Distributed Artificial Intelligence-driven open and programmable architecture for 6G networks

D2.3 Requirements, use cases and system architecture

Document Summary Information

Project Identifier	HORIZON-JU-SNS-2022. Project 101095363	**Acronym**	ADROIT6G
Full Title	Distributed Artificial Intelligence-driven open and programmable architecture for 6G networks		
Start Date	01.01.2023	**Duration**	36 months
Project URL	https://adroit6g.eu/		
Deliverable	D2.3: Requirements, use cases and system architecture		
Work Package	WP2: Requirements, use cases and system architecture		
Contractual due date	31/10/2024	**Actual submission date**	28/01/2024

Co-funded by the European Union 6GSNS

'ADROIT6G project has received funding from the Smart Networks and Services Joint Undertaking (SNS JU) under the European Union's Horizon Europe research and innovation programme under Grand Agreement No 101095363. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.'

Type	Report	**Dissemination Level**	Public
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Revision history (including peer reviewing & quality control)

Version	**Issue Date**	**% Complete**	**Changes**	**Contributor(s)**
V1.0	30/05/2024	5%	Initial Table of Contents	John Vardakas (IQU)
V1.2	31/08/2024	50%	Contributions to chapters 3, 7 and 8	All partners
V1.3	31/10/2024	90%	Contributions to chapters 4, 5, 6	John Vardakas (IQU), Marius Iordache (ORO), Giacomo Bernini (NXW)
V1.5	30/11/2024	95%	Contributions to chapters 1, 2, 9	John Vardakas (IQU)
V1.9	21/01/2025	97%	Refinements after review and final version	John Vardakas (IQU)
V1.95	24/01/2025	99%	Quality Review	Rafaella Elia (eBOS)
V2.0		100%	Submitted Version – End deliverable creation process	John Vardakas (IQU)

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Glossary of terms and abbreviations

Abbreviation / Term	Description
aaS	as a Service
AE	Analytic Engine
AI	Artificial Intelligence
AF	Application Function
API	Application Programming Interface
AR	Augmented Reality
B2B	Business-to-Business
B2C	Business-to-Consumer
B2B2X	Business-to-Business and various intermediaries or partners
BDIx	Belief-Desire-Intention eXtended
CaaS	Cloud-as-a-Service
CAPEX	Capital expenditure
CI/CD	Continuous Integration and Continuous Deployment
CN	Core Network
CSH	Computing and Storage Hub
CSP	Computational & Storage Powerhouse
CSMF	Communication Service Management Function
CP	Control Plane
D	Deliverable
D2D	Device to Device
DCS	Device-to-Control Station
DAI	Distributed Artificial Intelligence

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DE	Decision Engine
DM	Decision-Making
DRL	Deep Reinforcement Learning
eMBB	Enhanced Mobile Broadband
E2E	End-to-End
ESG	Environmental, Sustainability, and Governance
ETCS	European Train Control System
ETSI	European Telecommunications Standards Institute
EU	European Union
FCAPS	Fault, Configuration, Accounting, Performance and Security
FL	Federated Learning
GA	Grand Agreement
GNSS	Global Navigation Satellite Systems
GNN	Graph Neural Network
GPU	Graphics Processing Unit
GSM-R	Global System for Mobile Communications – Railway
HIPAA	Health Insurance Portability and Accountability Act
IM	Information Model
IoT	Internet of Things
KPI	Key Performance Indicator
KPI	Key Performance Indicator
KVI	Key Value Indicator
KVIs	Key Value Indicators
LTE	Long Term Evolution

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M	Month
mBS	miniaturized Base Station
M&O	Management & Orchestration
MQTT	Message Queuing Telemetry Transport
MST	Minimum-weight Spanning Tree
MEC	Mobile Edge Computing
ML	Machine Learning
mMTC	Massive Machine-Type Communications
MR	Mixed Reality
NFV	Network function Virtualization
NR	New Radio
NTN	Non-terrestrial Networks
NWDAF	Network data analytics function
NSMF	Network Slice Management Function
NSSMF	Network Slice Subnet Management Function
OPEX	Operating expense
PoC	Proof of Concept
QCI	QoS Class Identifier
QoE	Quality of Experience
QoS	Quality of Service
RACI	Responsible, Accountable, Consulted and Informed
RAN	Radio Access Network
RAT	Radio Access Technology
REST	Representational State Transfer

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RF	Radio Frequency
RIT	Radio Interface
RL	Reinforcement Learning
SBA	Service-Based Architecture
SBMA	Service-Based-Management Architecture
SOCCER	Service Orchestrator in Continuum of Cloud and Edge Resources
SDUs	Service Data Units
SIL	Service Interlocking
SLAs	Service Level Agreements
SNS	Smart Networks and Services
SRIT	Set of Radio Interface
SUT	System Under Test
UAVs	Unmanned Aerial Vehicles
UC	Use case
UE-VBS	User Equipment as Virtual Base Station
UML	Unified Modelling Language
UPF	User Plane Function
URLL	Ultra-Reliable Low-Latency
UWB	Ultra-Wideband
VBS	Virtual Base Stations
VDT	Virtual Data Tunnel
VR	Virtual Reality
WLAN	Wireless LAN
WP	Work Package
XR	Extended Reality

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Executive Summary

ADROIT6G proposes a set of groundbreaking innovations with a sharp vision for establishing a 6G network architecture designed to meet the specific requirements of next-generation applications and achieve the ambitious KPIs defined for 6G networks. In particular, the key advancements identified by ADROIT6G as crucial for 6G network evolution include: i) leveraging AI/ML-driven optimizations throughout the network by exploring solutions in the "Distributed Artificial Intelligence (DAI)" space to enhance performance and enable automation; ii) transitioning to a fully cloud-native network software architecture, deployable across diverse edge-cloud platforms with built-in security embedded within the network's user layer; and iii) enabling software-driven, zero-touch operations, with the ultimate goal of fully automating all aspects of network functionality and service delivery.

ADROIT6G's network architecture evolves the existing 5G architecture, by adopting a fully distributed and dynamic paradigm, with functional elements automatically deployed on demand as virtual functions in cloud-native environments across multiple network domains, operated by different stakeholders. The proposed network architecture consists of three main frameworks: the AI-driven Management and Orchestration Framework, the Fully distributed and secure AI/ML Framework for CrowdSourcing AI Framework, the BDI- & AI-driven Unified & Open Control Operations Framework. The key features of these frameworks have been presented in ADROIT6G's deliverable D2.2. In the current deliverable, the description of the ADROIT6G architecture has been updated to further define the functionalities of the AI/ML Framework to fully support Crowdsourcing functionalities essential to creating a distributed ecosystem for the lifecycle of AI/ML services. In parallel, D2.3 provides a detailed description of the interfaces among the various building blocks of each ADROIT6G framework, as well as the externally exposed interfaces for inter-framework operations.

In more detail, deliverable D2.3 is the last deliverable of ADROIT6G's WP2, targeting to provide the final set of specifications of the ADROIT6G architecture and its main frameworks. To this end, Section 2 provides the description of the ADROIT6G architecture, highlighting the updates compared to the description provided in ADROIT6G's previous deliverable D2.2.

Section 3 is a key part of the deliverable, focusing on the presentation of the internal component communications of the three ADROIT6G architectural frameworks, i.e., the Management and Orchestration, AI/ML, and Control Operations frameworks. The information provided in this section includes details on the communication protocols utilized within the frameworks, as well as the interfaces for inter-framework operations.

Additionally, in Section 4, we outline the ADROIT6G physical infrastructure, detailing the Far-Edge, Edge, and Cloud domains. The Far-Edge domain of ADROIT6G employs innovative approaches aimed at transforming end-user devices into integral components of the 6G network infrastructure, capable of real-time decision-making. Simultaneously, the Edge domain focuses on bringing processing closer to data sources to reduce latency, improve service delivery, and create a seamless bridge between Far-Edge devices and Cloud providers. In this context, satellite communication and computing are examined to explore the potential of various satellite topologies for enhanced coverage and support of low-latency applications.

Section 5 discusses the main standards that are considered in the ADROIT6G architecture, focusing on the closed-loop automation through ETSI Zero touch network and Service Management, on

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autonomous network operation through the TM forum, as well as on Non-Terrestrial Networks (NTNs) through 3GPP's NTN-related working groups.

Section 6 provides the details for the ADROIT6G testing and verification methodology for the verification of the ADROIT6G architectural components, which considers a Test-Driven Development (TDD) approach. The considered approach provides general guidelines for managing the datasets utilized in the project, detailing how they can be treated by stakeholders within the identified application environments.

Section 7 provides a detailed presentation of the Key Performance Indicators (KPIs) and Key Value Indicators (KVIs), by presenting the way the final set of the considered KPIs and KVIs and how the considered values determine the phase of the ADROIT6G innovation and how they will be validated through the ADROIT6G POCs.

Finally, Section 8 provides a detailed description of the PoC experiments and validations of the technology solutions that will be developed by ADROIT6G. Specifically, 3 PoCs are described: PoC1 is about holographic teaching, PoC2 is about rail automation supported by non-terrestrial networks, and, PoC 3 is about collaborative construction robots. For each ADROIT6G PoC, this deliverable provides the functional and the non-functional requirements and specifications, as well as the considered validation criteria and metrics, which will considered for the implementation of each PoC under the framework of WP5.

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1 Introduction

This ADROIT6G deliverable reports on the WP2 activities for the requirements, use cases and system architecture until M22 of the project. These activities concentrate on the final definition of the main architectural frameworks of ADROIT6G, the considered interfaces among the building blocks of each framework and among the frameworks, the considered standards, the testing and verification methodology, the physical network infrastructure domains, the ADROIT6G PoCs, and the methodology for achieving the objectives of the ADROIT6G POCs by considering the defined KPIs and KVIs.

1.1 Mapping ADROIT6G Outputs

This section presents the ADROIT6G's Grand Agreement (GA) commitments, as extracted from the formal deliverable and task description, with respect to their outputs and work to be performed, as described in Table 1-1.

Table 1-1. Adherence to ADROIT6G's GA deliverable & tasks descriptions

ADROIT6G GA Component Title	ADROIT6G GA Component Outline	Respective Document Chapter(s)	Justification
DELIVERABLE D2.2			
D2.3: System Architecture – Final	This deliverable will provide the final approach on the ADROIT6G network architecture, from the perceptive of the interfaces among the building blocks of each framework and among the frameworks	Section 2 & Section 3 & Section 4 & Section 5 & Section 6 & Section 7 & Section 8	This deliverable presents final definition of the main architectural frameworks of ADROIT6G, the considered interfaces among the building blocks of each framework and among the frameworks, the considered standards, the testing and verification methodology, the physical network infrastructure domains, the ADROIT6G PoCs, and the methodology for achieving the objectives of the ADROIT6G POCs by considering the defined KPIs and KVIs
TASKS			
Task 2.1: Requirements'	The aim of this task is to lay the foundations for subsequent development work in the respective	Section 6 &	This deliverable provides a final description of the ADROIT6G PoCs. The deliverable also

analysis and use cases refinement	WPs and tasks. A use case stakeholders' requirement elicitation will be conducted in detail by CYENS, SIEMENS and CAFA to discover in the proposed extreme 6G use cases what the market expects to be offered by 6G networks in terms of extreme eMBB, extreme URLLC and extreme mMTC connectivity and functionalities. A wide range of technologies, methods, algorithmic schemes and models, standardisation initiatives, etc., relevant to the project will then be examined by the technological partners (ATH, CYENS, CNIT, EURE, OULU, IQU, NXW), the network equipment vendors (MLNX, SIEMENS), the testbed providers (ATH, EBOS, EURE, ORO, SIEMENS) and the telecom operators (ORO, NOVA) to make sure that the outcomes comply with the use case stakeholders' expectations and requirements. The identified requirements will then be analysed and mapped to functional requirements of the system, defined in a way to fully service the use case scenarios that have been defined in task T2.1. A comprehensive set of requirements contributed by the technological partners, equipment vendors, testbed providers, telecom operators and the use case stakeholders will be available by month M05 and serve as basis for the architecture design and technical requirements definition of the ADROIT6G system. A user-driven requirement analysis will continue till M22 of the project to ensure an iterative user-centric design and improvements. (Output: D2.1, D2.2, D2.3).	Section 8	describes how these innovative architectural elements will work in synergy to achieve the selected UCs as well as the functional and the non-functional requirements and specifications, and the considered validation criteria and metrics. For the later, the considered testing and verification methodology is presented in detail.
Task 2.2: KPIs/KVIs definition and evaluation	The aim of this task is to capture the requirements from the extreme use case stakeholders (CYENS, SIEMENS and CAFA), including the articulation of detailed usability and performance requirements needs, as well as relevant	Section 3	This deliverable provides an final description of 6G network-level KPIs and KVIs implied within the ADROIT6G architecture context, by extending the aims, and goals of KPIs/KVIs framework that

methodology	target technological network-level and application-level KPIs and KVIs, contributed by all consortium partners, which will be validated through the extreme use cases in the PoCs. This task will be divided into two key sub tasks: (a) systematic compilation of current use cases features and needs (b) requirements analysis. The performance characteristics of 6G networks to be able to serve the needs of such extreme use cases will be mapped to specific target KPI values in terms of throughput, bandwidth, latency, density, reliability, efficiency, energy efficiency, positioning accuracy, QoE, etc., as well as societal KVIs, which will set the baseline for conducting the measurements during the system validation in WP5. For evaluating the KVIs both consortium members as well as external stakeholders will be individually incentivised (e.g., with vouchers, coupons, etc.) to participate through questionnaires, interviews, focused groups surveys, etc., to provide their feedback on the expected societal impact. The evaluation methodology will also be detailed so that there would be a clear direction during the validations on the exact procedure to be followed to meet the target KPIs and KVIs to the highest possible degree, acknowledging the ambitious performance improvements of 1-2 orders of magnitude with respect to 5G KPIs. Finally, this task will define the results benchmarking methodology which will include real-time visualisation (e.g., via Grafana) and analytics processes that will be applied to the time series data of test results. The KPIs and KVIs will be fine-tuned in this task based on the impact assessment applied to the PoCs. (Output: D2.1, D2.2, D2.3)		were analyzed in previous ADROIT6G deliverables D2.1 and D2.2.
Task 2.3: Platform	This task will leverage the functional requirements analysed in T2.1 to derive	Section 2	The deliverable provides the final description of the ADROIT6G

architecture design and technical requirements	the technical requirements that are necessary to design and implement the various components of the ADROIT6G architecture and system. The task also focuses on producing the detailed low-level modular software architectural design of the ADROIT6G system, which involves: (a) the far edge, edge and cloud domains, (b) the AI-driven Management & Orchestration Framework, (c) BDIx & AI-driven Unified & Open Control Framework, and (d) the Fully distributed and secure AI/ML Framework for CrowdSourcing AI. This task will articulate the detailed design of the modules and frameworks and identify the proper technologies, software tools, AI models and datasets, including 8 Associated with document Ref. Ares(2022)7772618 - 10/11/2022 Project: 101095363 — ADROIT6G — HORIZON-JU-SNS-2022 the relevant interfaces for their development, integration, security, and privacy considerations. The output of this task will be used by the respective tasks of WP3 and WP4 to enable the development of the ADROIT6G system. (Output: D2.1, D2.2, D2.3)	& Section 3 & Section 4 & Section 7	architecture, through the presentation of its main frameworks, as well as the interfaces among these frameworks and among the building blocks of each framework. In addition, the deliverable also presents the ADROIT6G physical infrastructure, by providing details on the Far-Edge, and the Edge domains.
Task 2.4: Testing & verification methodology	This task will define the methodology for a comprehensive and robust testing and verification of ADROIT6G architectural components and enabling technologies in the PoCs in close collaboration with the use case partners (CYENS, SIEMENS, CAFA). The methodology will also cover resource scaling, cross-domain interaction and the entire ADROIT6G system functionality validation testing. The test process will fit neatly into the project's iterative agile development process and allow for the implementation of a Test-Driven Development methodology co-prepared by the use case partners, incorporating unit tests and acceptance tests. Moreover, interfaces in the use cases will be identified, described, and	Section 6	This deliverable provides a detailed description of the testing and evaluation methodology that is considered in ADROIT6G by providing general guidelines for managing the datasets utilized in the project, detailing how they can be treated by stakeholders within the identified application environments.

	feed to use case partners to ensure smooth integration. (Output: D2.1, D2.2, D2.3)		

1.2 Deliverable Overview and Report Structure

Section 2 provides the overall description of the final version of the ADROIT6G architecture. Section 3 discusses the interfaces among the multiple blocks of each one of the ADROIT6G frameworks as well as of the ADROIT6G closed-loop functions. Section 4 provides the description of the ADROIT6G physical infrastructure, while Section 5 discusses the relevant standards. Section 6 discusses the testing and verification methodology. Finally, Section 7 provides the definition of the relevant KPIs and KVIs per PoC, while Section 8 provides the definition of the ADROIT6G PoC, through the description of the functional and non-functional requirements and specifications.

Table 1-2Table 1-2 provides the relation of this D2.3 deliverable to the other project's output.

Table 1-2. Links to other project's outputs/ work

WP #	Task #	Deliverable No related	Content
WP2	T2.1 - T2.4	D2.1	D2.1 serves as a foundational document for D2.2 and D2.3, offering initial set of extreme 6G use cases, an initial design of the ADROIT6G conceptual architecture, a well-defined set of 6G network-level KPIs and KVIs, and an overview of the testing and validation procedure that will be followed.
WP2	T2.1 - T2.4	D2.2	D2.2 serves as the intermediate document between D2.1 and D2.2, providing the

2 Definition of the ADROIT6G Architecture

In Deliverable D2.2, the initial version of the ADROIT6G architecture has been presented, by defining the functionalities of its three main frameworks, as depicted in Figure 2-1: the *AI-driven Management and Orchestration Framework*, the *Fully distributed and secure AI/ML Framework for CrowdSourcing AI Framework*, and the *BDI- & AI-driven Unified & Open Control Operations Framework*. In addition, D2.2 also defines the *Closed-Loop Functions* approach of the ADROIT6G solution. These four blocks work in synergy to create a sophisticated and dynamic 6G network ecosystem able to achieve the ambitious goals set for 6G, ensuring the realization of a future-ready 6G network landscape.

