant and user-friendly offer design and display. Although a portal is provided for facilitating user access to the platform, supported services are exposed for programmable interaction between the Marketplace and other components of the 5G Architecture.
- **Resource and Service (Offer) Catalogue**: Portfolio of available (resource and service) digital assets and corresponding (product) offers for Marketplace parties to offer, discover, request and consume within the marketplace.
- **Smart Contracts Lifecycle Manager**: Key driver of how offers, SLAs and commercial agreements are autonomously created and processed through smart contracts. Integration with different DLTs implementation is supported through use of ledger-specific drivers in order to certify transactions ensuring transparency and trust among the participating stakeholders.
- **Communication Fabric**: Entity that takes care of the interoperation and communication between modules of the Marketplace Platform. Inspired by the ZSM architecture, this component facilitates the interaction among Marketplace services by playing both the roles of service consumer and service producer.
- **Governance Manager**: it provides functionalities to support a consortium governance model for 5GZORRO marketplace. In this way, decisions like admittance, revocation of membership and dispute resolution is managed in accordance with a mutually agreeable governance model.
- **Legal Prose Manager**: This element provides a shared repository of parameterised legal statement templates that can subsequently be associated with a given resource or service by providers. It is envisaged that such parameterised legal statement templates would be Verifiable Claims data schemas that are registered in the Governance DLT.
- **Identity and Permissions Manager**: it provides appropriate mechanisms to identify entities, services, resources, consumers, providers, and organizations, which allows decentralisation of the system without forgetting the security principles, a reliable authentication using DIDs, DID Documents, and Verifiable Credentials, and finally, a granular control access mechanism that standardises authorised access to data, resources, and services. These functionalities are more detailed in the following section.

Creating a commercial trading agreement between provider and consumer autonomously will be facilitated through smart contracts. Smart contracts ensure that an agreement and any associated

actions on that agreement are processed in accordance with the agreed terms by validating any transition of ledger state. What this means is that on entering into an agreement, whereby each party agrees terms and signs the transaction, from that point on there is a commercial agreement between the two legally identifiable entities backed by a legally enforceable contract (Ricardian Contract [6-46]).

Smart Contract templates will be developed to capture both the broader general terms of an agreement, and operational terms relating to a Service Level Objective (SLO), with specialized templates to serve the needs of each resource type to be traded as necessary. These templates will consist of parametrised legal prose to be utilised by stakeholders, crucially encapsulating real-world legally ratified contracts. Smart contract templates will give rise to legally enforceable smart contracts, but also the compelling improvement over existing working practices by standardising contract terms across all stakeholders.

Resource and service business meta-data will comprise concrete instantiations of these templates, producing a hierarchy of terms that outline the legal terms of the agreement, SLAs and their associated SLOs.

These agreements will be deployed and managed by a component that manages the lifecycle events of the contract. Smart Contracts will mirror that of the real-world contract and encapsulate logic to automate the calculation of SLA compliance. On deployment of the contract to the ledger, the autonomous set-up of monitoring and configuration of aggregation algorithms will be initiated by the Smart Contract Lifecycle Manager. During the course of the contract's lifetime, metrics can be posted to the smart contract by the monitoring aggregation service and at frequencies as agreed in the contract. Should a breach occur, the Smart Contract will enact any subsequent events, which might simply be to record the breach until such time that a threshold is reached or trigger the termination of the contract.

Smart contracts are ultimately providing autonomous near real-time execution of contract lifecycle stages, from creation, monitoring & SLA enforcement through to settlement, disbursement and finally termination.

6.5.2 Cross domain Identity & Permissions Management

Distributed trust models can allow network connections to be established between domains reliably, avoiding possible connections that could endanger user data integrity or compromise the security of service providers and end-users.

Key to the realisation of trust across domains is the use of decentralized identity management (DIdM), which is based on Decentralized Identifiers (DIDs).

DIDs are a novel type of identifiers proposed by W3C (https://www.w3.org/TR/did-core/) that allows associating any subjects such as stakeholders, resources, services, organizations, entities, and so on, with a digital identity. DIDs are global identifiers which enable verifiable and decentralized digital identity, allowing to uniquely identify any subject, e.g., a person, organization, abstract entities, etc. To achieve this purpose, DIDs are associated with cryptographic material, such as public keys, and service endpoints, making each DID globally unique, resolvable with high availability, and cryptographically verifiable.

The usage of DIDs provides to an application of self-administered identity management, enabling further self-managed capabilities such as authentication, authorization, role management, and identity information exchange between two identity domains.

Another concept related to DIdM is Verifiable Credentials. A Verifiable Credential (VC) [6-17] is a tamper-evident and privacy-preserving credential (set of claims) that can be demonstrated

through a cryptographic process. Verifiable Credentials can represent the same information that physical credentials represent in real life such as driving licenses, passports, health insurance card, and so on. Therefore, Verifiable Credentials represent statements made by an issuer in a tamper-evident and privacy-preserving manner.

The Identity Management is able to identify providers, consumers, services, resources, organizations, etc., using Decentralised Identifiers (DIDs) associated with DID Documents. DIDs are also used for authentication through Verifiable Credential linked to a DID Document. In the case of Permissions Management, this allows setting up a secure layer that regulates the access to resources, services, and delimited areas using a set of policies and rules. By means of policies and rules, each domain can determine the amount of information exposed, the duration for which that information is shared, what kind of information is shared, limiting resource capabilities, and so on. Therefore, each domain must define its policies and rules based on its criteria such as improving security, usability, availability, and cost-efficiency. In the end, Permissions Management attempts to prevent unauthorised access to services, resources, and data, making access control enforcement as granular as possible.

The Identity Management and Permissions Management functionalities are distributed across different domains in DID Agent Functionalities, securely communicating among each other by using P2P DID Communication protocols [6-45] and performing different DID Roles. Each DID Agent holds an Identity and Trust DLT Wallet. There are three main types of DID Agents:

- **Admin Issuer DID Agents** have functionalities to issue Verifiable Credentials associated with 5G Entities including Stakeholders Credentials and Marketplace Offers Credentials.
- **Holder DID Agents** communicate with Admin Agents to request the issue of Verifiable Credentials. Issued credentials are stored and maintained by the Holder DID Agent.
- **Verifier DID Agents** communicate with Holder DID Agents to request presentation proof of Verifiable Credentials.

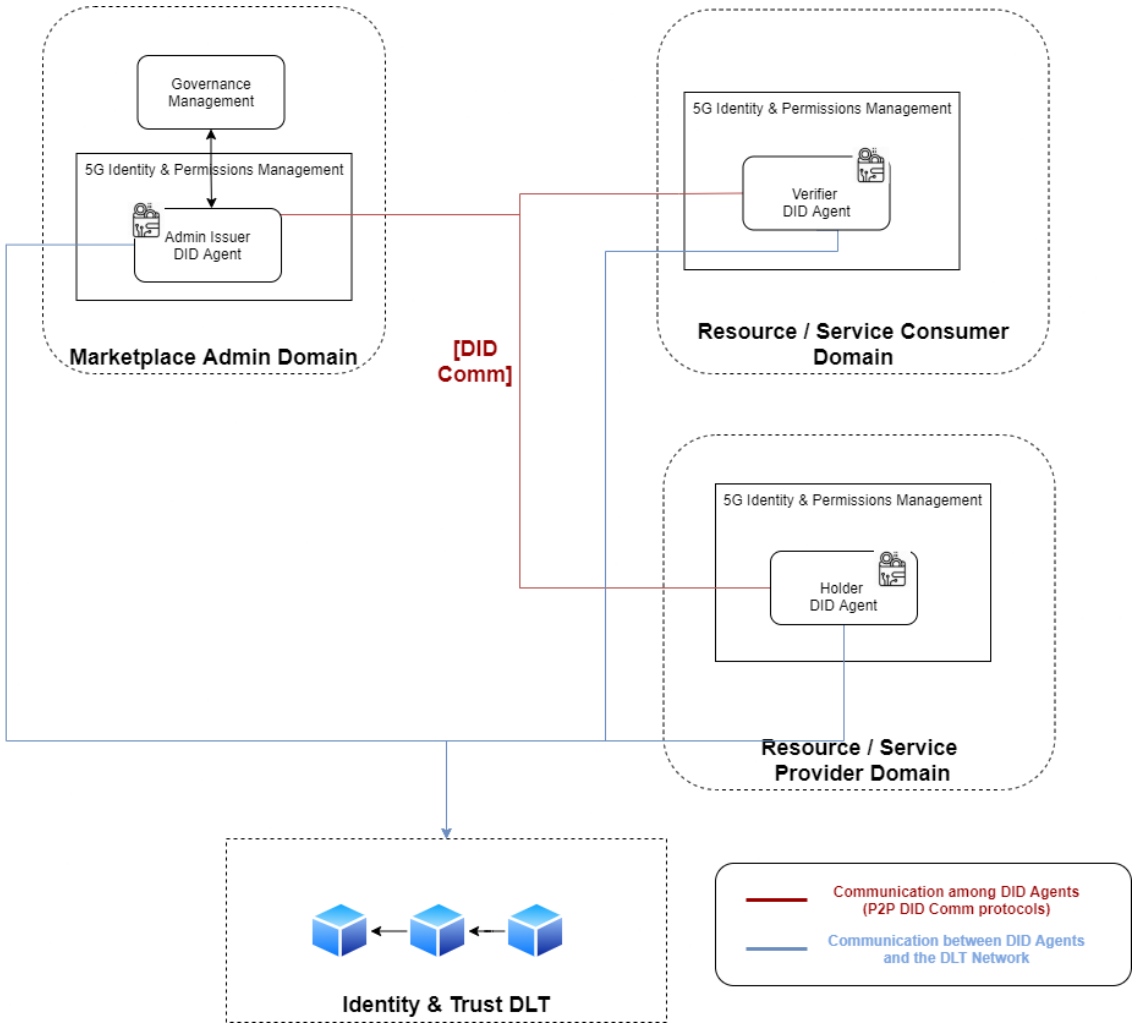

Figure 6-18: Identity & Permissions DID Agents distributed among different 5G domains

The Cross Domain 5G Identity and Permissions management framework potentially impacts all 5G cross-domain functionalities by supplying the mechanisms required for generating unique identifiers in 5G ecosystem, recognising communicating endpoints, identifying and authenticating entities, services, and organizations, and authorising consumer requests to access a preserved services and resources.

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7 Arch Instantiations and Validations

This chapter describes the way 5G PPP [7-1] projects instantiate their proposed network architectures to support vertical use cases based on 5G infrastructure. Particularly, three examples of the network architecture are introduced: i) end-to-end (E2E) network including multiple sites interworking; ii) service-based architecture to support vertical applications defined by SLAs (service-level agreements); iii) large scale deployment to cover a large number of tourists visiting historic places. This chapter also elaborates on performance evaluation from the E2E service perspective. As a promising solution to reduce the testing efforts of the 5G infrastructure and components, adoption of Testing-as-Service (TaaS) is investigated first. In addition, one network architecture for 5G KPIs validation or for service performance assessment is studied. Then, evaluation of the network slicing approaches is studied: i) a multi-slice UE in V2X networks, ii) dynamic E2E slicing, and iii) multiple E2E network slicing for video media service.

Architectural Solution	5GPPP Project	Additional Ref.
E2E Network of Multiple Sites Interworking	5G-VINNI	[7-2], [7-7], [7-8]
Service-based Architecture	FUDGE-5G	[7-9], [7-10]
Large Scale Deployment of 5G Infrastructure	5G-TOURS	[7-11]
E2E Service Validation	5GENESIS	[7-13], [7-14], [7-15], [7-16], [7-17]
Adoption of Testing-as-a-Service	5G-VINNI	[7-18]
5G SA with MEC in multi-slice UE	5G-HEART	[7-20], [7-21], [7-22]
Dynamic E2E service slicing	FUDGE-5G	[7-9], [7-23]
VNF based UHFM Video broadcasting and on demand delivery service	5G-SOLUTIONS	[7-25], [7-26]

7.1 Architecture Instantiation

7.1.1 E2E Network of Multiple Sites Interworking

Figure 7-1 depicts a high-level view of the conceptual E2E facility architecture and highlights the key elements. The various building blocks are organized in three layers: the Resources and Functional Level, the Service Level, and the Network Level as defined in the 5G PPP Architecture white paper [7-3]. The Resources and Functional Level of the E2E facility are comprised of the Radio Access Network (RAN), Backhaul, Mobile Core and Cloud Computing facilities. The Resources and Functional Level provides the physical resources to host the Service Level and Network Level elements such as the Virtual Network Functions (VNFs). These are interconnected to build dedicated logical networks, customized to support services, such as eMBB, URLLC and mMTC.

This modularity guarantees the highest degree of freedom of facility site configurations as well as of E2E facility interworking. Any Service Level or Network Level VNF from any facility site can be included within the logical network of another facility site. This creates an unbounded capability to implement and test use cases using the consolidated shared capabilities of all facilities, rather than limiting them to the capabilities of individual sites.