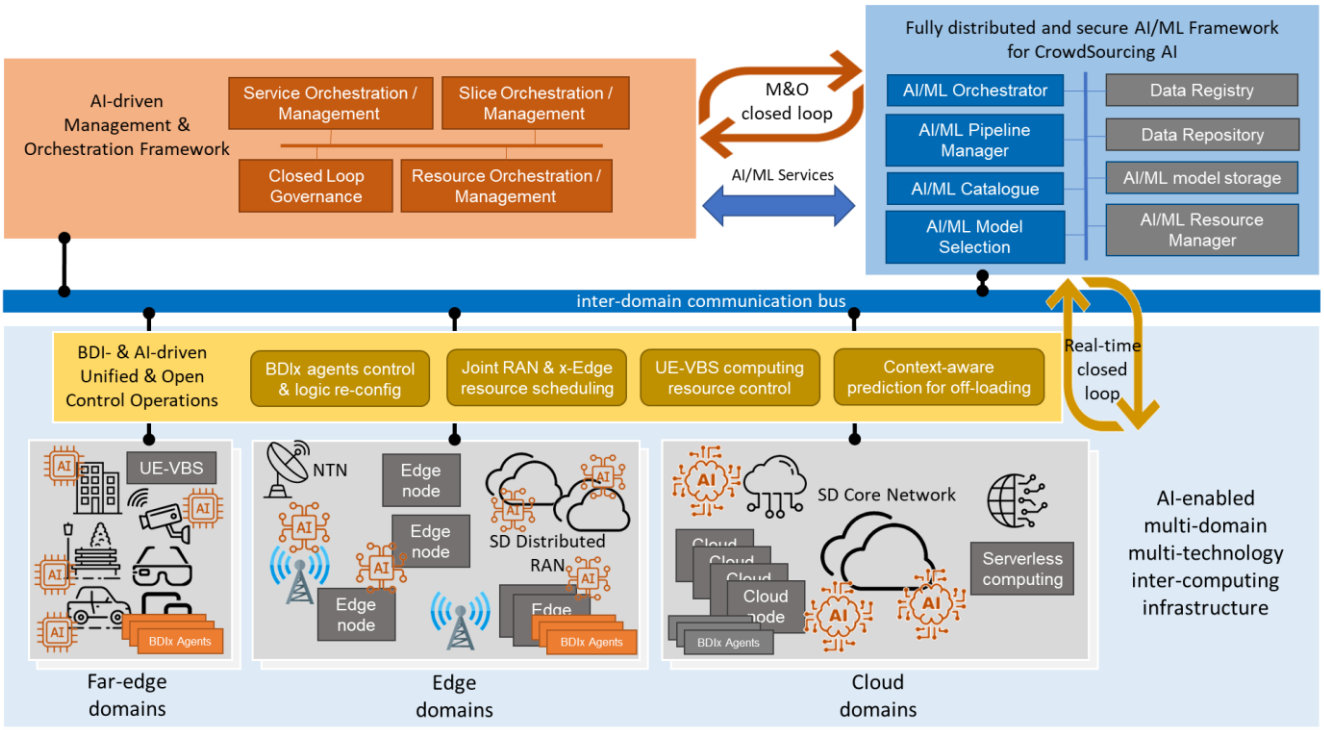

Figure 2-1. Initial version of the ADROIT6G architecture.

The architecture presented in D2.2 has been updated to describe the functionalities of the AI/ML Framework to fully support Crowdsourcing functionalities essential to creating a distributed ecosystem for the lifecycle of AI/ML services. Specifically, the framework architecture is broken-down into a set of functional blocks, containing a mix of both innovative and State of The Art elements, where the AI/ML Orchestrator serves as the central component within the AI/ML Framework for CrowdSourcing AI, as depicted in Figure 2-2.

Detailed explanations of each framework and their roles within the ADROIT6G architecture are provided in the next subsection, while also details on the interfaces among the blocks of each framework, as well as among the frameworks of the ADROIT6G architecture are provided in Section 3.

2.1 The final ADROIT6G architecture

The ADROIT6G architecture consists of the three main frameworks, as well as of the closed loop functions. The description of these frameworks is provided in the subsequent subsections.

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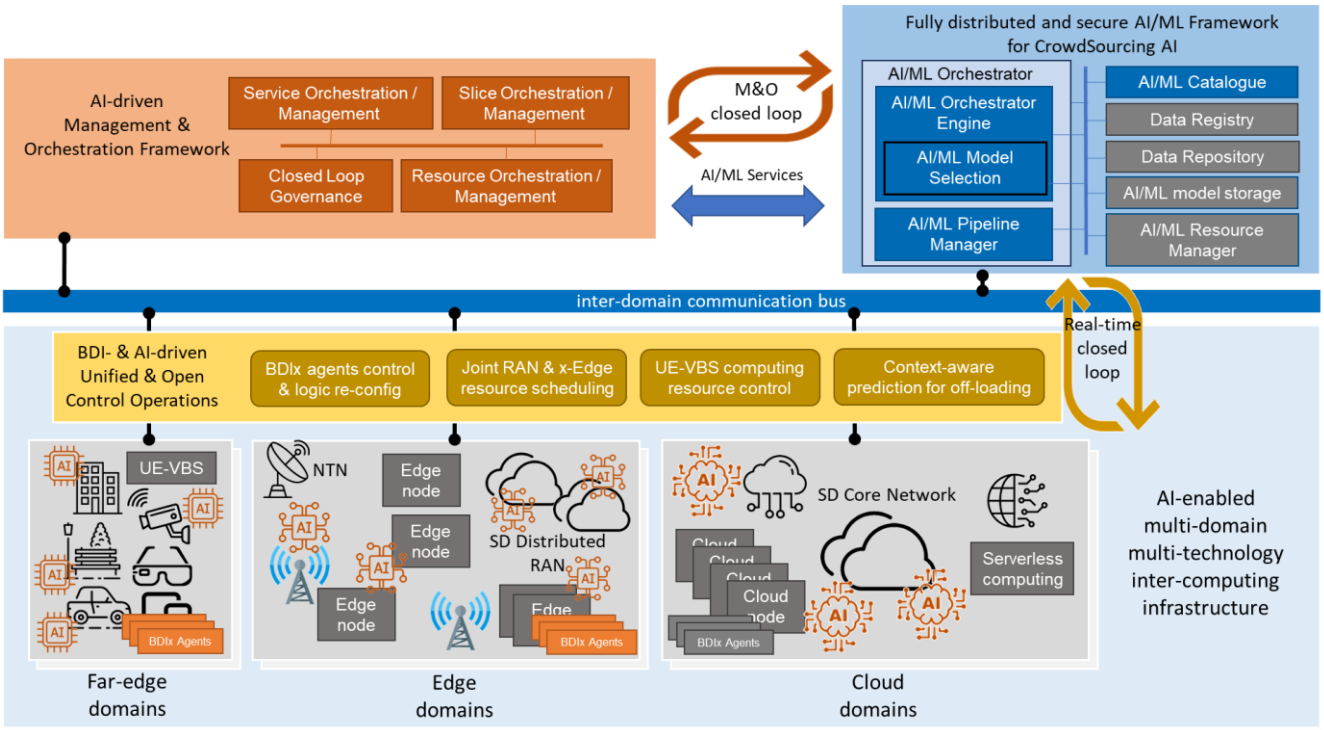

Figure 2-2. Final version of the ADROIT6G architecture.

2.1.1 The AI-driven Management and Orchestration Framework

The **AI-driven Management and Orchestration Framework** implements the logic for the end-to-end, automated management of the inter-computing and inter-domain network infrastructure. It is pivotal for managing distributed applications and services across various infrastructures, extending from traditional cloud environments to the heterogeneous edge and the far edge/device layer. It is designed to handle the complexities of advanced End-to-End (E2E) communication services that involve multiple stakeholders, including network operators, cloud service providers, and other service entities. It provides for efficient and effective deployment, management, and orchestration of network services and resources. The aim is to streamline the composition, deployment, and management of network slices, services, applications, and resources, facilitating seamless interoperability across diverse network segments and ensuring optimal network performance, reliability, and scalability.

The AI-driven Management and Orchestration Framework is presented in Figure 2-3 and is comprised of four main components: i) the service orchestration/management, ii) the slice orchestration/management, iii) the closed-loop governance, and, iv) the resource orchestration/management. In ADROIT6G, a service instance with a defined slice profile, optional edge or far-edge applications, and closed-loop capabilities is initiated through a *Service Orchestrator*. This process is guided by a service descriptor, which is built from a service blueprint and customized to meet the specific needs of the vertical service. Orchestration involves collaboration between various ADROIT6G orchestrators, which may include multi-operator interactions across distinct domains, such as satellite and terrestrial networks. These orchestrators dynamically allocate resources, deploy applications, and configure network slices to ensure optimal performance.

The support of UE-VBS in the Management and Orchestration framework facilitates the formation of decentralized computational and storage hubs through deployed UE-VBS controllers, enabling

low-latency communication, efficient data management, and seamless integration into the broader network infrastructure, thus ensuring the quality of service and experience necessary for future 6G networks.

In addition, the Closed-loop Governance mechanism plays a pivotal role in managing the instantiation and configuration of closed-loop functions to optimize resource usage and network performance, including requesting model instances for AI-enabled closed-loop functions from the Crowdsourcing AI framework.

This section provides a view of the operational flow of communication between ADROIT6G components for the case of instantiation of vertical services including applications and zero-touch closed-loop principles, exploiting satellite resources and/or UE-VBS with BDIx agents.

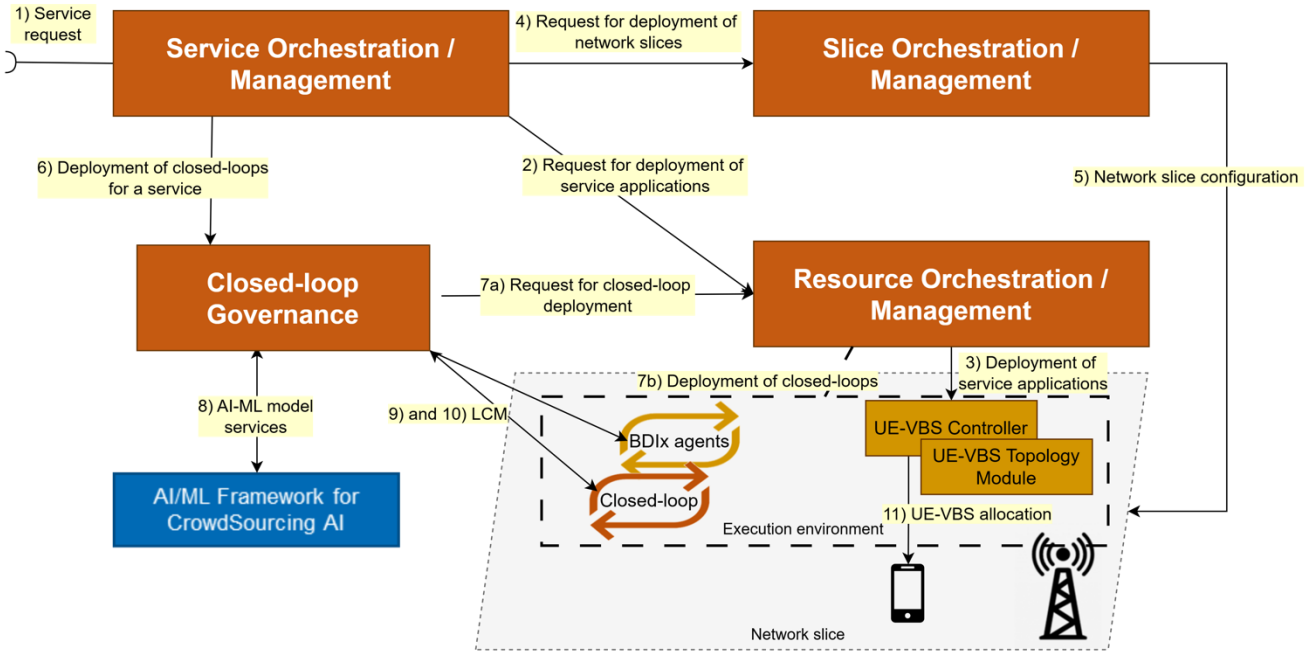

Figure 2-3. AI-Driven Management and Orchestration Framework

The AI-Driven Management and Orchestration Framework follows a specific procedure for the instantiation of services including applications and closed-loop, exploiting satellite resources and/or UE-VBS with BDIx agents. Specifically:

1. A service instance for a vertical service with a specific slice profile, edge/far edge application, and closed-loop is instantiated through the Service Orchestration and Management by a vertical user using a service descriptor built off a service blueprint.
   In a multi-domain / multi-stakeholder / multi-operator interaction (e.g., the 5G/6G network and the satellite network belong to different operators), different options for the federation could be achieved ([1]) in ADROIT6G architecture: *(i)* between the Service Orchestrator of each domain; *(ii)* between the Service Orchestrator and a Resource/Slice Orchestrator of a different domain; or *(iii)* between the Resource/Slice Orchestrators of each domain. In such scenarios, orchestrators in one domain collaborate with their counterparts in another domain to manage and allocate resources more effectively. By sharing information and coordinating actions, these orchestrators can dynamically adjust to changing demands and conditions.

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2. The Service Orchestrator requests the allocation of resources and deployment of service applications (e.g. UE-VBS controller, other VNFs) on resources (e.g. satellite, edge, core) defined in the service descriptor to the corresponding Resource Orchestrator.
3. The Resource Orchestrator allocates and deploys the service applications (ex. UE-VBS Controller, UE-VBS Topology Module) in the associated execution environment (far-edge, edge, cloud).
4. The Service Orchestrator requests the configuration of the network slice defined in the service descriptor through the Slice Orchestration and Management.
5. The Slice Orchestration and Management configures the requested slice profile.
6. The Service Orchestrator requests a closed-loop instance instantiation through the Closed-loop Governance passing the UUID of the requested closed-loop defined in the service descriptor, create topology instance.
7. The Closed-loop Governance retrieves the associated closed-loop descriptor from the UUID and requests the allocation of resources and deployment for the associated closed-loop functions on resources (e.g. satellite, edge, cloud) through the Resource Orchestrator which allocates and deploys the functions.
8. The Closed-loop Governance requests the deployment of models needed for the closed-loop functions defined in the closed-loop descriptors to the AI/ML Controller.
9. The Closed-loop Governance configures the closed-loop functions based on the closed-loop descriptor and the ML model inference endpoint returned by the AI/ML Controller.
10. The Closed-loop governance receives and stores run-time actions performed by the closed-loop.
11. The deployed UE-VBS Controller on each BS, allocates UE-VBS mobile devices under a gNodeB to act as storage hubs (CSHs), ensuring efficient data storage and computational processing near data sources. By selecting UE-VBS devices based on resource availability, location, and owner preferences, the controller strategically positions CSHs to form a decentralized Computational & Storage Powerhouse (CSP). These hubs manage caching, processing, and storage tasks, reducing latency and alleviating the load on centralized servers to optimize overall network performance. If the resulting D2D communication protocol achieves less than the optimal topology predicted using Deep Graph Neural Networks, the UE-VBS Controller dynamically optimizes the Device-to-Device (D2D) communication network. It assigns roles to UE-VBS devices as D2D-Relays or D2D-Clients, establishing Virtual Data Tunnels (VDTs) to streamline routing, reduce interference, and ensure low-latency communication. The controller continuously monitors network performance, adjusting roles, pathways, and resources in response to changing conditions. By integrating the D2D network with the broader UE-VBS Computing infrastructure, the controller ensures a resilient, adaptive network capable of meeting the stringent demands of 6G, delivering superior Quality of Service (QoS) and Quality of Experience (QoE).

2.1.2 The Fully distributed and secure AI/ML Framework for CrowdSourcing AI

The **Fully distributed and secure AI/ML Framework for CrowdSourcing AI** provides the AI mechanisms to assist the M&O and the control frameworks in their decisions. It represents a novel and forward-thinking approach to enhancing network operations, management, and service delivery using Artificial Intelligence (AI) and Machine Learning (ML). This framework implements the

innovative concept of *CrowdSourcing AI.* CrowdSourcing AI reinterprets the concept of ML-as-a-Service (MLaaS) with the aim to provide robust mechanisms for the efficient and effective management and distributed deployment of AI/ML pipelines, catering to the growing demand for scalable and resource-adaptive solutions. Central to this framework is the introduction of the AI/ML Orchestrator, which addresses AI/ML service requests generated by the AI-driven Management and Orchestration (M&O) framework.