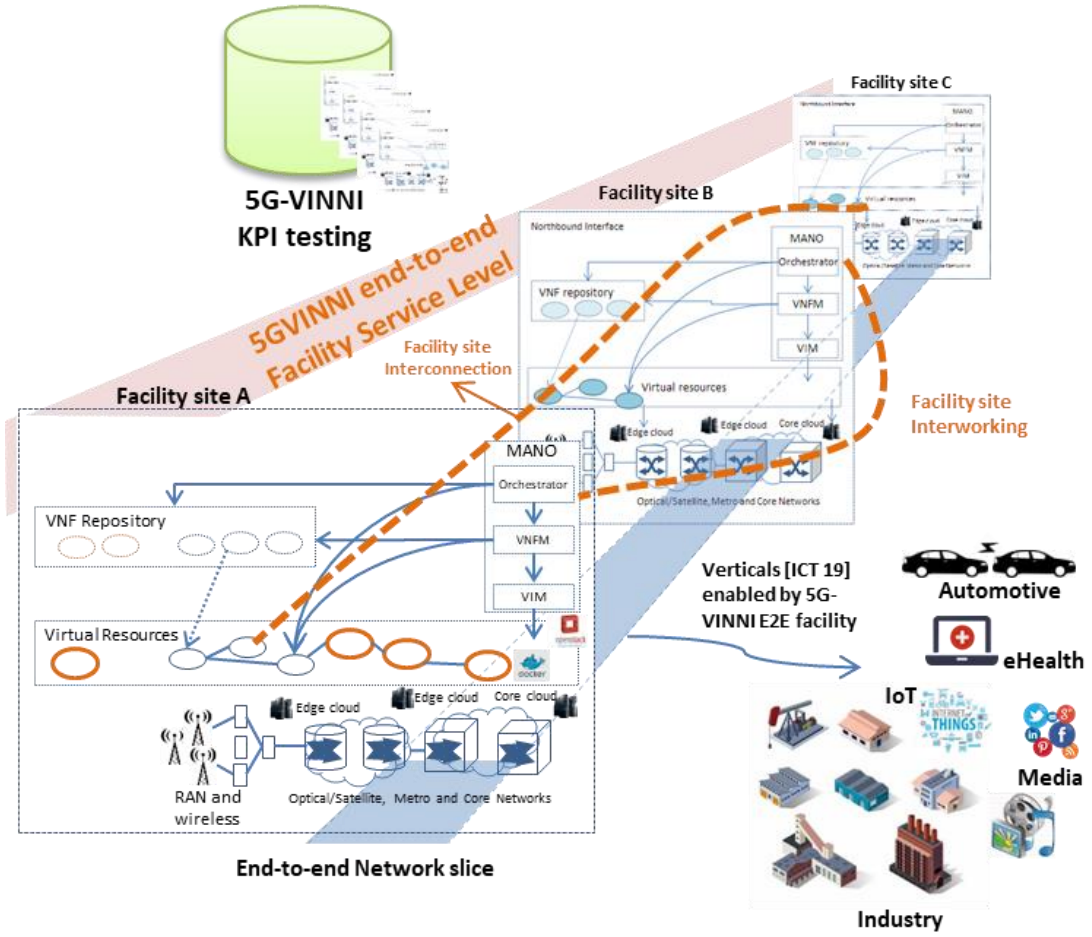

Figure 7-1: 5G-VINNI [7-2] E2E Network including multiple sites interworking

Due to the diversity of use cases and possible configurations, an agile open deployment framework must be adopted. Some scenarios may be confined to a single administrative domain. In this case, the distribution of the various building blocks may take place at the same or at different sites that are interworking. In contrast, in a multi-administrative-domain scenario multiple administrative authorities interact with each other, each one of them adopting possibly different implementations of common building blocks. From the viewpoint of the Network Level, network elements residing in different cloud sites or domains must be made agnostic to their network location. This introduces the concept of facility interworking that facilitates seamless deployment of services independent of location or domain authorities. From the viewpoint of the Services Layer, each facility site may encompass different components' implementations, e.g. Openstack Virtual Infrastructure Manger (VIM) [7-4] vs. Open Source MANO [7-5], OpenVIM, or ETSIs Open Source MANO implementation vs. Open Baton [7-6].

The requirements derived from the diversity of the use cases and possible configurations introduce a whole new set of intra- and inter-domain interworking issues. Their resolution is currently being addressed in various SDOs and there is a pressing need for harmonization and validation under realistic conditions. The Service Level E2E Facility is the reference environment in which this validation can take place, using agreed test plans.

The Service Level E2E Facility is an implementation of the Network and Service Management and Orchestration Plane defined in the 5G Architecture. Key aspects of this layer are the Network Capability Exposure function and the service orchestration functions: the E2E Service Management and Orchestration function and the Service Domain Orchestrator. The Network Capability Exposure function is critical for the utilization of the facility by vertical use cases.

Without effective exposure of network capabilities to vertical industry customers, the advance service capabilities offered by 5G networks has little or no value. Network capabilities are not limited to the capabilities that a single operator's infrastructure provides. Following the 5G PPP concept of recursion, a single service communication service provider's capability may consist of capabilities assembled from the services offered by other service providers. In these cases, the E2E Service Management and Orchestration function plays an instrumental role, transparently orchestrating the service life-cycle management across multiple service providers for a capability exposed as a service by a single service provider.

7.1.2 Service-based Architecture

The FUDGE-5G project [7-9] takes a holistic approach for instantiating its service-based architecture in an NFV-enabled (and if available SDN-enabled switching fabric) infrastructure combined with a 5G-VINNI RAN solely focusing on Non-Public Networks (NPNs). FUDGE-5G implements service routing and resource scheduling of the communication between 5G Core (5GC) Network Functions (NFs), cloud native orchestration of 5GC NFs and their monitoring for lifecycle management purposes inside their platform layer, as illustrated in Figure 7-2.

The platform is provisioned entirely as VNFs. Enterprise services such as 5G Core and vertical applications are then orchestrated via RESTful and service-centric Application Programming Interfaces (APIs) offered by the platform. It is worth noting that the infrastructure layer (in particular the Network Function Virtualisation orchestrator (NFVO) is not involved in the provisioning of any enterprise service. This layered concept is illustrated in Figure 7-2 where the platform layer functionality implements the Service-based Architecture (SBA) functionalities.

The provisioning of FUDGE-5G's SBA platform will be conducted over a range of NFVOs such as OpenStack, OpenShift and Azure across five different use cases (and ten trials in total). The open source ARDENT (Agnostic platfoRm DEploymeNt orchesTrator) [7-10] is being used for abstracting the various NFVO APIs and offers the required automation to allow the automated generation of NFVO resource descriptors. ARDENT can be conceptually seen as an extension to the technologies Open Network Automation Platform (ONAP) or Open Source Mano (OSM) that is slotted in between the NFVO and the VNF owners (i.e., the SBA platform).

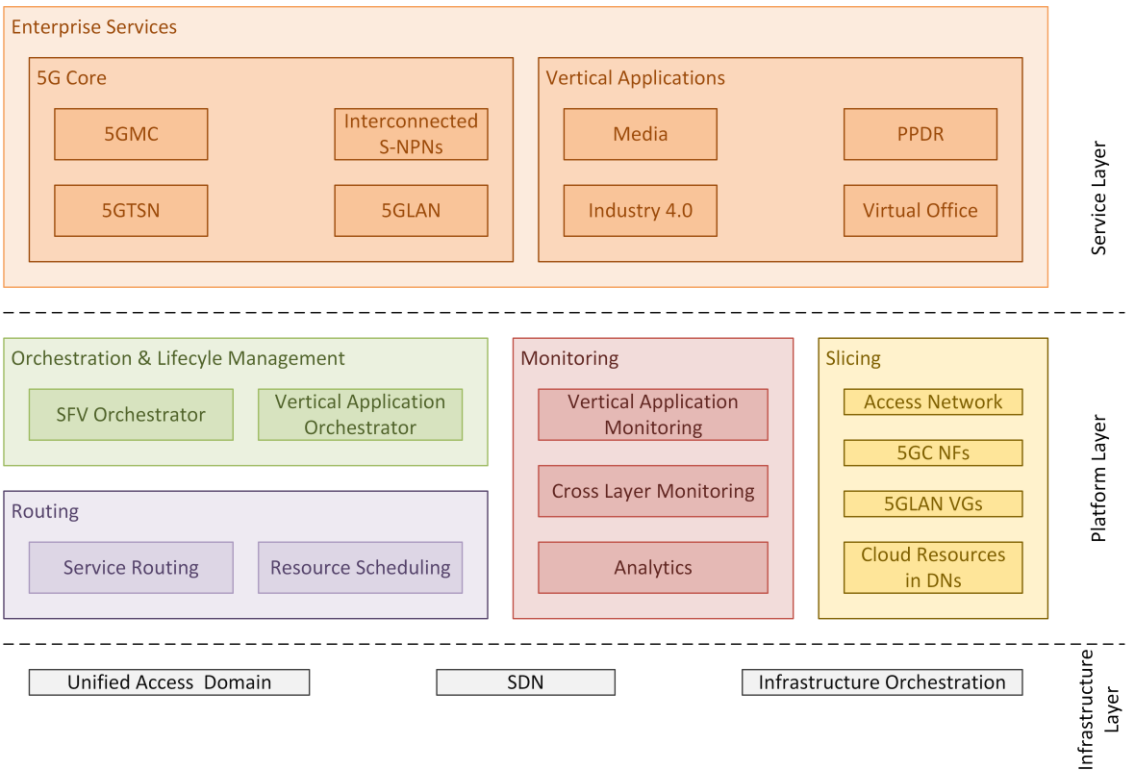

Figure 7-2: High-level system components of FUDGE-5G

7.1.3 Large Scale Deployment of 5G Infrastructure

The 5G-TOURS project [7-11] for Touristic City trial in Turin, Italy, is composed of a series of use cases aimed to support innovative user experiences which require the superior performance of 5G Networks in order to provide an improved touristic experience. By using one of the partner's commercial network, the 5G-TOURS network solution has been deployed based on the NSA Option 3 architecture [7-12] in which the RAN is composed of a LTE layer as "anchor layer" (working at 1800 MHz with 20 MHz bandwidth) and a 5G layer as secondary layer (working at 3.7 GHz with 80 MHz bandwidth); in this architecture LTE provides the control plane function while LTE and NR are used for the data plane. The RAN is then connected to the same EPC used for the other network operator customers. From the implementation perspective, the radio solution identified for the 5G indoor coverage is the Ericsson Radio 4422 with the Kathrein 80010922 antenna; in order to provide a stable coverage for the requested rooms, the solution consists of 4 different radio installations mounted on ad-hoc built pole and allows the mounting of all required components in terms of radio, antenna (two antennas for each radio), power supply and cabling (optical fiber and RF). To avoid any impact to the cultural value of the site, the optical fiber reaching each indoor radio units was laid using the available ducts infrastructure of the building that are already used for the electrical, fan coil and LAN provisioning.

Figure 7-3 shows the installations in Sala Quattro Stagioni and Sala Acaja of the Palazzo Madama Museum for the 5G indoor coverage and the rooftop antenna that provides the 5G outdoor coverage (camouflaged in a fake chimney). Based on this deployment, the 5G indoor coverage of Palazzo Madama consists of 4 different cells referred as V1, V2, V3 and V4 shown in Figure 7-4 (V1 and V3 for the ground floor and V2 and V4 for the first floor). The baseband unit for the 5G indoor coverage is the Ericsson Baseband 6630 located in the network exchange point (Torino Centrale) located 2.8 km far from Palazzo Madama. In order to provide the 5G fronthauling connection (based on Common Public Radio Interface) between the radio units inside Palazzo Madama and the baseband in Torino Centrale, an ad-hoc optical fiber connection has been

installed consisting of 8 couples of fibers of which 4 couples has been used to connect the 4 Radio 4422, 1 couple to provide broadband Internet connection for the use case's servers that will be installed at the museum and 3 spare couples as backup and/or future development of the 5G indoor coverage. The LTE anchor layer of the 5G indoor coverage is provided by the two outdoor LTE commercial sites that cover Palazzo Madama named Torino Pietro Micca and Piazza Castello; in particular, through a signal measurement campaign, Torino Pietro Micca site was identified as the anchor for the 5G indoor cells V1 and V2 while Torino Piazza Castello as the anchor for V3 and V4. For the 5G outdoor coverage, the Torino Pietro Micca site has been extended to provide a co-site 5G cell through the installation of an Ericsson Baseband 6630 and an Advanced Antenna System (AAS) Ericsson AIR 6488. Providing 5G connectivity into public places, such as the museums in the touristic city entails several challenges related to the setup of the wireless connectivity and the densification of the access point, handling the densification of the access points. More details are available in [7-11].

Figure 7-3: Installation for 5G indoor coverage in Sala Quattro Stagioni and Sala Acaja and rooftop antenna for the 5G outdoor coverage

Figure 7-4: Deployment of 5G-TOURS network solution at Palazzo Madama

7.2 Network Architecture Validation

7.2.1 E2E Service Validation

The 5GENESIS project [7-13] Facility provides a complete toolset to experimenters who wish to make use of 5G platforms either for 5G KPIs validation or for performance assessment of their services running on top of 5G. The three key layers of the experimentation facility are depicted in Figure 7-5.