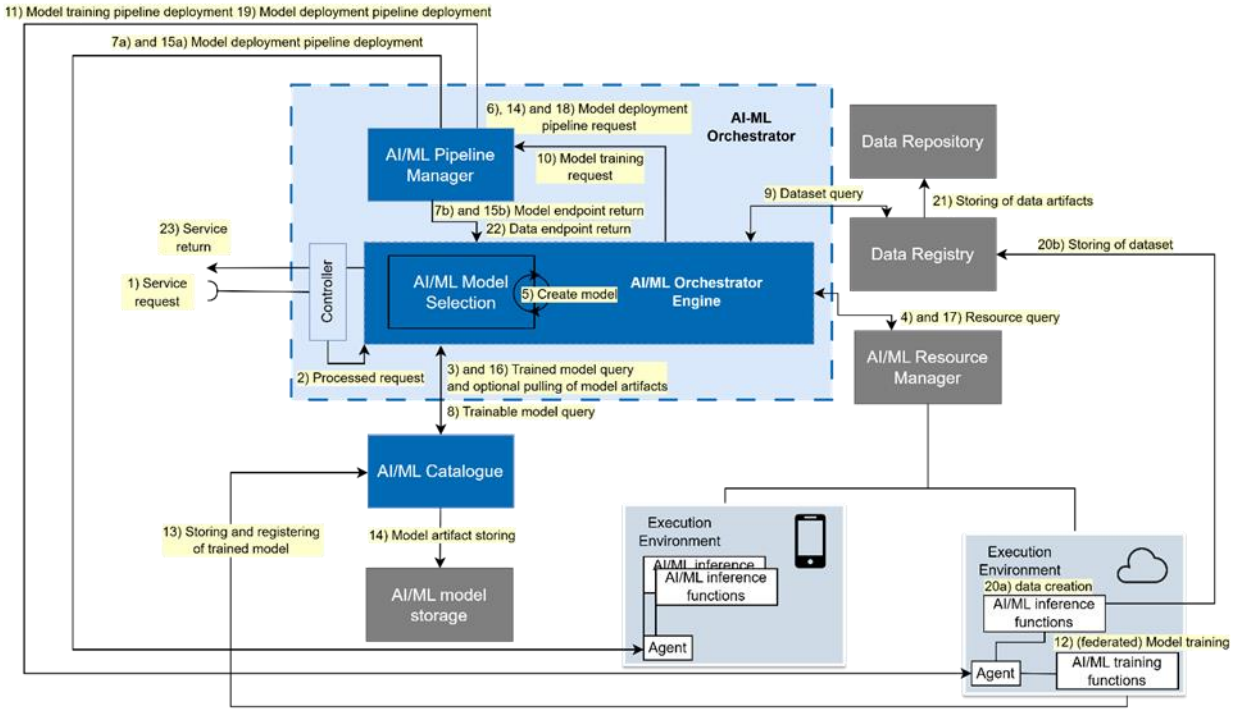

Figure 2-4. The Fully Distributed and Secure AI/ML Framework for Crowdsourcing AI.

The CrowdSourcing AI concept changes the way AI/ML models are created, trained, and utilized within distributed environments. It enables collaborative processes for training, fine-tuning, sharing, and usage of AI/ML models across a network of nodes, allowing for a continuous cycle of learning, refinement, and knowledge transfer. This collaborative approach not only enhances the adaptability and robustness of AI/ML models but also ensures their applicability across diverse domains and resource-constrained environments while contributing to making AI/ML pipelines more sustainable. Furthermore, CrowdSourcing AI techniques allow for lightweight and adaptable ML models that can operate efficiently on heterogeneous devices, including resource-limited edge and far-edge devices. This scalability ensures that the framework can meet the diverse requirements of modern AI/ML applications, from centralized to distributed training, to real-time inference at the edge.

The architectural design of the AI/ML framework is described in Figure 2-4, detailing the role of its various entities and the interactions between them that facilitate the implementation of a sustainable AI/ML pipeline. The AI/ML framework supports the execution of services including model serving, model pipeline and data onboarding, model training, data creation, and model selection. These services can be combined to create complex functionalities required by the forthcoming AI-enabled applications considered in ADROIT6G. This includes model creation, where a model can be tuned and/or trained and deployed for inference, based on model and resource

requirements, Figure 2-4 shows the flow of the communication between ADROIT6G components for model creation, considering various possibilities including finite available resources in the target node, required inference quality level, quantization level, inference time, as well as training data requirements. The individual steps of the model creation model are presented as follows:

1. From External entity (e.g., from Network Orchestrator, newly joining UE) to Controller: AI/ML service request for a trained model, including required ML model, max no. training rounds/required inference quality level, quantization level, inference time, target node where to deploy the trained model.
2. The controller passes the request to the AI/ML Orchestrator.
3. The AI/ML Orchestrator queries the AI/ML Catalogue for existing already-trained models that match the required ML model. If the service is requesting also the return of the model artifacts, the AI/ML Orchestrator pulls the artifacts from the AI/ML Storage via the AI/ML Catalogue. If there are no available trained versions of the requested model, then GO TO Step 8.
4. Then AI/ML Orchestrator queries the AI/ML Resource Manager for the resource availability at the target node.
5. The AI/ML Orchestrator Engine executes the MERGE algorithm with the AI/ML Model Selector to create an ML model that fulfils the requirements.
6. If it is possible to create an ML model that fulfils the requirements, The AI/ML Orchestrator Engine outputs to the AI/ML Pipeline Manager the location of the trained model of a suitable size matching the (i) required inference quality level, (ii) inference time, (iii) and resources the target nodes can allocate to its execution. If it is not possible, GO TO Step 8.
7. The AI/ML Pipeline Manager deploys the created model in the target node and returns the endpoint to the model to the AI/ML Orchestrator.

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8. If no suitable, trained ML model can be created, the AI/ML Orchestrator queries the AI/ML Storage and Catalogue for the type of requested ML model.
9. The AI/ML Orchestrator queries the Data Registry for datasets suitable for training the ML model.
10. If suitable datasets are available, then the AI/ML Orchestrator transfers the location of the AI/ML model and datasets to the AI/ML Pipeline Manager and requests to run train and deploy pipelines. Else GO TO Step 18.
11. The AI/ML Pipeline Manager configures, deploys and tracks the model training at the target node and in the target node, the configuration includes the model and datasets location, requirements in terms of max. no. of training rounds/ inference quality and quantization level.
12. Optional: The target node may then start a federated learning process to execute the ML model training according to the above requirements on the number of rounds.
13. The pipeline running in the target node registers the (possibly quantized) version of the trained model to the AI/ML model catalogue.
14. The Model Catalogue stores the artifacts of the model in the model storage.
15. When the training pipeline finishes, the AI/ML Pipeline Manager deploys the created model in the target node and returns the endpoint to the model to the AI/ML Orchestrator.

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16. If suitable datasets are not available, the AI/ML Orchestrator fetches an ML model suitable for synthetic data generation.

17. The AI/ML Orchestrator queries the AI/ML Resource Manager for the resource availability at the system nodes, which can be different from the target node and selects a node with suitable resources.
18. The AI/ML Orchestrator sends: the model location for synthetic data generation, the existing suitable dataset location (if any), and the indication of the selected node to the AI/ML Pipeline Manager.
19. The AI/ML Pipeline Manager configures and deploys the model pipeline for data generation at the selected node.
20. The pipeline running on the selected node runs data generation and registers the (updated/new) dataset to the Data Registry.
21. The Data Registry stores the artifacts of the data in the Data Repository.
22. When the data generation pipeline finishes, AI/ML Pipeline Manager returns the new data location to the AI/ML Orchestrator and the flow proceeds from Step 10.
23. The model endpoint (and optional model artifacts) along with a service report are returned to the External Entity from the AI/ML Orchestrator via the Controller.

2.1.3 The BDI- & AI-driven Unified & Open Control Operations Framework

The BDI- & AI-driven Unified & Open Control Operations Framework (as shown at the low-part of Figure 2-2) represents a cutting-edge approach to managing network automation in real-time and near-real-time contexts. This framework is meticulously designed to handle the dynamic and inter-domain resource allocation essential for modern networks. Leveraging both Belief-Desire-Intention (BDI) and Artificial Intelligence (AI) methodologies, the framework coordinates resource distribution based on the current network conditions and advanced context-aware predictions. It plays a crucial role in provisioning and controlling BDIx agents across various network domains and dynamically reconfiguring their logic to optimize performance. Additionally, the framework oversees the control of User Equipment as Virtual Base Station (UE-VBS) computing resources, particularly at the far edge, exploiting the computational capabilities of mobile devices. It also focuses on the joint scheduling of Radio Access Network (RAN) and edge/far-edge resources to enhance network performance and resource efficiency. By integrating context-aware prediction mechanisms for off-loading tasks, the framework ensures a seamless, efficient, and highly responsive network environment.

Furthermore, the framework is integral to managing network resource allocation and the large number of network devices, including those involved in Device-to-Device (D2D) communication networks that form under the BS. This aspect enhances the network's ability to support direct communication between devices, reducing latency and improving overall communication efficiency. By facilitating D2D communications, the framework helps in offloading traffic from the core network, thereby optimizing bandwidth usage and enhancing user experience. This comprehensive approach positions the framework as a vital component in the advancement of network automation and optimization, particularly in leveraging the capabilities of far-edge computing and enhancing the efficiency of D2D communications under the base station.

The BDI- & AI-driven Unified & Open Control Operations Framework is designed to facilitate the automatic deployment, management, and reconfiguration of services across 6G networks. To achieve this, it must be integrated with several key components within the AI-driven Management & Orchestration framework. These components include the AI/ML Orchestrator, Close-Loop

Governance (CLG), Service Orchestration / Management, Resource Orchestration / Management, Inter-domain Communication Bus, Logging and Reporting System, and Security Systems. Specifically:

- The AI/ML Orchestrator is responsible for selecting and deploying the appropriate machine learning models based on the device type and context. The framework must interface with it to ensure the right models are applied for efficient management and orchestration. This includes model deployment and orchestration commands, as well as context-aware predictions and off-loading decisions.
- Close-Loop Governance (CLG) ensures compliance with SLAs/KPIs and handles closed-loop reconfigurations. The framework must connect to it for real-time performance monitoring and adaptive adjustments, including initialization and compliance verification, as well as continuous performance monitoring and adjustments.
- Service Orchestration / Management is responsible for integrating devices into the network infrastructure and managing service configurations. The framework must interface with it to ensure seamless integration and service readiness, which involves service configuration details and resource allocation and management.
- Resource Orchestration / Management dynamically allocates resources as devices integrate into the network. The framework must connect to it to manage computational loads and network resources efficiently, including resource allocation and scheduling, as well as computational load distribution.
- The Inter-domain Communication Bus facilitates communication between different architectural components. The framework must connect to it to enable seamless data exchange during setup and operation, specifically addressing communication requirements and data exchange.
- The Logging and Reporting System logs the success of initialization phases and the readiness of the system. The framework must connect to it to ensure accurate logging and system readiness reporting, including log entries and readiness confirmation.
- Finally, Security Systems ensure secure data transmission and processing. The framework must connect to it to implement necessary security protocols and safeguard data integrity, specifically through security protocols activation and encryption details.

In summary, the BDI- & AI-driven Unified & Open Control Operations Framework must connect to these components to provide a cohesive and efficient management and orchestration solution for 6G networks. These connections enable the framework to automate model deployment, ensure compliance with operational requirements and performance metrics, dynamically allocate and manage resources, facilitate seamless communication and integration, and implement robust security measures. By integrating these components, the framework can support the deployment and management of E2E vertical services.

2.1.4 Closed-Loop Functions

In addition, the Closed-Loop Functions approach in ADROIT6G architecture are designed to address the complexities inherent in managing 6G networks by leveraging automation to optimize network and service operations while efficiently utilizing infrastructure resources. These functions are essential for adapting to the dynamic and variable nature of network traffic, devices, and

applications in real-time, utilizing a zero-touch automation approach that relies on a data-driven methodology. This approach ensures continuous optimization of infrastructure, services, and applications based on monitored data. ADROIT6G considers Management and Orchestration (M&O) closed-loop functions, i.e. the monitoring, analysis and decision functions, which operate dynamically according to different optimization scopes, time scales and domains, as well as real-time closed loop functions, with a form of Belief-Desire-Intention extended (BDIx) agents that autonomously make decisions based on predetermined objectives and goals.

The *Monitoring function* collects and processes data from the entity managed by the closed-loop service. For example, if a closed-loop service manages a network slice, the monitoring function could collect, aggregate, and distribute the network-related data to the other functions in the closed-loop. In a distributed scenario, monitoring functions implement a distributed data collection system by providing specific and tailored monitoring probes and data collection plugins, properly placed according to the specific data source required for the given closed-loop service.

The *Analytics closed-loop function*, based off the ETSI ZSM architecture, is responsible for deriving insights from available data from the Monitoring function as well as historical data. In ADROIT6G, AI-driven Analytics closed-loop functions make use of algorithms developed in the project, managed by the AI/ML framework. The algorithms and models can be placed within the Analytics function or be served by the AI/ML framework as a service and accessible to the Analytics function via interfaces exposed by deployed models.

Decision-Making (DM) may exist in different blocks of the ADROIT6G architecture or in the same block realizing competing objectives. The DM is part of slice runtime management and is enclosed within the slice. Also, it decides on the actions of Lifecycle Management (LCM) that are required to be applied to handle the issues that analytics detects.

The *Decision Engine* is responsible for resources and slice orchestration and slice deployment preparation to provide an optimal division of a slice into multiple domains. It implements control algorithms, such as Deep Reinforcement Learning (DRL) methods, by considering the monitoring data and the AE's outputs, to take online decisions regarding slice LCM actions and may propose network reconfiguration to solve the detected problems. The Decision Engine also analyzes alerts and notifications from analytics and make the appropriate decision. The decisions are either acquired locally or at a global level. Local decisions are taken by employing a local ML algorithm, based mainly on Reinforcement Learning (RL) but not limited to RL, or a predefined policy enforced by the Tenant through Intent, or a mixture of them. The engine may also gather notifications from several analytics, which may interact with monitoring at different technological domains to consider a global decision on the end-to-end network slice.

This section covers the preliminary concept of the Decision Engine (DE), outlining its specifications, functions, reference points, and the deployed algorithms within the modular architecture of ADROIT6G. A brief explanation will be provided regarding the distributed implementation of the DE and its granularity in terms of BS, Slice, and NVF, among others. According to the proposed high-level architecture of ADROIT6G, first, the relation between DE and other elements of the Closed-Loop functions known as Analytics, Monitoring, and Execution is described [The proposed framework is in line with the recently proposed ETSI ZSM closed-loop automation architecture]. In the following step, each reference point is described in detail, along with the general description of the blocks that make DE up. It is essential to mention that these blocks can be instantiated

differently based on the scope of the considered analysis; for instance, analysis can be done for domain, slice, or network functions. The cooperation between the different DEs needs to be managed through an orchestrator, which will be explained in detail in the future.

2.1.4.1 Generic Description

This subsection is divided into four main parts. First, the concept of the Closed-Loop functions is described, and then the high-level and in-detail nature of DE in the ADROIT6G is illustrated. Finally, the integration of the concept of MLOPs is explained.

Given the critical role of the decision element within the Closed-Loop Functions block, it is crucial to establish clear relationships between this element and the other components of the block. The Closed-Loop Functions block comprises four primary elements: monitoring, analysis, decision, and execution. During the monitoring phase, raw data from diverse sources is systematically gathered and pre-processed. Subsequently, this collected or monitored data is transmitted to the analysis stage, where insights are derived to inform decision-making. The execution stage then translates these decisions into actionable commands, yielding the desired output. To encapsulate this process:

The connection between the analysis element and the decision stage dictates that data from the monitoring phase, whether real-time or non-real-time, undergoes thorough analysis. This analysis serves the dual purpose of refining analytic models and initiating or concluding analytical processes.

The link between the decision phase and execution involves defining a set of action plans. These plans contribute to refining decision models and facilitate the initiation and termination of decision processes.

It is crucial to highlight that the decision stage possesses the capability to interact with other closed loops or external entities. This interaction allows for initiating or terminating decision processes, fine-tuning decision model configurations, retrieving outcomes from decision functions, and decision-making for external entities or other closed loops.

2.1.4.2 High-level Decision Engine in ADROIT6G architecture

As illustrated earlier, the proposed programmable architecture of ADROIT6G embodies a distributed framework driven by artificial intelligence, specifically designed for 6G networks. This comprehensive structure includes a crowdsourcing AI/ML framework and a management & orchestration framework. Within this setup, the DE serves as a crucial component situated in the Closed-Loop Functions block, positioned within the broader management and orchestration scope. The DE actively interacts with monitoring and analytic entities. This subsection aims to elucidate the interfaces between DE and key components such as the Monitoring System (MS), Analytics Engine (AE), and Actuator (ACT). It then delves into the essential elements of the DE, outlining their respective responsibilities in executing control algorithms and facilitating decision-making actions.

As depicted in Figure 2-5, the DE is interconnected with the AE, MS, and ACT, with the ACT potentially is able to located in various technical domains such as Far Edge, Edge, or Cloud. The MS, responsible for collecting raw data or information, can transmit this data to the DE or AE. Alternatively, there is an option to store the data in an online memory store (depicted as a yellow

cylinder). Leveraging an online memory store enhances the processing flexibility and length of both AE and DE without compromising the data sampling conducted by the MS.

The AE has the capability to receive stored information and process it for utilization by the DE. The processed data may include predictions, classifications, and other relevant insights. Alternatively, the AE can receive raw measurements directly from the MS, although this process necessitates synchronization. It is imperative to note that the External User Interface (EUI) plays a crucial role in defining and modifying the configurations of the DE (e.g., discount factor in DRL algorithms), AE (e.g., prediction interval), MS (e.g., granularity), and actuation.

Furthermore, the DE has the capability to acquire processed information, such as predicted Key Performance Indicators (KPIs), either by reading from the online memory store or directly receiving it from the AE. Additionally, the DE can access raw data or information directly from the MS. Once decisions are made, the DE can store them, along with AI metrics, in the online memory store or transmit them directly to the actuators for implementation. As illustrated in Figure 2-5, the DE can effectively send these decisions to the ACT.