From the performance validation perspective, the Coordination Layer is the one that interacts with the experimenter. Practically, the 5GENESIS Coordination Layer defines an entry point of a MANO (management and orchestration) building block, through a MANO Wrapper that i) manages all the experimentation requests in the Coordinator layer, and ii) performs the needed operations before a Network Slice can be deployed in the Infrastructure. All these procedures have been released as part of the open5GENESIS suite [7-14].

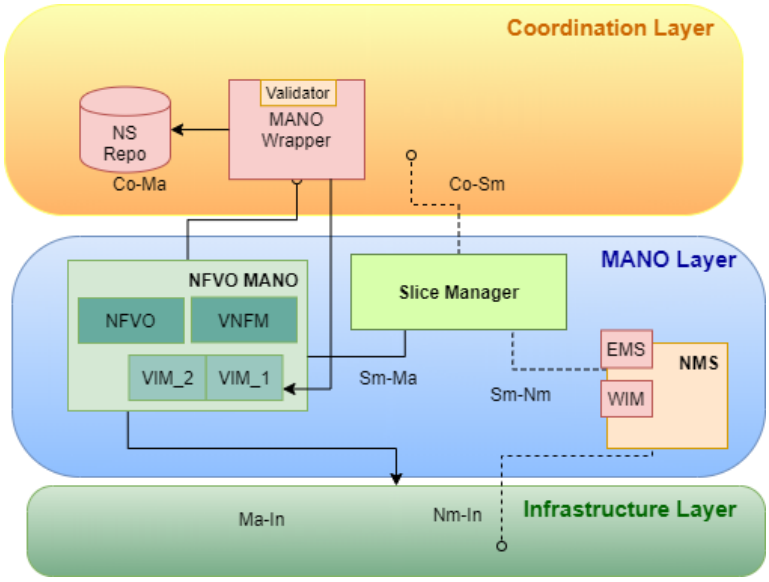

Figure 7-5: Three Layer architecture in 5GENESIS facility

Focusing on the experimentation process the 5GENESIS facility provides:

- **ELCM:** The Experiment Lifecycle Manager (ELCM) oversees the execution of an experiment from the start until the end of the experiment. The ELCM is able to receive execution requests generated by the 5GENESIS Portal in the form of the experiment descriptor and is able to perform the execution of multiple experiments in parallel. By sending requests to the Slice Manager's REST API the ELCM is able to instantiate the network services required by the experiment, and decommission them once the execution finishes, freeing the resources for other experiments. More information about the development and functionality of this component is provided in [7-15].
- **PORTAL**: The 5GENESIS web Portal allows the definition of experiments that can be executed in the 5GENESIS Platform, and the visualization of the most important results of an execution. The Portal provides a web-based user interface that experimenters interact with in order to define and execute experiments in the 5GENESIS Platforms. The Portal also allows experimenters to view a selection of the most relevant results generated by their experiments in the form of custom Grafana dashboards. An Open API is embedded as part of the Portal and the ELCM, which makes the communication between these two components direct. More information about the Portal can be seen in [7-16]. An experimenter/vertical has two options for performing an experiment:

  - Through the 5GENESIS GUI (Graphic User Interface)/Portal, where the experiment descriptor is automatically generated and sent to the dispatcher (ideal for E2E KPI assessment)
  - Directly via the 5GENESIS open API, allowing the experimenter to use the facility with its own scripts (ideal for validation of a new component or service).
- **DISPATCHER** The Dispatcher module obtains the experiment descriptor from the Portal, initiates the validation of the descriptor and sends the experimentation plan to the scheduler that enqueues the execution until all necessary resources are available. Once the MANO Layer confirms that the required resources are available then the execution of the experiment starts. The Dispatcher is also able to send part of an experiment descriptor to a Dispatcher on another 5GENESIS Platform for distributed execution of experiments. Upon availability of the resources the Slice manager creates the requested E2E network slice instance allowing the multi-tenant use of the facility by different experimenters. The created network slice instance crosses all the components of infrastructure, starting from the Core NFVI (Network Function Virtualization Infrastructure), the transport network, the Edge, the RAT and finally the UEs.
- **MONITORING AND ANALYTICS:** The analytics module performs the analysis of the raw data generated during an experiment execution, performing the calculation of the KPIs of the experiment. Several probes have been developed and integrated, as well as scripts for processing the results provided by these probes. More information about these probes is available in [7-17].

7.2.2 Adoption of Testing-as-a-Service

By using the Testing-as-a-Service (TaaS) principle, a testing system can be implemented for KPI validation of individual test facility sites as well as the E2E facility. At the same time TaaS facilitates the exposure of the test platform to vertical industry experimenters to enable test campaign design and execution. Figure 7-6 shows an example of an TaaS architecture [7-18].

OpenTAP [7-19] is an open-source test tool developed by KeySight. It allows for the experimenter to define test cases and establish test campaigns to be executed toward the System Under Test (SUT) by using the Test Case Editor and Test Campaign Manager. The SUT interfaces with the TaaS environment through the Execution Function. OpenTAP is implemented as a Kubernetes cluster of microservices, with external execution environments dedicated to each facility site. Test campaigns are initiated towards the sites' Service Orchestrator and NFVO.

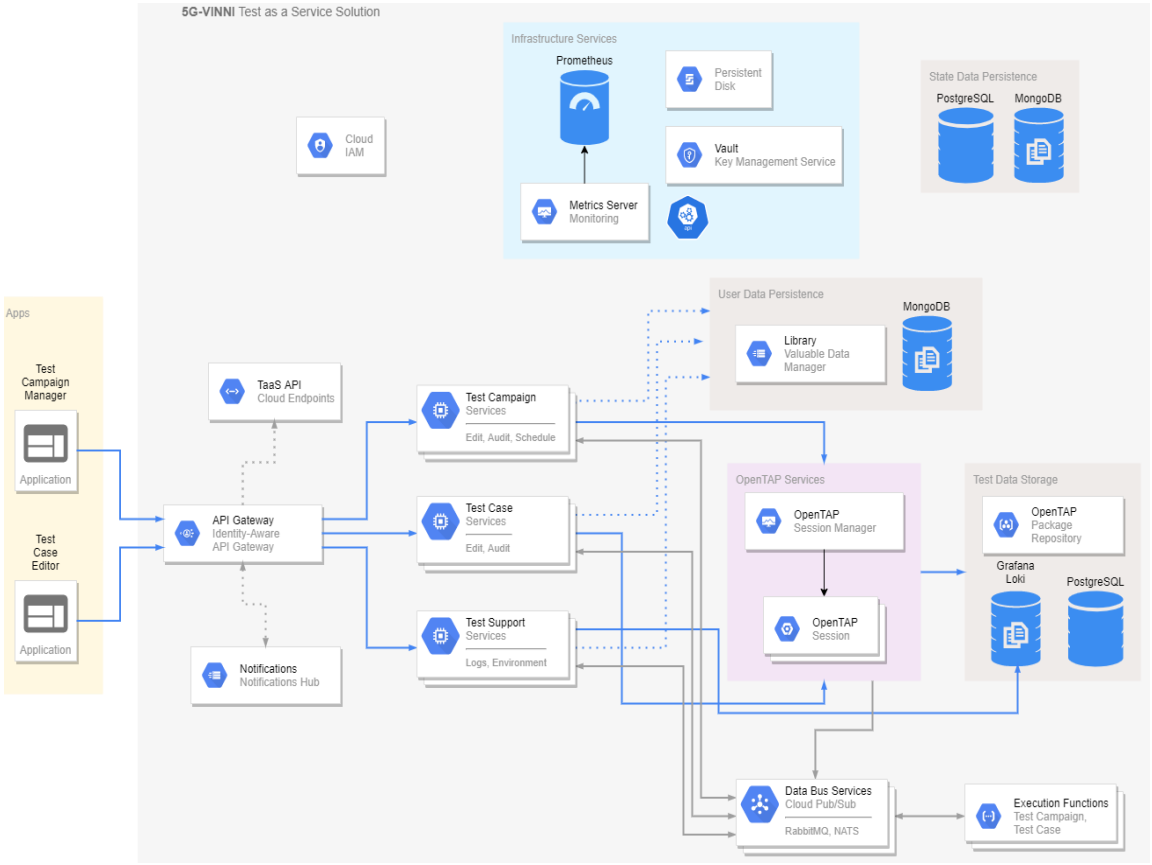

Figure 7-6: An example of Testing-as-a-Service implementation

The components of TaaS architecture illustrated in Figure 7-6 are described in Table 7-1.

Table 7-1: TaaS Architecture description

Domain	Services	Description
Apps	Test Campaign Manager, Test Case Editor	The Apps allow the user to manage the lifecycle of the Test Campaigns, and perform detailed editing of the individual Test Cases
	TaaS API	Exposure of API for external programmatic consumption of the TaaS services
	Notifications	Notification hub for aggregating the notifications from all the internal services and forward them to the user in a multi-channel way (UI notifications, slack, email)
	API Gateway	Identity-aware border protection for the system. It allows to decouple the internal services from the user interaction
Test Campaign	Edit, Audit, Schedule	The domain manages the lifecycle of the Test Campaigns, from creation, to execution management, to availability and reachability of results
Test Case	Edit, Audit	The domain manages the lifecycle of the Test Cases, from creation, to execution management, to availability and reachability of results

Test Support	Logs, Environment	The domain contains support services, in particular the management of Test Environments, and Logging of the Test Cases execution
OpenTAP Services	Session Manager, Sessions	The domain contains the OpenTAP automation support that is the core of the system
Data Bus Services	RabbitMQ, NATS	The buses are used for internal notifications and distributed test logging
User Data Persistence	Library, MongoDB	The domain takes care of storing and serving valuable user data (e.g., Test Cases, Test Campaigns)
Test Data Storage	Package Repository, Loki, PostgreSQL	The domain contains all the needed data for performing tests and the results of it.
Execution Functions	Test Campaign and Test Case Execution	The domain is bounded to the execution of all the test objects. They are implemented with a similar concept as Lambda functions, but designed for on-prem use
State Data Persistence	PostgreSQL, MongoDB	The domain provides stateful persistence of all the objects and microservice states (they are all implemented as stateless)
	Cloud IAM	Authentication and Authorization provider
Infrastructure Services	Logs, Metrics, Certificate Management, Credential rotation	Set of services provided by Kubernetes or other Open-Source components for solidifying the foundation infrastructure of the business application

7.2.3 5G SA with MEC for a multi-slice UE

In 5G-HEART [7-20], we have improved the 5G network infrastructure in the Netherlands (5Groningen [7-21]) by deploying a new experimental edge computing site (Hoogezand) and further developing an existing one (Helmond).

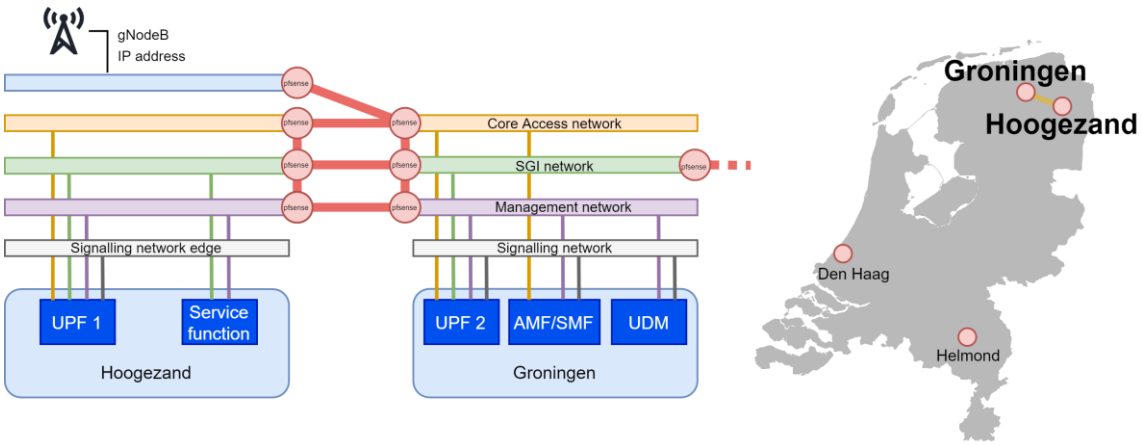

Figure 7-7: Networking within the Groningen-Hoogezand cloud

Hoogezand has servers with good computation capabilities, including a GPU (graphics processing unit) for heavy matrix computations such as computer vision algorithms. The servers are managed through VIO (VMware Integrated OpenStack) and are connected to another location in Groningen. Both locations are managed as a single cloud, with each location being a different availability zone. The locations are interconnected through a VPN (virtual private network). On top of that, the core access networks, SGI networks, and management networks of each availability zone are bridged together, providing connectivity between the locations seamlessly for the VMs, see Figure 7-7.