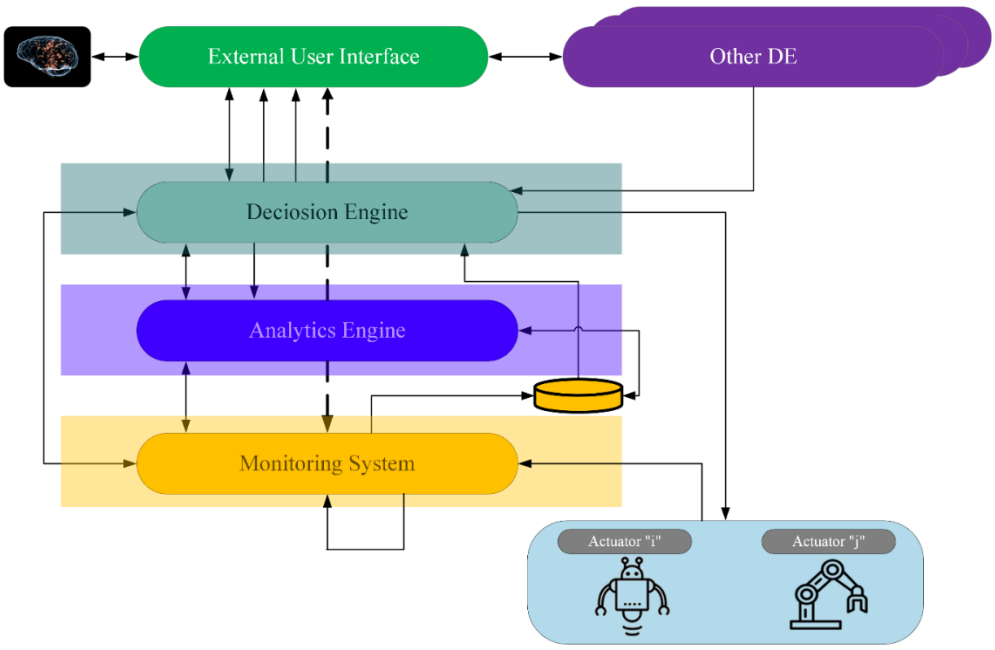

Figure 2-5. Interfaces between MS, AE, DE and Actuator.

2.1.4.3 DE functional Blocks and Reference Points Overview

In this subsection, we delve into a detailed exploration of the DE components. As depicted in Figure 2-6, the DE consists of three primary blocks: the input pre-processor, control trigger, and output pre-processor (highlighted in cyan functional blocks).

Primarily, the input pre-processing block is responsible for extracting insights and learning from raw data across diverse domains, determining which knowledge is pertinent for subsequent processing within the DE. Given various data sources' distinct languages and protocols, the data ingestion procedure features diverse implementations tailored to specific operational requirements. Subsequently, the data normalization procedure plays a pivotal role in ensuring uniformity in data format and structure.

The input pre-processing block establishes a direct link with the control trigger process, comprising three key sub-blocks: situation awareness, model-driven engineering, and policy management.

The situation awareness functional block engages in perceiving and comprehending elements within the current scenario, projecting data into future states. In the Model Driven Engineering (MDE) functional block, decisions are made regarding implementing selected actions derived from the situation awareness functional block, based on software development principles. Finally, the policy management sub-block orchestrates the transformation of data and information from their native formats into structures conducive to generating outputs intelligible to assistive systems.

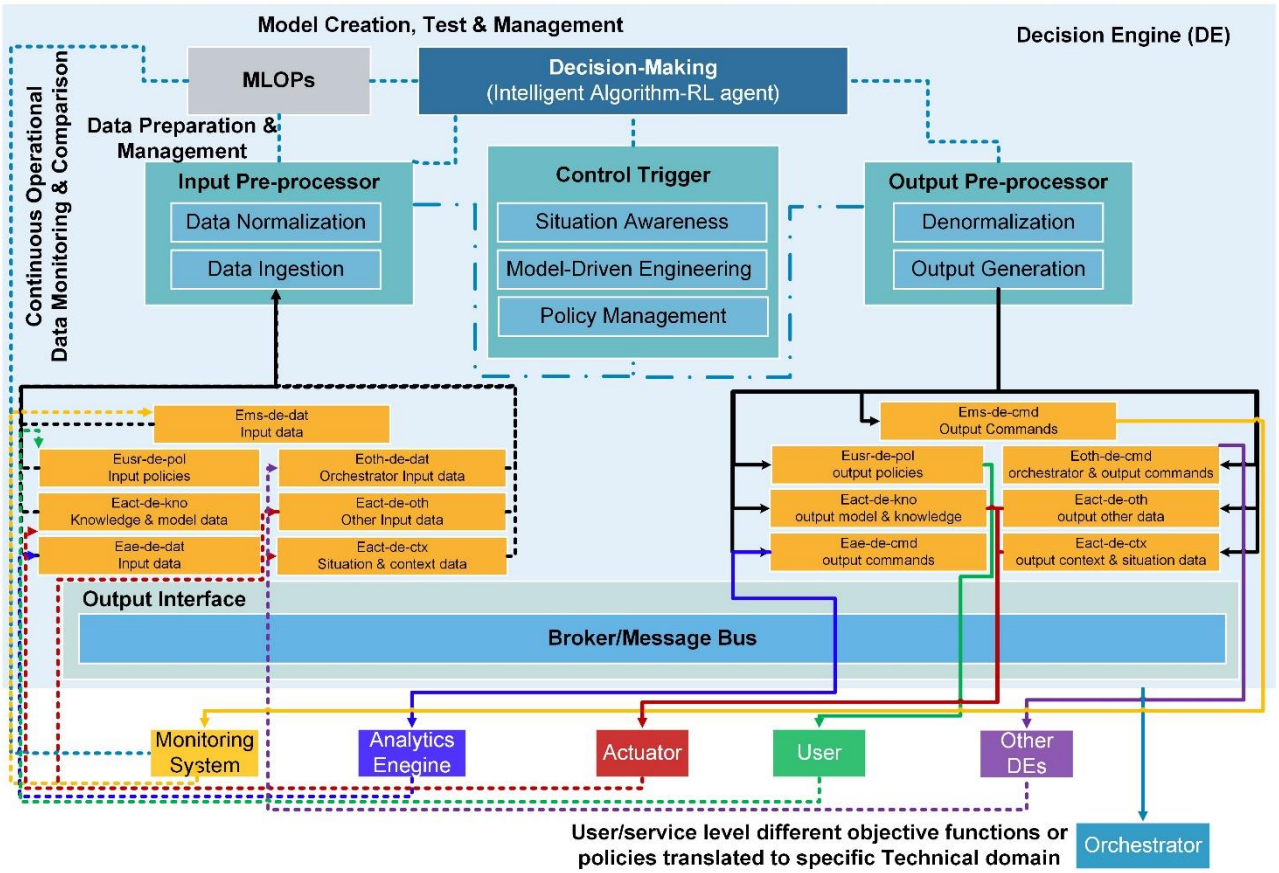

Figure 2-6. Architectural Functional Blocks of DE.

2.2 ADROIT6G roles and stakeholders

support a wider set of capabilities and functionalities, which will go beyond only communication offered to end-users and different verticals. While the path towards a standard 6G network architecture is still at its early stages and will be consolidated starting from 2025 as part of the 3GPP specification roadmap, research initiatives in Europe and around the globe, like ADROIT6G, are focusing on identifying a set of key technology enablers which provide innovative functionalities, services and interfaces to deliver 6G services to applications, verticals, users and aiming at enabling additional value. This is translating, in ADROIT6G and other similar research and innovation actions, into the proposition of 6G platform solutions which integrates several interconnected and interdependent technology enablers to realize a 6G end-to-end system view.

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Indeed, 6G is expected to act as a platform providing a flexible set of services to the applications, adapted to the current application, vertical and user needs and requirements. At the 6G platform side, networks will need to expose a diverse set of APIs to applications, users, and verticals, which can be extended over time. In practice, the focus with 6G will be still on services related to communication functionality but augmented with novel solutions for management and orchestration (AI based), as well as additional innovative services for applications and networks. Indeed, a broader range of services can be offered to applications, with networks not only responsible for transporting data (communication), but also acting as intelligent programmable networks, able to offer beyond new communication services auxiliary features (relying on processing and storing of data) as well as acting as a key source of data themselves, not possible within today's networks

Moreover, 6G is also expected to create new business opportunities and relationships by offering novel digital services that will significantly innovate the application and vertical domains (by fulfilling their requirements in terms of performances, density, scale, mobility, sustainability, etc.) leveraging on advanced communication capabilities. In practice, this will introduce novel beyond-communication services, deeply integrated within 6G platforms and end-to-end systems, which will range in general from AI functionalities and capabilities, to advanced computer services, integrated sensing, network digital twins, etc. In the context of ADROIT6G, intelligent beyond communication services such as AI, advanced analysis and network and resources optimization are expected to facilitate and benefit from the integration and systematic adoption of AI/ML inside the network. This is aiming at realizing the in-network AI paradigm to provide automation of network operations as well as unlocking the optimization of heterogeneous vertical services and applications. Moreover, ADROIT6G relies on advanced distributed compute services and functionalities to provide real-time and near-real time resource allocation and control, which involves and integrates the far-edge domain (up to end-user devices) to realize a transparent multi-domain and multi-technology inter-computing infrastructure.

When considering the involved and targeted stakeholders, 6G is going to realize a wide ecosystem of collaboration, which is expected to go beyond current mobile network operators centered view, and that will include several additional actors, such as cloud providers, enterprises, vertical industries, integrators, application developers, application service providers, end users. In particular, the ADROIT6G platforms and end-to-end systems view is defined to accommodate more fragmented value creation chains, where novel beyond-communication services are supported and composed of mixed and integrated capabilities from multiple stakeholders. Indeed, ADROIT6G considers 6G networks as agile platforms interfacing with heterogeneous applications and capable to fulfill their concurrent needs, through several key architectural innovations, as follows:

- AI/ML-powered optimizations across the entire network for improved performance and automation.
- Cloud-native network software implementation across edge-cloud platforms.
- Integration with Non-Terrestrial Networks (satellites).
- Zero-touch operations and automation of network management.
- Distributed AI framework using CrowdSourcing AI concept.
- Energy efficiency improved by an order of magnitude (>90% reduction).
- Support for extreme use cases like holographic telepresence, massive IoT, and collaborative robots.

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- In terms of relevant stakeholders, actors and roles, ADROIT6G relies on the 3GPP[1] definitions and high-level functional model of business roles which is depicted in Figure 2-7 and summarized in Table 2-1.

Table 2-1. 3GPP high level functional model of business roles

3GPP Role	Description
Communication Service Customer (CSC)	It requests and consumes communication services.
Communication Service Provider (CSP)	It provides and exposes communication services, in the form of B2C, B2B and B2B2X relationships, and is responsible to design, build and operate its communication services.
Network Operator (NOP)	It provides and exposes network connectivity services, and is responsible to design, build and operate its networks to offer such services.
Virtualization Infrastructure Service Provider (VISP)	It provides virtualized infrastructure services on top of its virtualization infrastructure. It can offer them also to other types of customers directly, i.e. without going through the NOP.
Data Centre Service Provider (DCSP)	It provides data center services to accommodate possibly multiple VISP requirements and needs.
Network Equipment Provider (NEP)	It supplies network equipment, covering both the case of physical and virtual (cloud-native) network functions.
NFVI Supplier	It supplies network function virtualization infrastructure to its customers.
Hardware Supplier	It generally supplies hardware, being it commodity (in the context of softwarized and virtual services and functions) or specialized.

3GPP already identifies the roles defined in Figure 2-7 and the related model of interactions as not restricting tailored hierarchy or layering, thus not preclude relations between non-neighboring roles. This is key to consider this high-level model as flexible enough to accommodate the identification of stakeholders and roles for the 6G case and for ADROIT6G, as detailed in the following sub-section.

2.3 Mapping with the ADROIT6G architecture

Starting from the 3GPP definitions shown in Figure 2-7 and summarized in Table 2-1, ADROIT6G augments the related model to introduce and accommodate the digital service concept as a

[1] 5G; Management and orchestration; Architecture framework (3GPP TS 28.533 version 15.0.0 Release 15); ETSI TS 128 533 V15.0.0 (2018-10)

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generalization of the communication service, specifically to embrace the novel beyond-communication services expected to be offered and consumed within the 6G platforms. Table 2-2. summarizes the high-level functional model of business roles specifically mapped to the 6G platform architecture proposed in ADROIT6G.

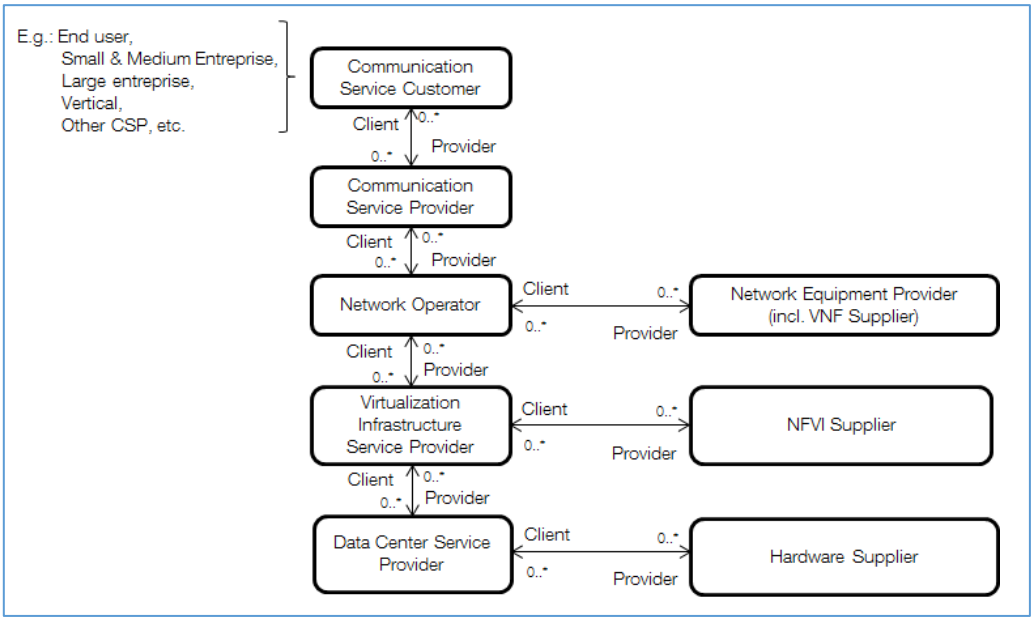

Figure 2-7. 3GPP definitions

Table 2-2. ADROIT6G high level functional model of business roles

ADROIT6G Role	Description	
Digital Service Consumer (DSC)	It is the consumer of digital services, and in general of novel beyond-communication services expected for 6G. It can generally be covered by a vertical, as well as from enterprises, other DSPs (see below), end-users. It can be considered as a generalization of the CSC role which in general can consume digital and communication services.	
Digital Service Provider (DSP)	It delivers digital content and applications by managing digital platforms and services. It provides value-added digital services and handles digital service integration, being responsible for digital service quality. The CSP defined by 3GPP can be considered as a special case of DSP, which deals (i.e. it provides and offers) with communication services for end-users (including verticals), managing service delivery and quality while handling customer relationships.	
Mobile Network Operator (MNO)	It providesbile connectivity services, thus directly managing network resources and services at large (including spectrum). It handles network	It provides and offers digital mobile connectivity services, thus directly managing network resources and services at large (including spectrum). It

	operations and maintenance, and is responsible for network coverage and quality. In practice it operates the mobile network infrastructure, which can be composed by a mix of domains and technologies (thus possibly integrating and composing different network equipment and virtual infrastructures also offered by other stakeholders, as per 3GPP model above).	handles network operations and maintenance, and is responsible for network coverage and quality. In practice it operates the mobile network infrastructure, which can be composed by a mix of domains and technologies (thus possibly integrating and composing different network equipment and virtual infrastructures also offered by other stakeholders, as per 3GPP model above).
Edge/Cloud provider	It can be considered as a specific category of virtual infrastructure providers, as edge and cloud providers (including public clouds and hyperscalers) are expanding their offerings to accommodate MNO's requirements for compute continuum resources. Moreover, MNOs themselves will be more and more acting as edge/cloud providers with 6G following the GSMA Telco Edge Cloud (TEC) initiative which aims at creating interoperable and portable ecosystems for edge platform deployments.	

As anticipated above, 6G is expected to facilitate a more dynamic, flexible and agile ecosystem of business relationships and collaborations, which will not be frozen around a few pre-defined interaction models. Aligned with this, the proposed ADROIT6G platform and system architecture allows for several models and ways of interactions (i.e. service ownership and consumption approaches), as detailed in Table 2-3.

Table 2-3. Mapping of ADROIT6G frameworks with business roles

ADROIT6G Framework	**Mapping with high level functional model of business roles**
AI-driven Management and Orchestration Framework	The options for AI-driven Management and Orchestration ownership are: • A Digital Service Provider, offering AI-driven management and orchestration capabilities as novel-beyond communications services which combine and integrates application and vertical services with communication services. • A Communication Service Provider, offering AI-driven management and orchestration capabilities for communication services only (i.e. not dealing with applications and vertical services). • A Mobile Network Operator which aims at implementing and offering the AI-driven management and orchestration capabilities

	for network connectivity services only on top of its network infrastructure. The AI-driven Management and Orchestration Framework is a consumer of the services offered by the AI/ML Framework for Crowdsourcing AI and the BDI-x and AI-driven Control Operations Framework. It deploys its service components on the resources exposed by the multi-domain, multi-technology, inter-computing infrastructure, either directly (e.g. if directly owned as part its infrastructure) or indirectly (e.g. through the services exposed by a Mobile Network Operator).
AI/ML Framework for Crowdsourcing AI	The options for AI/ML Framework for Crowdsourcing ownership are: • A standalone Digital Service Provider offering advanced AI capabilities as novel beyond-communication services in support of other Digital Service Providers, Communication Service Providers and Mobile Network Operators. • A Digital Service Provider which owns an integrated solution formed by the AI-driven Management and Orchestration Framework and the AI/ML Framework for Crowdsourcing. • A Mobile Network Operator offering advanced AI capabilities and services on top of its network infrastructure (e.g. for network related only AI services). The AI/ML Framework for Crowdsourcing AI uses resources in the multi-domain, multi-technology, inter-computing infrastructure, either directly (e.g. if directly owned as part of its infrastructure) or indirectly (e.g. through the services exposed by a Mobile Network Operator).
BDI-x and AI-driven Control Operations Framework	The options for BDI-x and AI-driven Control Operations Framework ownership are: • A Digital Service Provider which owns an integrated solution formed by the AI-driven Management and Orchestration Framework and the BDI-x and AI-driven Control Operations Framework. • A Mobile Network Operator to offer advanced distributed compute services and functionalities to provide real-time and near-real time resource allocation and control in the compute continuum combined with its network service connectivity.
Multi-domain, multi-technology, inter-computing infrastructure	The options for multi-domain, multi-technology, inter-computing infrastructure ownership are: • A Mobile Network Operator, to support the Telco Edge Cloud paradigm and combine compute continuum resource management with mobile network connectivity and services. • One or more edge/cloud providers.

A non-restrictive example of a possible model of relationships and ownership supported by the ADROIT6G platform architecture is shown in Figure 2-8. Vertical users, e.g. implementing services and applications related to ADROIT6G Use Cases, act as Digital Service Consumers. A first Digital Service Provider supports the AI-driven Management and Orchestration capabilities and interacts with a second Digital Service Provider to consume novel AI services in support of network and service automation and AI-driven real-time control operations. Both the Digital Service Providers relies on multi-domain infrastructure and capabilities offered by a Mobile Network Operator (acting as edge/cloud provider as well), to create network connectivity services (e.g. slices in support of vertical services) and deploy distributed application and AI-service components in the compute continuum.

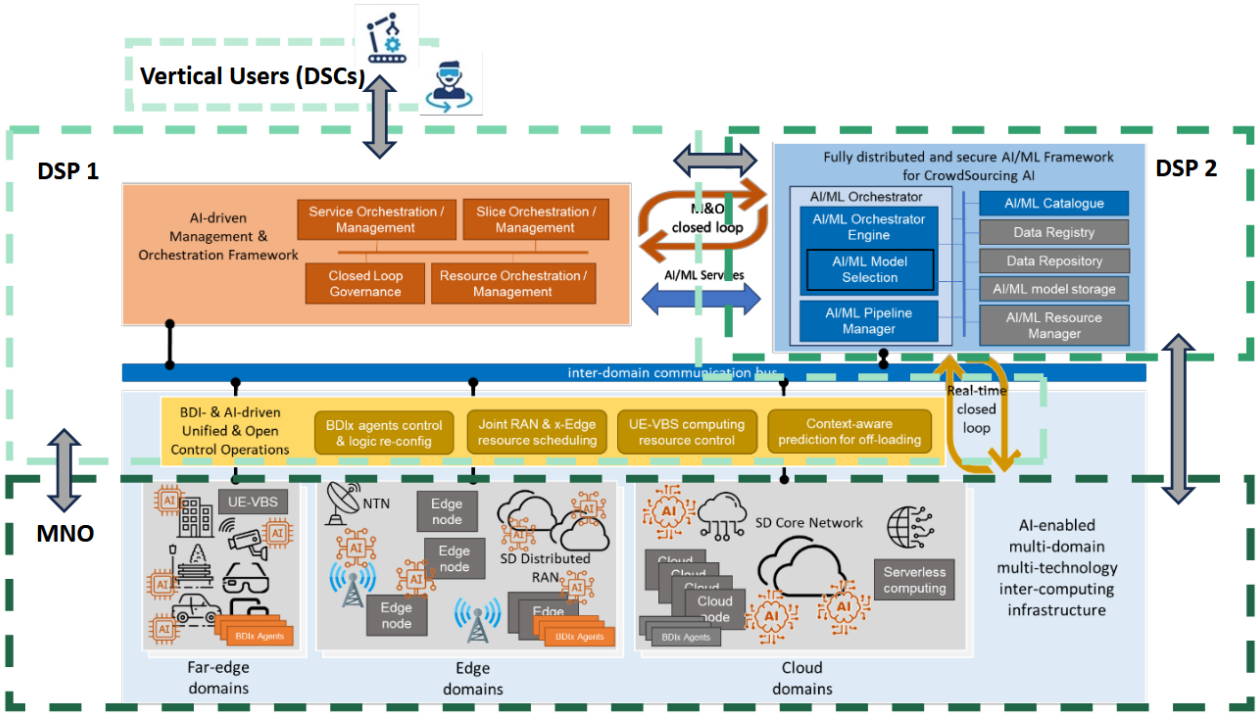

Figure 2-8. Example of business roles mapped with ADROIT6G architecture

However, irrespectively of the actual split of the various roles and ADROIT6G frameworks among the potential stakeholders, the ADROIT6G platform and end-to-end system is conceived to offer verticals and end-users advanced digital services in the form of novel beyond-communication capabilities. This means that specifically verticals interact with the ADROIT6G platform following an Over-the-top (OTT) approach, but still allowing the ADROIT6G system to orchestrate and take care of the deployment and runtime operation (e.g., scaling, migration) of the vertical service components and applications. In practice, the combination of the AI-driven Management Orchestration and BDI-x and AI-driven control frameworks allow to orchestrate and control the service components and required combination of resources across the compute continuum and multi-domain infrastructure on behalf of the vertical (i.e., the Digital Service Consumer), including network connectivity services (e.g., in the form of tailored network slices to accommodate the specific vertical performance requirements). In addition to that, ADROIT6G offers additional beyond-communication capabilities in the form of crowdsourcing AI services that can be integrated with the management and orchestration and BDI-x control mechanism to improve network and service automation, network performance optimization, resource consumption and energy

efficiency. Still, verticals are required to provide on top of their services the tailored application management functionalities related to their specific applications logics, still without caring to directly manage the underlying network and compute continuum infrastructure resources.

3 ADROIT6G interfaces

The ADROIT6G solution is comprised of 3 frameworks:

- **AI-driven Management and Orchestration** providing intelligent vertical service and slice deployment and management using AI-driven decision solutions over distributed, heterogeneous systems including far edge, edge, and cloud resources, via terrestrial and non-terrestrial networks
- **AI/ML for Crowdsourcing** enabling collaborative training of ML models and the execution of inference tasks through such models, using distributed techniques and enabling a continuous cycle for learning creation, validation, refinement, and transfer of ML models across domains
- **BDI- & AI-driven Control Operations** responsible for the real-time and near-real-time close loops for the network automation

Details on the innovation in the individual frameworks can be found in deliverables D4.1 and D3.2.

This section provides details on the internal component communications of the Management and Orchestration, AI/ML, and Control Operations frameworks. The information provided includes details on the communication protocols utilized within the frameworks, as well as the externally exposed interfaces for inter-framework operations.

3.1 AI-Driven Management and Orchestration Framework

The AI-driven Management & Orchestration framework for 6G Networks has been designed to support the deployment and management of E2E vertical services, including those utilizing resources in the cloud, edge, and far edge, across TN and NTN, exploiting UE-VBS and closed-loop services for zero-touch dynamic reconfigurations. The framework is integrated with the ADROIT6G AI/ML framework for Crowdsourcing AI for the automatic deployment and management of AI services used in AI-driven closed-loops for inference.

In was follows, the interfaces among the different components of the framework are discussed, following the configuration of the framework that is presented in Figure 2-3.

3.1.1 Service Orchestration and Management

The Service Management and Orchestration interacts with the other ADROIT6G AI-driven Management & Orchestration blocks via exposed interfaces. This includes the Slice Orchestration and Management for instantiating network slices for services, the Resource Orchestration and Management for the provisioning of resources (far edge, edge, cloud) and deployment of applications attached to vertical services, and the Closed-loop Governance for closed-loop creation and configuration. The interactions with these components produce the following actions:

- To the Slice Orchestration & Management to instantiate, terminate, query, or scale a network slice.
- To the Resource Orchestration & Management to instantiate, terminate, query, or scale network resources associated to a service.
- To the Closed-loop Governance to instantiate, terminate, query, or update a closed-loop service associated to a service.

The Service Management and Orchestration supplies interfaces for triggering actions from a vertical or another ADROIT6G component including the onboarding of vertical service blueprints/vertical service descriptors, instantiation, termination, modification, or scaling of a service instance. Details of these concepts are given in D4.1.

The requirements for Service Management and Orchestration interfaces can be dived into 4 groups of services described below.

3.1.1.1 Vertical service blueprints

Vertical service blueprints (VSBs), detailed in D4.1, contain the service parameters adapted to the knowledge and capabilities of the vertical (i.e. application services without detailing the infrastructure resources required). The Service Orchestration and Management provides 4 functionalities from the vs blueprint interface, as listed in Table 3-1.

Table 3-1. Vertical service blueprint APIs.

API Name & Endpoint	Description	Input Parameters	Output (Response)
vs-blueprint GET /api/v1/vsb-catalogue/vs-blueprint	Lists all vertical service blueprints (VSBs) stored in the Service Orchestration & Management catalogue	No parameters	List of available VSB blueprints
vs-blueprint POST /api/v1/vsb-catalogue/vs-blueprint	Onboards a vertical service blueprint into the Service Orchestration & Management catalogue	VSB*	The UUID of the onboarded VSB*
vs-blueprint GET /api/v1/vsb-catalogue/vs-blueprint/{vsblueprintUUID}	Provides details of a vertical service blueprint stored in the Service Orchestration & Management catalogue	UUID of the VSB to get from VSB catalogue	Details of the VSB*
vs-blueprint DELETE /api/v1/vsb-catalogue/vs-blueprint/{vsBlueprintUuid}	Removes a vertical service blueprint from the Service Orchestration & Management catalogue	UUID of the VSB to get from VSB catalogue	Confirmation of removal from the catalogue
*Details in text			

*Details of the vertical service blueprint returned by the Service Orchestration and Management include:

- Universally Unique Identifier (UUID)
- The version of the Vertical Service Blueprint

- Name
- Description
- Details of the functional blocks of the Vertical Service (e.g. applications)
- Service Endpoints represent the interfaces exposed by the Vertical Service, they can also describe the slice profile characteristics (data rate, latency, etc…)
- The connectivity service models logical links which establish the logical relationships between the components of the vertical service (including the endpoints attached)
- A map containing the id of an input parameter and a name as the value, these parameters can be filled in by the Vertical at the provisioning time to customize the service instance
- The application metrics exposed by the vertical service
- The owner associated to the Vertical Service Blueprint
- An identifier for the Vertical Service Blueprint
- An identifier of the associated closed-loop of the service if any
- The target state/performance and function for an automated service action (ex. application migration based on latency and computational availability)

3.1.1.2 Vertical service descriptors

Vertical service descriptors build on a service blueprint for a specific service request, containing customized information including Service Level Agreement (SLA) requirements and other properties of the vertical service. The Service Orchestration and Management provides 4 functionalities to a vertical from the vs descriptor interface, as listed in Table 3-2.

Table 3-2. Vertical service descriptor APIs.

API Name & Endpoint	Description	Input Parameters	Output (Response)
vs-descriptor GET /api/v1/vsb-catalogue/vs-descriptor	Lists all vertical service descriptors (VSDs) stored in the Service Orchestration & Management catalogue	No parameters	List of available VSD blueprints*
vs-descriptor POST /api/v1/vsb-catalogue/vs-descriptor	Onboarding a vertical service descriptor in the Service Orchestration & Management catalogue	VSD*	The UUID of the onboarded VSD*
vs-descriptor GET /api/v1/vsb-catalogue/vs-blueprint/{vsblueprintUUID}	Provides details of a vertical service descriptor stored in the Service Orchestration & Management catalogue	UUID of the VSD to get from VSD catalogue	Details of the VSD*

vs-descriptor DELETE /api/v1/vsb-catalogue/vs-blueprint/{vsBlueprintUuid}	Removes a vertical service descriptor stored in the Service Orchestration & Management catalogue	UUID of the VSD to get from VSD catalogue	Confirmation of removal
*Details in text			

*Details of the Vertical Service Descriptor (VSD) returned by the Service Orchestration and Management include the following information:

- Universally Unique Identifier (UUID)
- A human readable name of the Vertical Service Descriptor
- The version of the Vertical Service Descriptor
- The Unique ID for the associated blueprint (VSB)
- A Map containing the id of an input parameter and a name as the value, these parameters can be filled in by the Vertical at the provisioning time to customize the service instance
- If the VSD will be advertised the to all tenants
- The owner associated to the Vertical Service Descriptor
- Constraints of each component of the service (computing capacity, hardware constraints, type of computing: resource edge, cloud, and location)
- An identifier for the Vertical Service Descriptor
- An identifier of the associated closed-loop of the service if any
- The target state/performance and function for an automated service action (ex. application migration based on latency and computational availability)

3.1.1.3 Lifecycle management of a service instance

The lifecycle management of vertical service instances can be done via interfaces of the Service Orchestration and Management, as reported in Table 3-3. These include service instantiation, termination, reconfiguration of service components, scaling of resources for the service, modification of the service, and migration. The consumer of these interfaces can be the vertical, as well as the execution functions attached to the service via closed-loops.

Table 3-3. Service lifecycle management APIs

API Name & Endpoint	Description	Input Parameters	Output (Response)
terminate POST /api/v1/service-instance-lcm/{serviceInstanceId}/terminate	Terminates a service instance, removing the instance from infrastructure and freeing the resource allocations	UUID of the Service Instance	Confirmation of service instance termination

scale POST /api/v1/service-instance-lcm/{serviceInstanceId}/scale	Scales the resources of a service instance in terms of CPU, memory, storage, and replicas	UUID of the Service Instance and request body with scale request details	The updated instance description*
reconfigure POST /api/v1/service-instance-lcm/{serviceInstanceId}/reconfigure	Reconfiguration of a service instance's components, including applications and closed-loops	UUID of the Service Instance and request body with reconfiguration details	The updated instance description*
modify POST /api/v1/service-instance-lcm/{serviceInstanceId}/modify	Modify a service instance during runtime - dedicated APIs may be added according to specific use case or vertical service automation requirements	UUID of the Service Instance and request body with modification	The updated instance description*
migrate POST /api/v1/service-instance-lcm/{serviceInstanceId}/migrate	Migrates a service instance from one set of resources to another	UUID of the Service Instance and request body with migration details	The updated instance description*
instantiate POST /api/v1/service-instance-lcm/{serviceInstanceId}/instantiate	Service instance instantiation instantiate a service instance onto physical infrastructure from a created service instance	UUID of the Service Instance and request body with instantiation details	The updated instance description*
POST /api/v1/service-instance-lcm/	Creates a service instance from an onboarded vertical service descriptor, to be stored in the instance catalogue for retrieval during service instantiation	Service instance descriptor and request body with service instance details	The updated instance description*
*Details in text			

*Details of the vertical service instance details returned by the Service Orchestration and Management include the following information:

- Universally Unique Identifier (UUID) of the instance
- VSB UUID of the associated VSB
- VSD UUID of the associated VSD
- Tenant UUID associated to the instance
- Name of the instance
- Description of the instance
- Status of the instance (e.g. "CREATED")
- Input parameters
- Error messages of the instance if any
- Closed-loop instance UUID if any
- Service components of the instances including an id, replicas, ports, configuration parameters, nodes, allocated CPU, memory and storage, service component template location and any additional deployment information

3.1.1.4 Vertical service instance catalogue

The vertical service instance catalogue stores the information on service instances used the Service Orchestration and Management as described in the above sub-section. The Service Orchestration and Management retrieves this information from the vertical service instance catalogue via an API interface, as described in Table 3-4.

Table 3-4. Vertical service instance catalogue APIs

API Name & Endpoint	Description	Input Parameters	Output (Response)
vs-descriptor GET /api/v1/service-instance-catalogue/{serviceInstanceId}	Retrieval of a service instance from the Service Orchestration & Management catalogue by its UUID	UUID of the Service Instance to be retrieved	Details of the service instance*
vs-descriptor DELETE /api/v1/service-instance-catalogue/{serviceInstanceId}	Instance deletion from the Service Orchestration & Management catalogue by its UUID	UUID of the Service Instance to be removed	Confirmation of instance deletion
vs-descriptor GET /api/v1/service-instance-catalogue/	Queries of service instances from the Service Orchestration & Management catalogue	No Parameters	Details of service instances*
*Details in text above			

3.1.2 Slice Orchestration and Management

Slice Management and Orchestration Descriptors (SMODs) are essential elements in the lifecycle management of network slices. They provide detailed information about the configuration, requirements, and operational parameters of a network slice. These descriptors build upon the high-level definitions provided by VS-Blueprints and offer specific, customized information necessary for the instantiation, management, and optimization of network slices.