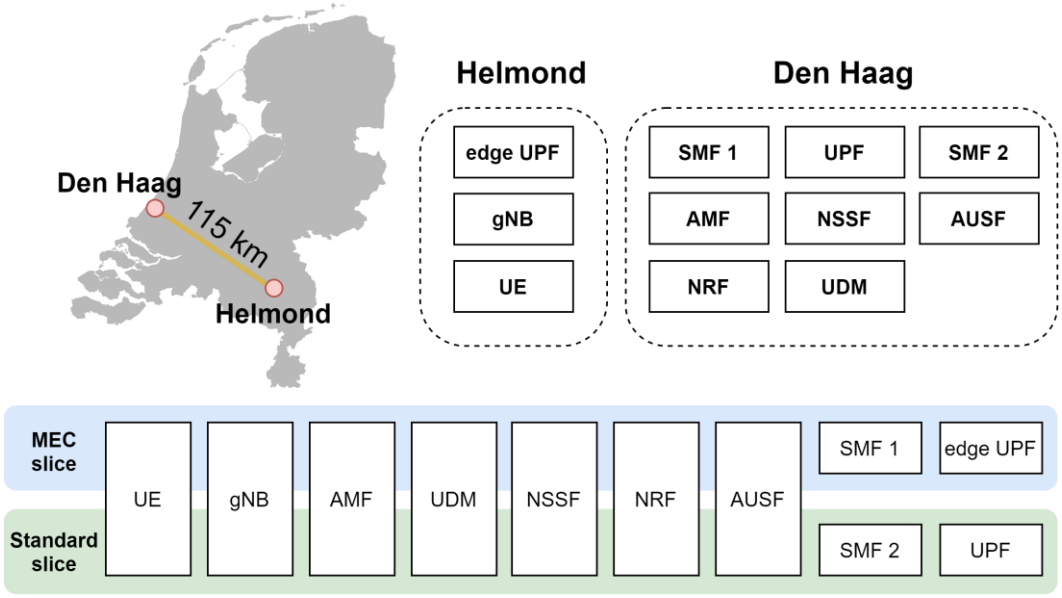

Figure 7-8: Configurations of multi-slice UE in 5G SA with MEC

The 5G SA setup illustrated in Figure 7-8 corresponds to the Helmond setup, and it has been evaluated in a real-world scenario using several slices simultaneously, one of them with mobile edge computing (MEC), in the context of vehicular communication. The 5G SA-enabled UE is placed on board of a vehicle and can connect to two slices in the core network simultaneously where each slice has a separate SMF (session management function) and UPF (user plane function). One of the UPFs is located in an edge server next to the antenna while the other UPF is located together with the rest of the core network. The edge slice is used for vehicular communication (e.g., for road/traffic information exchange) while the other slice is used for general internet traffic (e.g., for entertainment by human users). Testing shows that the MEC slice has less latency than the centrally routed traffic slice, which is an expected result. The details of initial experiments can be found in [7-22].

For the core network, we use an open-source core network (Open5GS). In this setup, the different core functions are deployed as services on several VMs in two different clouds (Den Haag and Helmond) connected via VPN. In Den Haag, two separate VMs are in use, one of them contains the central database and the other contains all the control plane function and a UPF. In Helmond, two VMs are in use also, one of them holds the edge UPF while the other works as an edge application server. For the radio configuration we use an Ericsson 4422 gNB with 5G SA and 5G NSA capabilities.

7.2.4 Dynamic E2E Service Slicing

Generally speaking, slicing is the ability to isolate and enforce QoS for a set of predefined resources. These resources can be physical resources (access to a medium either wired or wireless), networking resources (throughput, latency), cloud resources (compute, memory, storage) or

functional resources (service availability, responsiveness, etc.). What becomes apparent from the holistic view on the E2E communication between UEs and services hosted in Data Networks (DN) is that a 5G system has full control over resources on the 3GPP access network and the user plane within the communication domain under control of the 5G Core (5GC). However, any resources within the DN are not captured in the current 5G QoS enforcement domain except input by an Application Function (AF) on steering traffic to a specific application. FUDGE-5G [7-9] takes a holistic approach studying the opportunities for an SBA vision on the control and user plane to address these boundaries through an orchestration component within the platform layer that targets the service provisioning and lifecycle management and control of enterprise services, i.e. 5GC Network Functions (NF) and vertical applications, as illustrated in Figure 7-2. While changes to how slices are requested and instantiated by UEs and 5GCs in a more dynamic ad-hoc fashion are impossible to reduce to practise in the planned five trials due to the fact that modem implementations cannot be changed by the project, FUDGE-5G utilises the concept of 5GLAN Virtual Groups (VGs) by implementing and demonstrating this 3GPP Release 16 concept allowing the logical grouping of UEs into the same Local Area Network (LAN) domain using a dedicated 5GLAN VG manager.

In addition to demonstrating and validating the 5GLAN concept, FUDGE-5G offers a service routing capability at platform layer implementing the Service Communication Proxy (SCP) functionality, as introduced in 3GPP Release 15. The Name-based Routing (NbR) technology [7-23], one of the three official SCP deployment options [7-24], routes traffic between 5GC consumers and producers based on their HTTP header information (mainly FQDN and URI) instead of using the IP address resolved by an DNS server. This allows the logical isolation (aka slicing) between two independent 5GCs or a pinning of consumer and producer communication to a subset of instances of a core triggered by UE slice requests. As FUDGE-5G's SCP operates at the granularity of HTTP transactions (request/response equals one completed transaction), the decision which consumers and producer instances are logically grouped can be controlled and changed transparently to the 5GC NFs for each new HTTP request a consumer issues. This concept will be demonstrated and validated in FUDGE-5G as part of the proposed holistic dynamic slicing approach.

7.2.5 VNF based UHFM Video broadcasting and on demand delivery service

In order to test the potential of producing and distributing UHFM (Ultra High-Fidelity Media) over emerging 5G networks, current and upcoming applications, content and services will be provided to the 5G-SOLUTIONS project [7-25] University of Patras (UOP) 5G-VINNI testbed. In addition, a set of comprehensive scenarios will be defined so to provide meaningful outcomes to analyze technological, application and business aspects. The main aim is to measure latency in a wide range of experiments using caching services running as a shared network service. Additionally, quality guarantee services, density and mobility issues will be tested as well. The key objective is to test unicast distribution of linear content to concurrent users stressing 5G radio and network capabilities. This could be supported by the setup of specific QoS/SLA requirements under a network slicing approach. Relevant service classes: eMBB, eMTC [7-26].