Lifecycle management of network slices refers to the comprehensive process of overseeing the existence and functionality of a network slice from its initial creation through to its eventual termination. This lifecycle management process is designed to ensure that network slices are effectively managed, optimized, and maintained in alignment with the evolving service requirements and operational objectives. *The key phases of network slice lifecycle management include creation, modification, monitoring, scaling, and termination. Here is a full list of functionalities that should be considered* (Table 3-5):

- *Modify Network Slice*: This functionality provides an interface that allows for the dynamic updating of configurations or parameters within an existing network slice, enabling adaptability to changing requirements or conditions.
- *Pause/Resume Network Slice*: These interfaces enable operators to temporarily suspend or resume the operation of a network slice. This can be particularly useful for maintenance activities or during periods of reduced demand, ensuring that resources are used efficiently.
- *Health Check*: This interface facilitates the execution of regular health checks on network slices, ensuring they operate correctly and efficiently. It helps in identifying potential issues before they impact on the overall performance or reliability of the network slice.
- *Event Notification*: This interface is responsible for handling and distributing event notifications related to any changes in the state or performance of network slices. It ensures that operators are immediately informed of any significant events that may require attention or action.
- *Performance Metrics*: This interface allows for the retrieval of detailed performance metrics and logs associated with a network slice. Such data is essential for monitoring performance, diagnosing issues, and making informed decisions regarding the optimization of network slices.
- *Fault Management*: This interface manages fault detection, isolation, and recovery processes within network slices. It ensures that any faults are quickly identified and resolved, minimizing downtime and maintaining service continuity.

Table 3-5. Slice Orchestration and Management APIs

API Name & Endpoint	Description	Input Parameters	Output (Response)
Create Network Slice POST /api/v1/nsm/slices	Creates a new network slice based on provided SMOD configurations.	slice_id (string), config (JSON or XML with slice parameters), blueprint_id (string)	status (string), slice_id (string), message (string)

Modify Network Slice PUT /api/v1/nsm/slices/{sliceId}	Modifies the configuration or parameters of an existing network slice.	slice_id (string), config_updates (JSON or XML with updated parameters)	status (string), message (string), updated_slice_id (string)
Pause Network Slice POST /api/v1/nsm/slices/{sliceId}/pause	Temporarily suspends the operation of a specified network slice.	slice_id (string)	status (string), message (string)
Resume Network Slice POST /api/v1/nsm/slices/{sliceId}/resume	Resumes the operation of a previously paused network slice.	slice_id (string)	status (string), message (string)
Health Check **GET** /api/v1/nsm/slices/{sliceId}/health	Performs a health check on a specific network slice to ensure correct operation.	slice_id (string)	status (string), health_status (string), message (string)
Event Notification POST /api/v1/nsm/events	Handles event notifications related to changes in the state or performance.	eventId (string), slice_id (string), eventDetails (JSON or XML)	status (string), eventId (string), message (string)
Performance Metrics GET /api/v1/nsm/slices/{sliceId}/metrics	Retrieves detailed performance metrics and logs for a specific network slice.	slice_id (string), metric_type (string, e.g., latency, throughput), time_range (start_time, end_time)	status (string), metrics_data (JSON or XML with performance metrics), message (string)

3.1.3 Resource Orchestration and Management

Resource orchestration and management interfaces are essential components in the administration of network infrastructure. These interfaces facilitate the efficient allocation, monitoring, and scaling of resources, ensuring that network services and slices operate optimally. They provide a structured

way to handle the lifecycle of resources, including their creation, update, deletion, and real-time monitoring. Key functionalities include the ability to allocate resources to specific network slices or service instances, deallocating them as needed, and scaling their capacity based on dynamic network demands. Additionally, these interfaces support the retrieval of performance metrics and usage statistics, enabling proactive management and optimization of resources. By leveraging these interfaces, network operators can ensure that resources are utilized effectively, maintaining high levels of service performance and reliability. The list of these interfaces is provided in Table 3-6.

Table 3-6. Resource Orchestration and Management APIs

API Name & Endpoint	**Description**	**Input Parameters**	**Output (Response)**
Create POST /api/v1/resources	Create a new resource	resourceId, resourceType (e.g., compute, storage, network), resourceSpecifications	status, resourceId
Query Resource GET/api/v1/ resources/{resourceId}	Retrieve details of a specific resource	resourceId	resourceId, resourceType, resourceSpecification, status
Update Resource PUT/api/v1/ /resources/{resourceId}	Update an existing resource	resourceId, resourceType, resourceSpecifications	status, resourceId, updatedResourceSpecifications
Delete Resource DELETE /api/v1/resources/{resourceId}	Delete an existing resource	resourceId	status, resourceId
Allocate Resource POST /api/v1/resources/{resourceId}/allocate	Allocate a resource to a network slice or service instance	resourceId, allocationDetails (e.g.,targetSliceId, targetInstanceId, amount)	status, resourceId, allocationDetails
Deallocate Resource POST /resources/{resourceId}/deallocate	Deallocate a resource from a network slice or service instance	resourceId, deallocationDetails (e.g.,targetSliceId, targetInstanceId, amount)	status, resourceId, deallocationDetails

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Scale Resource PUT/api/v1/resources/{resourceId}/scale	Scale the capacity of a specific resource	resourceId, scaleType (up or down), scaleParameters (e.g.,newCapacity, newSpecifications)	status, resourceId, newResourceSpecifications
Monitor Resource GET /api/v1/resources/{resourceId}/monitor	Retrieve the monitoring data of a specific resource	resourceId	resourceId, currentStatus, performanceMetrics
Query Resource Usage GET/api/v1/resources/{resourceId}/usage	Retrieve usage statistics of a specific resource	resourceId	resourceId, usageStatistics
Retrieve Resource List GET/api/v1/ resources	Retrieve list of all resources	None	resources (list of resources with resourceId, resourceType, resourceSpecifications)

3.1.4 Closed-loop Governance

The Closed-loop Governance interacts with the Service Orchestration & Management and the AI/ML for CrowdSourcing AI framework blocks as shown in Figure 2-2. The Closed-loop Governance interacts with the Service Orchestration and Management for receiving closed-loop service requests, the Resource Orchestration & Management for sending requests for deployment of closed-loop functions, the closed-loop functions for Lifecycle management, and the CrowdSourcing AI for setting up needed AI/ML services for closed-loop functions.

The Closed-loop Governance supplies interfaces for triggering actions from a including the onboarding of closed-loop and closed-loop functions service descriptors, instantiation, termination, modification, or monitoring of a closed-loop attached to a vertical service.

The requirements for the interfaces can be dived into 4 groups of services described below.

3.1.4.1 Closed-loop descriptors

Closed-loop descriptors contain information on the closed-loop composition such as goals, policies, and components and are used to create and deploy closed-loop instances attached to vertical services. The descriptors can be onboarded into the Closed-loop Governance catalogue for use in vertical services to perform specific actions for a service (e.g. service migration based on metrics). Each descriptor receives a UUID from the Governance when it is onboarded, which can be included in a vertical service descriptor used by the Service Orchestration and Management.

Table 3-7 presents the 4 provided functionalities from the closed-loop descriptors interface.

Table 3-7. Closed-loop descriptors APIs

API Name & Endpoint	Description	Input Parameters	Output (Response)
cl-descriptor GET /api/v1/cl-catalogue/cl-descriptor/	List all closed loop composite functions descriptors stored in the CL Function repository	No Parameters	Details on all closed-loop descriptors*
cl-descriptor POST /api/v1/cl-catalogue/cl-descriptor/	Onboards a closed loop composite function descriptor- this contains the information on the function such as type, input events, input metrics, output events, etc.	Closed-loop descriptor	The saved closed-loop descriptor
cl-descriptor GET /api/v1/cl-catalogue/cl-descriptor/{id}	Provides details of a a closed loop composite function descriptor that has been stored in the CL Function repository, using the descriptor ID	UUID of the Closed loop Descriptor to get from Closed-loop catalogue	Details on the closed-loop descriptor*
cl-descriptor DELETE /api/v1/cl-catalogue/cl-descriptor/{id}	Removes a closed loop composite function descriptor from the CL Function repository using descriptor ID	UUID of the Closed loop Descriptor to get from Closed-loop catalogue	Confirmation of descriptor deletion
*Details in text			

*Details of the closed-loop descriptor returned by the Service Orchestration and Management include the following information about the closed-loop service:

- UUID
- Name
- Description
- Version
- Vendor
- Priority of the closed-loop service
- Timing Category (e.g. SHORT_TERM, LONG_TERM)
- Reaction Category (e.g. REACTIVE, PREDICTIVE)
- Target layer of the network (e.g. SERVICE)
- Cognitive Cl signals if the closed-loop leverage AI/ML models
- Coordination Support signals if this closed-loop requires coordination with other closed-loops
- Details and conditions of the goals of the closed-loop (e.g. type, conditions, targets, actions)

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- Manageable entities of the closed-loop (e.g. application resources)
- Policies of the closed-loop
- UUIDs of the components of the closed-loop (e. Monitoring, analysis, decision, execution) Closed-loop report scheme (e.g. PERIODICAL, 10 seconds intervals)

3.1.4.2 Closed-loop function descriptors

Closed-loops are comprised of a set of closed-loop functions (the composite blocks of a closed-loop). The supported closed-loop functions in ADROIT6G include the composite functions of BDIx agents as well as:

Monitoring (ME): for ingestion and processing of real-time and near-real time data from the system being monitored and optimized by the closed-loop.

Analytics (AE): for analysis of the incoming data stream from the monitoring function, the analytics of the data could be done using AI/ML algorithms provisioned by the Closed-loop Governance;

Decision/Execution (DE): for determining and executing an action to achieve a desired state defined in closed-loop policies, which also could include AI/ML elements for assisted decision making.

The Closed-loop governance is responsible for creating closed-loop services from these composite functions, instantiating and configuring the service using information provided in descriptors. Table 3-8 presents the 4 provided functionalities from the closed-loop descriptors interface.

Table 3-8. Closed-loop function descriptor APIs

API Name & Endpoint	**Description**	**Input Parameters**	**Output (Response)**
function-descriptor GET /api/v1/cl-catalogue/function-descriptor/	Lists all closed loop descriptors stored in the repository – these descriptors are used to create closed-loop instances and contain information on composite closed-loop functions	No Parameters	Details on all closed-loop functions *
function-descriptor POST /api/v1/cl-catalogue/function-descriptor/	Onboards a closed loop function descriptor into the Closed-loop Governance catalogue, this can be later used to instantiate a closed-loop service	Closed-loop descriptor	The saved closed-loop function descriptor
function-descriptor GET /api/v1/cl-catalogue/function-descriptor/{id}	Provides a closed loop descriptor from the repository using the descriptor ID	UUID of the Closed loop Descriptor to get from	Details on the closed-loop function *

		Closed-loop catalogue	
function-descriptor DELETE /api/v1/cl-catalogue/function-descriptor/{id}	Removes a closed loop function's descriptor from the Closed-loop Governance catalogue using the descriptor ID	UUID of the Closed loop Descriptor to get from Closed-loop catalogue	Confirmation of descriptor deletion
*Details in text			

*Details on the closed-loop function include the description, if it has been orchestrated, if it is a sharable between closed-loops, the number of replicas, the orchestration template, any input parameters (e.g., parameter data, input/output topic from the inter-function communication), and model details if the function leverages AI/ML.

3.1.4.3 Lifecycle management of closed-loop instances

The lifecycle management of closed-loop instances includes instantiation, termination, dynamic updates to the services, as well as providing information on the state of the instances. Table 3-9 lists the supported actions on a closed-loop instance available through the lifecycle management interface.

Table 3-9. Lifecycle management of closed-loop instances APIs

API Name & Endpoint	Description	Input Parameters	Output (Response)
update POST /api/v1/closed-loop/update/{closedLoopInstanceId}	Updates a closed-loop using instance ID to scale or alter the closed-loop or composite functions at runtime	UUID of the closed-loop instance	Details of the closed-loop instance*
terminate POST /api/v1/closed-loop/terminate/{closedLoopInstanceId}	Terminates a closed-loop instance, removing it from infrastructure and freeing allocated resources	UUID of the closed-loop instance	Confirmation of instance termination

instantiate POST /api/v1/closed-loop/instantiate/{closedLoopInstanceId}	Instantiates a closed-loop instance	UUID of the closed-loop instance	Details of the instantiated instance
instances GET /api/v1/closed-loop/instances	Lists all closed-loop instances that have been created and stored in the repository, see workflow 1 above for details on how instances are used by the Closed-loop Governance	No parameter	Details of all closed-loop instances
instances POST /api/v1/closed-loop/instances	Creates a closed-loop instance that can then be called for instantiation	Closed-loop descriptor ID and any additional parameters*	Details of the created instance
instances GET /api/v1/closed-loop/instances/{closedLoopInstanceId}	Provides details of a closed-loop instance*	UUID of the closed-loop instance	Details of the closed-loop instance*
cl-event	Lists details of the receive/notify (type, cl instance id, function instance id, affected resources) from the closed-loop instance	UUID of the closed-loop instance, ID of the closed-loop function instance	List of all events of the functions*
*Details in text			

*Details of the closed-loop instance include UUID, name, description, closed-loop descriptor UUID, priority, status of the instance, and information on the composite functions including deployment information and configuration parameters.

Additional parameters that can be provided in the creation of a closed-loop instance in addition to the descriptor include name, description, priority, and configuration parameters.

3.1.4.4 Closed-loop policies

Closed-loop policies contain the information regarding

Closed-loop policies contain the plans that are used as the basis for closed-loop operations, called policy statements. This can include information such as closed-loop goals, conflict rules, and

interactions among closed-loop functions. Table 3-10 lists the supported actions on a closed-loop policy available through the closed-loop policy interface.

Table 3-10. Closed-loop policies APIs

API Name & Endpoint	Description	Input Parameters	Output (Response)
policy GET/api/v1/policy-catalogue/policy	Lists all closed loop policies that have been onboarded and stored in the repository	Optional query parameters*	list of closed-loop policies matching the query parameters
policy POST /api/v1/ policy-catalogue/policy	Onboards a closed loop policy, policies are exploited heavily in the governance of BDIx agents to govern the state of the target system	Policy descriptor*	UUID of the policy
policy GET/api/v1/ policy-catalogue/policy /{closedLoopPolicyId}	Provides details of a closed loop policy that has been onboarded and stored in the repository using the policy UUID	UUID of the policy	Policy descriptor*
policy DELETE /api/v1/ policy-catalogue/policy /{closedLoopPolicyId}	Removes a closed loop policy from the repository using policy UUID	UUID of the policy	confirmation
update POST /api/v1/ policy-catalogue/update/{closedLoopPolicyId}	Updates a closed loop policy, update the attributes, type, or description of a policy using the policy UUID	UUID of the policy	New policy descriptor
*Details in text			

*Query parameters for the closed-loop policies can include closed-loop descriptor ID, name of policy, and the closed-loop function type/ID.

*Policy descriptors contain the name, target descriptor/function, and policy statement.

3.2 AI/ML Framework for Crowdsourcing

As defined in Section 2.1.2, the Fully distributed and secure AI/ML Framework for CrowdSourcing AI provides the AI mechanisms to assist the M&O and the control frameworks in their decisions. In what follows, the interfaces among the different components of the framework are discussed, following the configuration of the framework that is presented in Figure 2-4.

3.2.1 AI-ML Orchestrator

The AI/ML Orchestrator is responsible for processing requests pertaining to model services such as model training, selection, and deployment. The Orchestrator encompasses the AI/ML Pipeline Manager, AI/ML Orchestrator Engine, and the AI/ML Model Selection functionalities which execute the requests. To offer a complete E2E solution for deployment of model services, the Orchestrator consumes the interfaces from the Model Catalogue for model information, Data Registry for data information, and the AI/ML Resource Manager/Agents for deploying applications of model services.

The interfaces exposed by the AI/ML Orchestrator fall under 5 categories: pipelines, traditional centralized model training, model selection, model deployment, and model federations.

3.2.1.1 Pipelines

Pipelines are built from pipeline blueprints which contain the basic steps in a model training or deployment process (e.g. pull data, model tuning, train model, evaluate model, push model), as illustrated for centralized model training in Figure 3-1. In addition to the information contained in the blueprint, a pipeline instance contains information for a particular deployment (e.g. required resources, deployment constraints, etc.).

A simple deployed training pipeline reads training data from an endpoint, performs model-dependent transformations, trains the model, and evaluates the model before the model, performance, and metadata are saved to the Model Catalogue. The complexity of the training pipeline blueprint, and in turn of the deployed pipeline, depends on the requirements of the processes (centralized/federated) and model development. A deployment pipeline blueprint on the other hand, contains the steps needed to deploy an instance of a model serving, either reachable via an interface to the user for continuous inference, or in a one-shot inference the output of the model is returned to the user.

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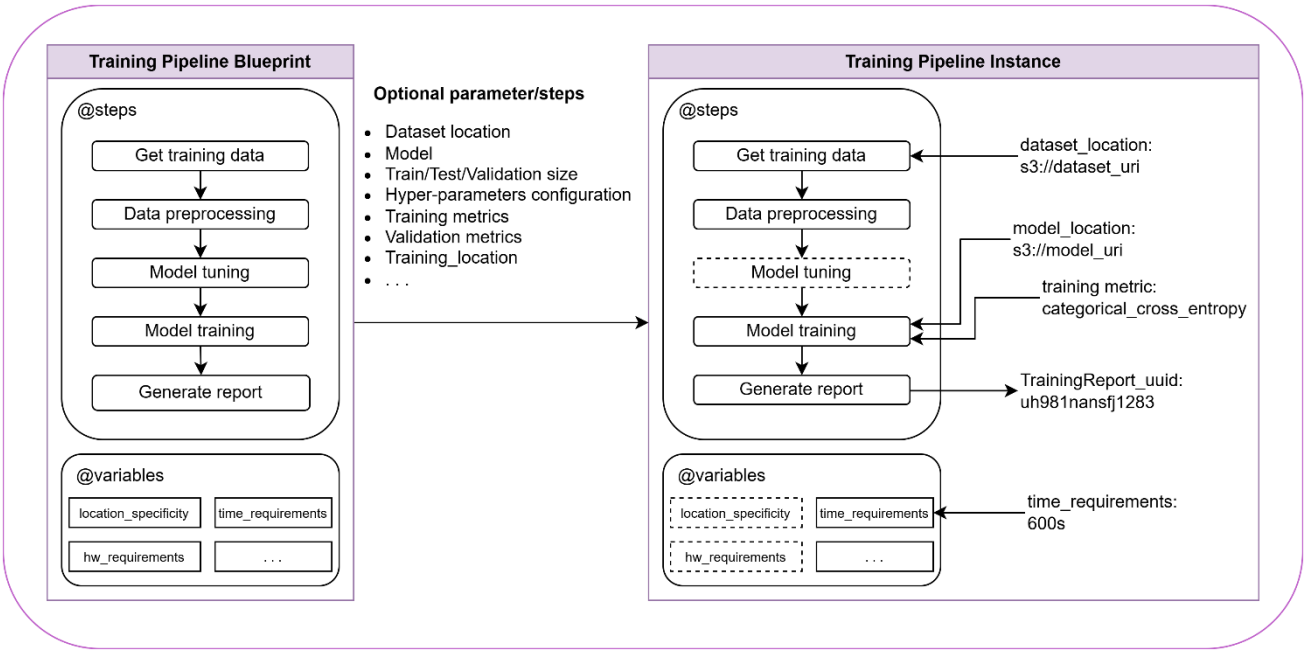

Figure 3-1. Model training pipeline blueprint and pipeline instance

Table 3-11 lists the APIs of the AI/ML Orchestrator that involve pipeline and pipeline blueprint actions.

Table 3-11. Model pipeline APIs

API Name & Endpoint	Description	Input Parameters	Output (Response)
ml-pipeline-blueprint GET /api/v1/pl-catalogue/	List all pipeline blueprints available in the pipeline catalogue	No Parameters	Details on all pipeline blueprints *
ml-pipeline-blueprint POST /api/v1/pl-catalogue/	Onboards a pipeline blueprint into the pipeline catalogue	Pipeline blueprint	Pipeline blueprint UUID
ml-pipeline-blueprint GET /api/v1/pl-catalogue/{id}	Provides details of a pipeline blueprint*	UUID of the pipeline to get from the catalogue	Details on the pipeline blueprint*
ml-pipeline-blueprint DELETE /api/v1/pl-catalogue/{id}	Removes a pipeline blueprint from the pipeline catalogue	UUID of the pipeline to get from	Confirmation of pipeline blueprint deletion

		the catalogue	
ml-pipeline GET /api/v1/pl-catalogue/	List all pipelines available in the pipeline catalogue	No Parameters	Details on all pipeline instances *
ml-pipeline POST /api/v1/pl-catalogue/	Onboards a pipeline into the pipeline catalogue	pipeline	Pipeline UUID
ml-pipeline GET /api/v1/pl-catalogue/{id}	Provides details of a pipeline*	UUID of the pipeline to get from the catalogue	Details on the pipeline instance *
ml-pipeline DELETE /api/v1/pl-catalogue/{id}	Removes a pipeline from the pipeline catalogue	UUID of the pipeline to get from the catalogue	Confirmation of pipeline deletion
*Details in text			

*Details on a pipeline blueprint provided by the AI/ML Orchestrator include a list and description of the composite functions that constitute the model training or deployment. Details on a pipeline instance include the reference blueprint and deployment history.

3.2.1.2 Traditional centralized model training

For traditional centralized model training/retraining, a training pipeline is deployed in a single location to produce a model to be stored, along with metadata, in the Model Catalogue. The deployed training pipeline is considered a training instance with a unique id (UUID), tracked by the Pipeline Manager. Table 3-12 lists the APIs of the AI/ML Orchestrator that involve traditional centralized model training.

Table 3-12. Centralized model training APIs

API Name & Endpoint	Description	Input Parameters	Output (Response)
model-training POST /api/v1/model-training/	Instantiates a training instance of a model on infrastructure	Pipeline UUID, additional deployment	Model-training instance UUID and information on the

		constraints (optional)	training instance*
model-training POST /api/v1/model-training/{modelID}	Instantiates a model training instance to train a new version of a model pre-existing in the catalogue	UUID of the pipeline	Model-training instance UUID and information on the training*
training-instance GET /api/v1/model-training/{trainingID}	Queries an instantiated training instance	Model-training instance UUID	Model-training instance UUID and information on the training*
training-instance GET /api/v1/model-training	Lists all instantiated training instances	-	Details on all instantiated training instances*
training-instance DELETE /api/v1/model-training/{trainingID}	Terminates a running training instance, freeing allocated resources	Model-training instance UUID	Confirmation of training instance deletion
*Details in text			

*Information on the training instance include the training instance UUID, associated pipeline UUID, and the execution logs for the training instance.

3.2.1.3 Model deployment

Model deployment involves making a model available for inference on infrastructure. A model deployment instance is created from a deployment pipeline stored in a Pipeline Manager catalogue. There are 2 categories of model deployment considered by the AI/ML Orchestrator. The first is for one-shot inference, where an actor requires an inference response from a model. The actor can choose to provide the input data or set requirements about the input data that the Orchestrator Engine can use to create the required dataset. In this scenario, if a model is not already deployed, a model instance is created on infrastructure that meets the requirements of the model and actor, and a dataset is used to obtain an inference returned to the actor.

The second category involves a model instance that allows continuous inference through a model interface, accessible by the actor requesting the model instance. An example of this is a closed-loop

function that leverages AI for the continuous analysis of a stream of input data. The location of the model instance can be chosen by the actor or chosen by the Orchestrator based on actor defined parameters (i.e. requirements on latency, computational resources, etc.).

Table 3-13 lists the APIs from the AI/ML Orchestrator for actions on model deployments.

Table 3-13. Model Deployment APIs

API Name & Endpoint	Description	Input Parameters	Output (Response)
model-deploy POST /api/v1/model-deploy	Deploys a model inference instance using a model-deployment pipeline	Pipeline UUID, deployment parameters*	Deployment UUID
model-deploy DELETE /api/v1/ model-deploy	Terminate a running model deployment instance, freeing allocated resources	Deployment UUID	Confirmation of deployment termination
model-deploy GET /api/v1/model-deploy/{deploymentId}	Retrieve information on a running, finished, or terminated model deployment instance	Deployment UUID	Status information on the deployment instance
model-deploy GET /api/v1/model-deploy/	Retrieve all deployment instances	No parameters	Status information on all deployment instances
model-deploy POST /api/v1/model-deploy/{deploymentId}	Update a deployment instance	Deployment UUID	Confirmation of deployment instance update
*Details in text			

*Deployment parameters include the model UUID, location for deployment, required resources (CPU, storage, etc.), and any user-defined parameters for the model.

3.2.2 AI/ML Catalogue

The AI/ML Catalogue is responsible for the organization and tracking of ML models in the Model Storage. The Catalogue interacts with the AI/ML Orchestrator or other actor to seamlessly provide

model information including model file endpoints, metadata, and tags. Model metadata and tags are used by the Orchestrator in the model selection functionality. Tags allow for a high-level selection process based on categories, including model type, target execution environment, and target application. The metadata can be used for a more fine-grained selection on properties such as training metrics and performance. Table 3-14 lists the APIs associated with the AI/ML Catalogue interface.

Table 3-14. Model Catalogue APIs

API Name & Endpoint	Description	Input Parameters	Output (Response)
ml-catalogue GET /api/v1/ml-catalogue	Query the model catalogue for all available stored models	Tags(optional)*	List of model UUIDs
model POST /api/v1/ml-catalogue/model	Saves and registers a new model in the Model Catalogue	Model file, model metadata*	UUID for the model in the model catalogue
model POST /api/v1/ ml-catalogue/model/{modelId}	Registers a new version of an existing registered model in the Model Catalogue	Model UUID, model file, metadata	Confirmation of new model version
model POST /api/v1/ml-catalogue/model-update	Updates model tags in the Model Catalogue	Tags, model UUID, version(optional)	Updated information on the model
model GET /api/v1/ml-catalogue/model/{modelId}	Provides details about a model stored in the Model Catalogue	Model UUID	Information on the model*
model DELETE /api/v1/ml-catalogue/model/{modelId}	Delete a model that has been previously stored in the model catalogue	Model UUID, version to be deleted {optional}	Confirmation of the removal of the model from the Model Catalogue
*Details in text			

*Model tags are used to group models for model selection purposes, they contain generalized information including model type, purpose, and features (e.g. GPU optimized). The model metadata includes the input and output schema of the model, execution environment requirements, training

metrics, training dataset information, model description, and training parameters. The model information returned by the Model Catalogue includes training metrics, tags, and versions.

3.2.3 State-of-the-Art components used by ADROIT6G

i) Agents

The AI/ML Framework leverages several State-of-the-Art (SoTA) components to act as agents located on edge/cloud resources that create instances of AI services for training and model serving. Supported agents include Prefect Workers [11], Seld on Operators [12], and KServe Controllers [13]. These agents create instances of services that are accessible either through the Prefect Server or via APIs, as depicted in Figure 3-2.

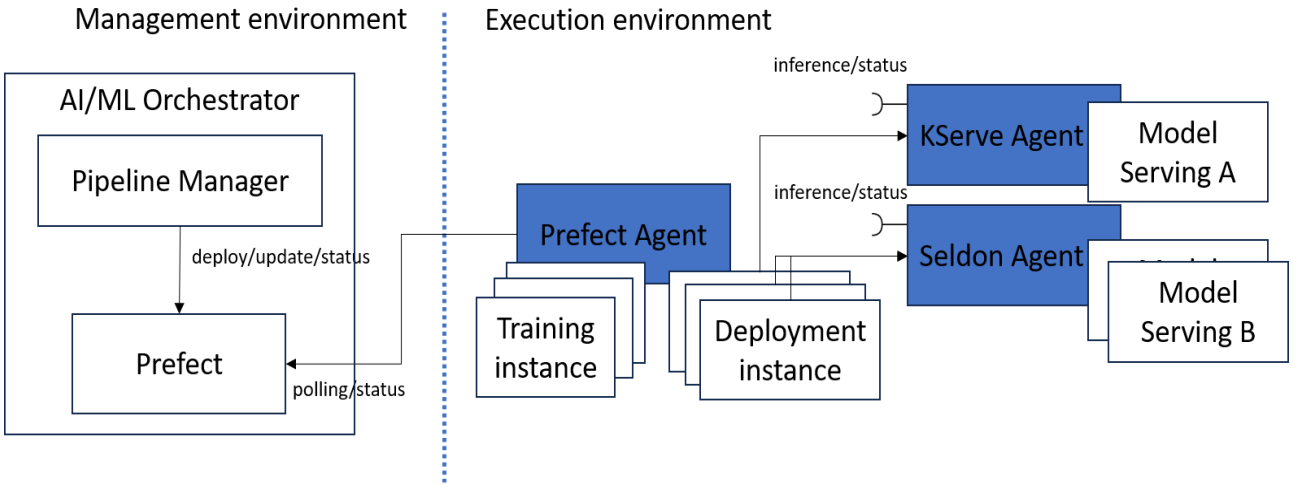

Figure 3-2. Interface scheme for Agents used by the Pipeline Manager.

ii) Model storage

The AI/ML Framework uses PostgreSQL [14] as a backend store for model training entities (e.g. runs, parameters, metrics, tags, notes, and metadata) and MinIO [15] to store model training artifacts (e.g. models, datasets and configuration files). These solutions have been integrated into the framework.

iii) Data repository

ADROIT6G will consider a state-of-the-art data repository module, which is able to store and organize data in a secured and structured environment, as well as to allow easy data access, data retrieval, and data sharing. The functionality of this module follows the Unified Data Repository Services of ETSI and includes:

a. Data Storage: This unit is responsible for the storage of all data, including, and very importantly, datasets to be used for ML model training.
b. Configuration Management: It stores configurations for network devices such as routers, switches, firewalls, and servers. This includes storing configuration backups, version histories, and templates for deploying configurations across multiple devices.

c. Fault Management: The repository stores logs and records of network faults, errors, and alarms generated by network devices.
d. Security Event Logging: Security-related are stored in the repository for auditing, compliance, and forensic analysis purposes.
e. Subscriber Data Management: The repository may store subscriber profiles, service subscriptions, and other user-related data.
f. Policy and Compliance Management: It stores network policies, access control lists, compliance regulations, and regulatory requirements. This facilitates adherence to security policies and regulatory standards.
g. Data Analytics and Reporting: The repository may support data analytics tools and reporting capabilities for extracting insights from network data, generating performance reports, trend analysis, capacity planning, and forecasting.
h. Backup and Disaster Recovery: Regular backups of data are stored in the repository to ensure data integrity and facilitate disaster recovery in case of system failures, data corruption, or security breaches.

iv) Data registry

ADROIT6G will consider a state-of-the-art data registry module which is responsible for managing metadata, schemas, and data definitions across the network infrastructure. The data registry follows the principles of DataHub or Apache Atlas, and it focuses on the organization, validation, and standardization of data structures and semantics within the network environment. In addition, the data registry module is able to ensure data consistency, quality, and interoperability within network applications, enabling efficient data management, governance, and innovation across the network ecosystem. The data registry may include the following functionalities:

a. Schema Management, which is required for the definition and management of data schemas.
b. Metadata Repository, which serves as a central repository for storing metadata, including descriptive information, data lineage, data ownership, versioning information, and relationships between data entities.
c. Data Standardization, which aims at ensuring consistency, interoperability, and compliance of the data with industry standards and organizational policies.
d. Data Validation and Verification, which ensures data integrity, accuracy, completeness, and adherence to specified data standards.
e. Data Governance and Compliance, which provides data governance initiatives support, by enforcing data governance policies, access controls, data lineage tracking, and audit trails. This ensures regulatory compliance, data privacy, and security requirements.
f. Data Discovery and Cataloging, which provides mechanisms for discovering, searching, and browsing data schemas, metadata, and data dictionaries.
g. Data Lifecycle Management, in order to manage the lifecycle of data schemas and metadata, including creation, registration, modification, deprecation, and retirement of data entities. This ensures proper governance and maintenance of network data assets.

v) Resource manager

The AI/ML framework uses REC-EXEC (Resource Orchestrator for Continuum across Extreme-edge, Edge, Cloud) to provide resource discovery, resource monitoring, resource inventory, and cross-platform service deployment. RecExec is a software prototype by NXW for resource orchestration in (extreme) edge – cloud continuum developed in the Hexa-x-ii project [16]. RecExec It includes multi-platform support for K8s, K3s, MicroK8s, and OpenStack, and extensible resource modelling for definition of computing nodes with additional capabilities and constraints (IoT, sensors and actuators, robots/cobots, drones, cameras, etc.).

3.3 BDI- & AI-driven Unified & Open Control Operations Framework

The BDI- & AI-driven Unified & Open Control Operations Framework is responsible for the real-time and near-real-time close loops for the network automation. It coordinates the dynamic and inter-domain resource allocation in the short term, based on the current network condition and context-aware predictions. This framework is also responsible for the provisioning and control of the BDIx agents in the various domains and the dynamic re-configuration of their logic, and the control of the UE-VBS Computing resources exploiting the capabilities of the Mobile devices at the far edge. In addition, it provides for the joint scheduling of RAN and edge/far-edge resources and for the context-aware prediction for off-loading, targeting enhanced network performance and resource efficiency. In what follows, the interfaces among the different components of the framework are discussed, following the configuration of the BDI- & AI-driven Unified & Open Control Operations Framework.

3.3.1 BDIx agents

The BDIx agents interact with various system components to provide decentralized, distributed control and bring intelligence to every mobile device in the network, as illustrated at the low part of Figure 2-2. The BDIx agents' interface with the Service Orchestration & Management and AI/ML components for managing autonomous decisions across the network, the Resource Orchestration & Management for deploying agent-related functions, and the Volumetric Capture System for capturing real-time data. These interactions leverage REST APIs for all exposed interfaces.

Key Components of BDIx agent:

- **Beliefs**: These are the informational states or data that an agent has about the world, which can be updated based on sensor inputs or communications from other agents. Beliefs help the agent form an understanding of the current state of the environment.
- **Desires**: These represent the goals or objectives that an agent wants to achieve. Desires are influenced by the agent's beliefs and can lead to specific intentions if they align with the current context and priorities.
- **Intentions**: These are the committed plans or actions that an agent decides to pursue to achieve its desires. Intentions guide the agent's behavior and dictate the sequence of actions it will take.
- **Plans**: These are predefined sequences of actions or strategies that an agent can execute to achieve its intentions. Plans are related to the beliefs and desires of the agent.
- **Goals**: These are the desired outcomes or end states that an agent aims to achieve. Goals are more specific than desires and are typically tied to concrete actions and plans.

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- **ANFIS (Adaptive Neuro-Fuzzy Inference System) Plan Library**: This is a repository of all possible plans that an agent can execute. The plan library allows the agent to select and execute the appropriate plan based on its current beliefs and desires and by setting prioritise values. ANFIS is a type of artificial intelligence model that combines neural networks and fuzzy logic principles to create a system capable of learning and adapting. ANFIS models are used to update the decision-making capabilities of BDIx agents.
-

Interface Schema for BDIx Agents:

Actions Involving Descriptors: These actions manage the descriptors for BDIx functions and general descriptors. They involve retrieving, onboarding, and removing descriptors, as described in Table 3-15Table 3-15.

Table 3-15. BDIx agents' APIs for actions involving descriptors.