Specifically, E2E network slices are composed of multiple Network Slice Subnet Instances (NSSI), which generally correspond to the RAN, Edge and Cloud Technological Domains (TD). Resource policies applied to each NSSI and its *horizontal stitching* (i.e., logical interconnection) realise the concept of an E2E network slice. Currently, Edge and Cloud TD can be easily stitched together and provide system resources according to a determined policy. Moreover, given the maturity of specifications and tools used at these TD (e.g. IEEE networking standards, OpenStack) an administrator may easily embed specific configuration into NFV descriptor files

at the NFV orchestrator [7-27]. Nevertheless, the integration of the RAN TD into this picture is still under development.

Despite leveraging state-of-the-art open source and industry tools for 5G infrastructure (e.g., OpenStack, NetData, Prometheus, Amarisoft CallBox), lacking the ability to concurrently execute multiple E2E network slices forces service owners to think about alternative ways for implementation. Such alternatives should *emulate* a real E2E 5G infrastructure in a way which could easily be *ported* to the final infrastructure once the aforementioned limitations are circumvented. The following list gathers features not being able to be implemented given current infrastructure limitations.

Table 7-2: Infrastructure limitations and Features not implemented

Use case	Test goal	Limitations
Ultra-High-Fidelity media	• Automatically setup live streaming at orchestration time. • Ensure system resources via network slices. • Leverage SNMP for remote controlling encoders.	None. Current tools allow the configuration of all TD, yielding the collection of resources needed for the successful implementation.

The challenge of emulating a virtual CDN (vCDN) with a limited set of nodes and clients (vCDN nodes and UEs, respectively) can be achieved. Given the focus is to analyse how content should be distributed among vCDN nodes in order to reduce latency for users, slices' resources can well be emulated leveraging a Platform as a Service (PaaS) as a Container Infrastructure System Instance (CISI), which could easily be ported to 5G-VINNI. Such PaaS may contain the necessary scenario to emulate content distribution, resources and user behaviour.

In Figure 7.9, an OSS/BSS (Operations Support System/Business Support System) emulating an orchestration request can deploy a set of emulated vCDN nodes running on top of a Platform as a Service (PaaS). An in-slice software component, referred to as Scenario Manager in the figure proceeds to distribute subsets of a global content Library to such nodes. Later, random user requests following commonly used distributions (e.g., Zipf, Normal) are directed toward the vCDN deployment, which are then load-balanced among vCDN nodes. Failed requests, successful hit counts (content requests matched at local vCDN node) and required content pulls (from higher vCDN hierarchy, i.e., cloud) are gathered and analysed. Based on such analysis different content replacement strategies (i.e., Least Recently Used (LRU), Windowed-LRU) are applied in order to minimize the accumulated waiting time (i.e., due to failed cache) for a determined distribution of Users and requests. In summary, such scenario leverages cloud-native tools and recently standardized NFV objects (i.e., Kubernetes and PaaS via NFV IFA 029, respectively) to emulate and develop new strategies for increasing caching efficiency in common 5G multimedia scenarios.

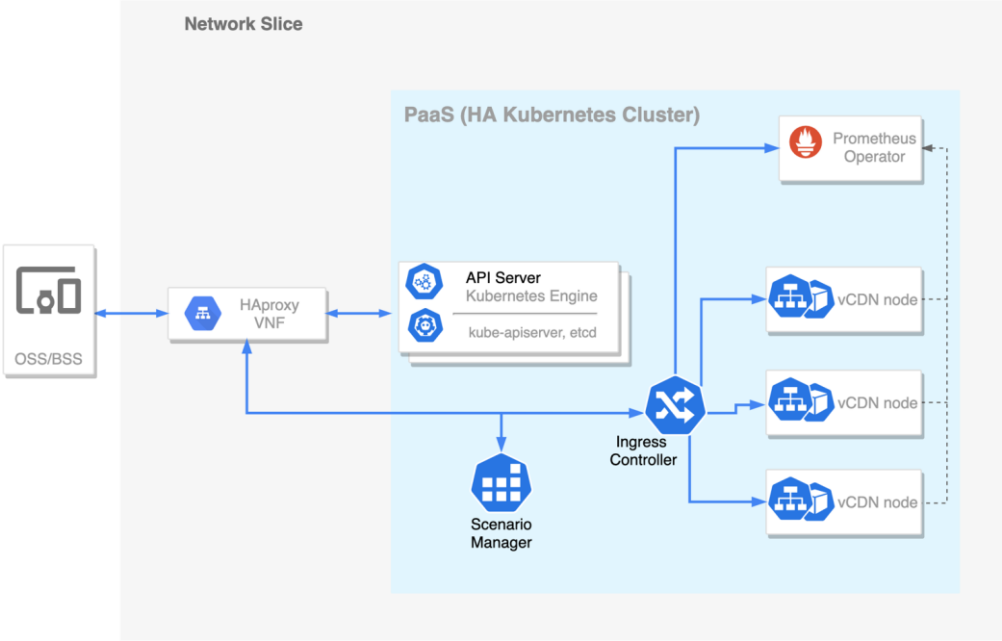

Figure 7.9: CDN emulation leveraging PaaS

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8 Conclusions and Outlook

In this document, the current architectural trends and technology components for the 5G system (5GS) have been presented in a very important transition phase, where the 5G is gaining market share due to the already significant availability of both deployments and terminals. Nevertheless, the research work is already discussing the beyond 5G technologies, as a fundamental intermediate step needed to shape the next generation of wireless and mobile communications system, namely 6G.

This white paper has been divided into three main technological domains (Access, Core, and Management and Orchestration-MANO), and three transversal ones (Overall Architecture, Cross Domain, and Architectural Instantiation), to capture all dimensions of the 5GPPP Projects, Research, and Standardization works. In each of them, outstanding trends can be found which will likely have a direct impact on the deployment of current technologies that will steer the research trends during the next few years. Throughout the white paper, various aspects have been analysed, such as the new stakeholders model, which is especially important in the context of the Non Public Network (NPN), and the availability of the Service Layer to support Vertical Operations.

Another area that is gaining a lot of traction is the edge and extreme edge technologies for the radio access, with solutions based on reconfigurable intelligent surfaces (RIS) and THz bands that are promising superior performance for ultra-reliable and low latency communications (URLLC). Solutions based on those approaches are hence creating new requirements for the cloudified environments.

Managing such heterogenous landscape (with novel aspects such as 5G LAN or multicast delivery) certainly requires novel functionality in the MANO as discussed herein, e.g., network automation based on Artificial Intelligence (AI) and Machine Learning (ML) are experiencing a vast adoption and will be the starting point for the next generation network. This includes also aspects related to network slicing management (over different infrastructure deployments), monitoring, and the roaming aspects.

Finally, in this white paper, projects' efforts in bringing the technology into practice have been illustrated, validating the promises of enhanced KPIs and offering to verticals the availability of the first trials for the 5G-empowered NetApps.

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