API Name & Endpoint	Description	Input Parameters	Output (Response)
GET /function-bdix-catalogue	Retrieve all BDIx functions descriptors	None	List of BDIx function descriptors
POST /function-bdix-catalogue	Onboard a BDIx function descriptor	BDIx function descriptor	Confirmation of function onboarding
GET /function-bdix-catalogue/{functionId}	Retrieve a specific BDIx function descriptor	functionId	Specific BDIx function descriptor
DELETE /function-bdix-catalogue/{functionId}	Remove a BDIx function descriptor	functionId	Confirmation of function removal
GET /descriptor-bdix-catalogue	Retrieve all BDIx descriptors	None	List of BDIx descriptors
POST /descriptor-bdix-catalogue	Onboard a BDIx descriptor	BDIx descriptor	Confirmation of descriptor onboarding
GET /descriptor-bdix-catalogue/{descriptorId}	Retrieve a specific BDIx descriptor	descriptorId	Specific BDIx descriptor
DELETE	Remove a BDIx descriptor	descriptorId	Confirmation of descriptor removal

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/descriptor-bdix-catalogue/{descriptorId}			

Actions Involving Instances: These actions manage the instances of BDIx agents. They include creating, retrieving, and notifying events related to BDIx instances, as presented in Table 3-16. The agent initialization process involves sending the necessary beliefs, desires, and plans related to the desires (e.g., DAIS) to the agent. The agent also receives the policy XML file, which is linked to the agent's unique ID. As part of handling the policy XML file, the agent first deletes all existing policies and then resets its policies based on the new XML file. Subsequently, the agent trains the ANFIS model according to the updated policies. Additional instructions may be sent to the agent before finally creating the BDIx agent instance and retrieving the associated agent ID.

Table 3-16. BDIx agents' APIs for actions involving instances.

API Name & Endpoint	Description	Input Parameters	Output (Response)
GET /bdix-instances	Retrieve BDIx instances	None	List of BDIx instances
POST /bdix-instances	Create a BDIx instance	BDIx instance data such as Beliefs, Desires, Plans related to Desires, Policy XML file (according to the Figure YYY)	Confirmation of BDIx instance creation with BDIx agent ID
GET /bdix-instances/{instanceId}	Retrieve a specific BDIx instance	instanceId	Specific BDIx instance
POST /bdix-event	Receive/notify events (type, instance id, function instance id, affected resources)	Event data (type, instance id, function instance id, affected resources)	Confirmation of event receipt/notification

Actions Involving Policies: These actions handle policies related to BDIx agents. They include retrieving, onboarding, and removing policies, as well as managing the BDIx agent lifecycle, as presented in Table 3-17.

Table 3-17. BDIx agents' APIs for actions involving policies

API Name & Endpoint	Description	Input Parameters	Output (Response)
GET /bdix-policy	Retrieve all BDIx policies	None	List of BDIx policies

POST /bdix-policy	Onboard a BDIx policy	BDIx policy data	Confirmation of BDIx policy onboarding with Policy Id
GET /bdix-policy/{policyId}	Retrieve a specific BDIx policy	policyId	Specific BDIx policy
DELETE /bdix-policy/{policyId}	Remove a BDIx policy	policyId	Confirmation of BDIx policy removal
POST /bdix-lcm/update	Update the BDIx agent lifecycle	BDIx lifecycle data	Confirmation of lifecycle update
POST /bdix-lcm/terminate	Terminate the BDIx agent lifecycle	BDIx agent ID	Confirmation of lifecycle termination
POST /bdix-lcm/instantiate	Instantiate the BDIx agent lifecycle	BDIx lifecycle data	Confirmation of lifecycle instantiation

Actions Involving Beliefs: These actions manage the beliefs within BDIx agents, including onboarding, retrieving, and notifying events related to beliefs, as described in Table 3-18.

Table 3-18. BDIx agents' APIs for actions involving descriptors

API Name & Endpoint	Description	Input Parameters	Output (Response)
GET /beliefs-catalogue	Retrieve all beliefs descriptors	None	List of beliefs descriptors
POST /beliefs-catalogue	Onboard a belief descriptor	Belief descriptor	Confirmation of belief onboarding
GET /beliefs-catalogue/{beliefId}	Retrieve a specific belief descriptor	beliefId	Specific belief descriptor
DELETE /beliefs-catalogue/{beliefId}	Remove a belief descriptor	beliefId	Confirmation of belief removal
GET /beliefs-instances	Retrieve instances of beliefs	None	List of belief instances
POST /beliefs-instances	Create an instance of a belief	Belief data	Confirmation of belief instance creation
GET /beliefs-instances/{instanceId}	Retrieve a specific instance of a belief	instanceId	Specific belief instance
POST /beliefs-event	Receive/notify belief-related events (type, instance id, function instance id, affected resources)	Event data (type, instance id, function instance id, affected resources)	Confirmation of event receipt/notification

Actions Involving Desires: These actions manage the desires within BDIx agents, including onboarding, retrieving, and notifying events related to desires, as described in Table 3-19Table 3-19.

Table 3-19. BDIx agents' APIs for actions involving desires

API Name & Endpoint	Description	Input Parameters	Output (Response)
GET /desires-catalogue	Retrieve all desires descriptors	None	List of desires descriptors
POST /desires-catalogue	Onboard a desire descriptor	Desire descriptor	Confirmation of desire onboarding with desire id
GET /desires-catalogue/{desireId}	Retrieve a specific desire descriptor	desireId	Specific desire descriptor
DELETE /desires-catalogue/{desireId}	Remove a desire descriptor	desireId	Confirmation of desire removal
GET /desires-instances	Retrieve instances of desires	None	List of desire instances
POST /desires-instances	Create an instance of a desire	Desire data	Confirmation of desire instance creation
GET /desires-instances/{instanceId}	Retrieve a specific instance of a desire	instanceId	Specific desire instance
POST /desires-event	Receive/notify desire-related events (type, instance id, function instance id, affected resources)	Event data (type, instance id, function instance id, affected resources)	Confirmation of event receipt/notification

Actions Involving Intentions: These actions manage the intentions within BDIx agents, including onboarding, retrieving, and notifying events related to intentions, as presented in Table 3-20.

Table 3-20. BDIx agents' APIs for actions involving intentions.

API Name & Endpoint	Description	Input Parameters	Output (Response)
GET /intentions-catalogue	Retrieve all intentions descriptors	None	List of intentions descriptors
GET /intentions-catalogue/{intentionId}	Retrieve a specific intention descriptor	intentionId	Specific intention descriptor

GET /intentions-instances	Retrieve instances of intentions	None	List of intention instances
GET /intentions-instances/{instanceId}	Retrieve a specific instance of an intention	instanceId	Specific intention instance
POST /intentions-event	Receive/notify intention-related events (type, instance id, function instance id, affected resources)	Event data (type, instance id, function instance id, affected resources)	Confirmation of event receipt/notification

Actions Involving Plans Related to Desire: These actions manage plans related to desires within BDIx agents, including onboarding, retrieving, and notifying events related to plans (Table 3-21).

Table 3-21. BDIx agents' APIs for actions involving plans related to desire.

API Name & Endpoint	Description	Input Parameters	Output (Response)
GET /plans-catalogue	Retrieve all plans descriptors	None	List of plans descriptors
POST /plans-catalogue	Onboard a plan descriptor to a specific Desire	Plan descriptor, Desire ID	Confirmation of plan onboarding
GET /plans-catalogue/{planId}	Retrieve a specific plan descriptor	planId	Specific plan descriptor
DELETE /plans-catalogue/{planId}	Remove a plan descriptor	planId	Confirmation of plan removal
GET /plans-instances	Retrieve instances of plans	None	List of plan instances
POST /plans-instances	Create an instance of a plan	Plan data	Confirmation of plan instance creation
GET /plans-instances/{instanceId}	Retrieve a specific instance of a plan	instanceId	Specific plan instance
POST /plans-event	Receive/notify plan-related events (type, instance id, function instance id, affected resources)	Event data (type, instance id, function instance id, affected resources)	Confirmation of event receipt/notification

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Actions Involving ANFIS Model Plan Library: These actions manage ANFIS model updates within BDIx agents, including onboarding, retrieving, and updating ANFIS models (Table 3-22).

Table 3-22. BDIx agents' APIs for actions involving ANFIS model plan library.

API Name & Endpoint	Description	Input Parameters	Output (Response)
GET /anfis-instances	Retrieve instance of ANFIS model	Id of the instance	Instance of ANFIS model
POST /anfis-instances	Create an instance of an ANFIS model and substitute the existing	None	Confirmation of instance creation with Id of the instance
GET /anfis-train	Train the ANFIS model from local policies	None	Training confirmation
POST /anfis-retrain	Retrain the ANFIS model with new dataset of policies (policy XML file)	Policy XML file	Retraining confirmation
POST /anfis-update	Update an ANFIS model with new model data	New model data	Update confirmation

Actions Involving Goals: These actions manage goals within BDIx agents, including onboarding, retrieving, and notifying events related to goals (Table 3-23).

Table 3-23. BDIx agents' APIs for actions involving goals.

API Name & Endpoint	Description	Input Parameters	Output (Response)
GET /goals-catalogue	Retrieve all goals descriptors	None	List of goals descriptors
GET /goals-catalogue/{goalId}	Retrieve a specific goal descriptor	goalId	Specific goal descriptor
GET /goals-instances	Retrieve instances of goals	None	List of goal instances
GET /goals-instances/{instanceId}	Retrieve a specific instance of a goal	instanceId	Specific goal instance
POST /goals-event	Receive/notify goal-related events (type, instance id, function	Event data (type, instance id, function instance id, affected resources)	Confirmation of event receipt/notification

	instance id, affected resources)		

Interaction Summary

BDIx agents interact with the Service Orchestration & Management for receiving BDIx service requests, the Resource Orchestration & Management for sending deployment requests for BDIx functions, and the AI/ML components for setting up necessary AI services for BDIx functions. The governance uses REST APIs for all exposed interfaces, facilitating efficient communication and control across the network. These interactions ensure that BDIx agents can autonomously manage network events, make real-time decisions, and optimize network performance by leveraging distributed artificial intelligence. This architecture allows the BDIx agents to operate in a modular, component-based manner, enabling flexible composition and arrangement of machine learning techniques to meet specific network goals, ultimately creating a highly efficient, decentralized, and intelligent cellular infrastructure.

3.3.2 UE-VBS Computing Resource Control

The UE-VBS Computing Resource Control block aims to control and leverage UE-VBS Computing "open-resource" infrastructures formed directly from Mobile Devices (i.e., Smartphones, Tablets, etc.) at the far-edge domain by harnessing their storage, computational, and networking resources. This approach augments the network's cellular, storage, and computational capabilities, making the 6G cellular landscape more open, transparent, adaptable, and fully decentralized. To achieve this, a comprehensive set of Application Programming Interfaces (APIs) is necessary to facilitate seamless communication, efficient resource management, and dynamic role assignment between the UE-VBS Controller (centralized at the gNodeB) and the UE-VBS Component and BDIx agent (deployed on the mobile devices).

Key Components of UE-VBS Computing Resource Control:

- **UE-VBS Component**: This component is deployed in the User Equipment and is crucial in evolving it into a UE-VBS, integrating it into the "open-resources" UE-VBS Computing Infrastructure. It makes the device a multi-functional network node capable of acting as a miniaturized Base Station (mBS), Relay Station (RS), and Computing and Storage Hub (CSH). The **UE-VBS Profile**, stored in this component, documents basic device details, model specifications, device capabilities, and owner's preferences regarding the device's exploitation (e.g., mBS, RS, CSH).
- **UE-VBS Controller**: This serves as an orchestrator residing within the gNodeB in the 6G landscape, integrating all the intelligence needed for monitoring and managing the UE-VBSs within the coverage area. It dynamically designates roles to the devices based on feedback, ensuring optimal QoS and QoE for all users.

The APIs provided below have been mainly designed based on the description of the UE-VBS Computing Resource Control Algorithm described in deliverable D4.1, which orchestrates the interaction between the UE-VBS Controller and the UE-VBS Components incorporated in the UE-

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VBS devices. These interactions leverage REST APIs for all exposed interfaces, facilitating efficient communication and control across the network. The APIs are categorized to cover initialization, data collection, resource analysis, role assignment, continuous optimization, real-time adaptation, performance monitoring and feedback, etc., thereby addressing the full spectrum of operations necessary for the optimal functioning of the UE-VBS Computing framework. The UE-VBS Controller's APIs are provided in Table 3-24 and the UE-VBS Component's APIs in Table 3-25. These tables include the name and a detailed description of the API, the endpoint which is the web address where the API sends its request to perform a specific action, the input parameters required for the API to function, and the output (response) returned by the API after processing the request.

Table 3-24. UE-VBS Controller APIs

API Name & Endpoint	Description	Input Parameters	Output (Response)
loadUEVBSProfiles POST /UE-VBS_Controller/initialize/loadUEVBSProfiles	Loads the profiles of the registered UE-VBS devices, including details like device ID, model specifications, capabilities, owner's preferences, and device-specific constraints. The UE-VBS profiles are stored in the UE-VBS Controller when the UE-VBS Device is registered (see Table 3-25; registerDevice) This information is essential for the UE-VBS Controller to understand the capabilities and limitations of each UE-VBS device that is available to augment and provide support to the Cell.	None	Confirmation of profiles loaded
setupCommunicationChannels POST /UE-VBS_Controller/initialize/setupCommunicationChannels	Establishes secure communication channels with all UE-VBS devices, enabling the exchange of data and remote management of these devices. This step ensures that the UE-VBS Controller can send instructions and receive updates from each UE-VBS.	None	Confirmation of communication channels established
collectDeviceData GET /UE-VBS_Controller/data/collectDeviceData	Requests real-time data from each UE-VBS device, including its physical location (GPS), resource availability (network bandwidth, CPU/GPU usage, battery level), and operational status. This data is	List of Device IDs	Device data

	crucial for making informed role assignments. Note that this process is performed for the cell of the gNodeB that the UE-VBS Controller is deployed.		
collectNetworkData GET /UE-VBS_Controller/data/collectNetworkData	Gathers network data from UE-VBS devices and UEs, such as signal strength, interference levels, and network congestion. This information helps in assessing the current state of the network and planning optimal role assignments. Note that this process is performed for the cell of the gNodeB that the UE-VBS Controller is deployed.	None	Network data
collectDemandData GET /UE-VBS_Controller/data/collectDemandData	Collects data on areas needing network support from Closed Loop Governance, UE-VBS and UEs including, the locations where the cell needs support, and per location the required bandwidth, data rates, computational power, and storage. This helps in identifying high-demand areas and planning resource allocation. Note that this process is performed for the cell of the gNodeB that the UE-VBS Controller is deployed.	None	Demand data
assessNetworkDemand POST /UE-VBS_Controller/analysis/assessNetworkDemand	Analyzes the data to identify areas with high demands for capacity, computing, and storage. This assessment is crucial for assigning UE-VBS devices to roles that best address these demands.	Demand data	Demand assessment report
analyzeResources POST /UE-VBS_Controller/analysis/analyzeResources	Evaluates the geographic distribution and resource availability of UE-VBS devices and assesses current network conditions to generate a comprehensive resource analysis report. This report guides the decision-making process for role assignments.	Network data, Device data	Resource analysis report
assignRoles	Assigns roles (mBS, RS, CSH) to UE-VBS devices based on resource	Resource analysis	Role assignment confirmation

POST /UE-VBS_Controller/assignments/assignRoles	analysis and network demand. This ensures that each device is utilized effectively to optimize network performance. • If the UE-VBS is assigned as an mBS the UE-VBS device is also instructed the frequency band it will use to support the UE-Clients (aiming to avoid inter-mBSs interference and increase spectrum efficiency). • If a UE-VBS is assigned as a RS the UE-VBS device is also instructed with the other two ends (i.e., other RSs or a fixed Base Station) that it will be connected to and how (i.e., frequency band, network interface, etc.). • If the UE-VBS is assigned as a CSH then the **synchronizeCSHs** service will be then executed to form the CSP that will support the cell in the required location.	report, Demand assessment report	
monitorPerformance GET /UE-VBS_Controller/optimization/monitorPerformance	Continuously monitors network performance metrics such as data rates, latency, overall network health, UE-VBS device status, etc. This ongoing monitoring helps in maintaining optimal network performance and making necessary adjustments (Collaborates with the BDIx agents).	None	Performance data
receiveFeedback POST /UE-VBS_Controller/feedback/receiveFeedback	Receives feedback from BDIx agents on local optimizations and operational status of UE-VBS devices. This feedback loop is essential for continuous improvement and real-time adjustments in the network.	Feedback data	Feedback confirmation
synchronizeCSHs POST /UE-VBS_Controller/synchronization/synchronizeCSHs	Ensures synchronization between CSHs for data consistency and task coordination. This involves using distributed file systems and synchronization protocols to keep data up-to-date across all CSHs and	Synchronization Data	Synchronization confirmation

	form the Computing and Storage Powerhouse (CSP).		
manageCSHTasks POST /UE-VBS_Controller/tasks/manageCSHTasks	Coordinates computational and storage tasks required to be performed among the CSHs based on the computing and storage demands required by the CSP formed. It aims to ensure efficient distribution of data and processing tasks within the Computing and Storage Powerhouse (CSP) by directing tasks to appropriate CSHs based on their current load and capabilities. If the local CSP resources are insufficient additional processing tasks will be allocated to cloud servers.	Task Data, Device Data,	Task assignment confirmation
monitorCSHHealth GET /UE-VBS_Controller/health/monitorCSHHealth	Monitors the health and performance of CSHs, ensuring they are operating efficiently and effectively. This includes tracking resource usage, task completion times, and any potential issues that might arise.	None	CSH Health data
adjustRoles POST /UE-VBS_Controller/optimization/adjustRoles	Dynamically adjusts role assignments and resource allocation based on real-time data and feedback from UE-VBS devices. This ensures that the network adapts to changing conditions and maintains optimal performance.	Performance data, Feedback Data, CSH Health Data	Role adjustment confirmation

Table 3-25. UE-VBS Components' APIs

API Name & Endpoint	Description	Input Parameters	Output (Response)
registerDevice POST /UE-VBS_Component/device/registerDevice	Registers the UE-VBS device with the UE-VBS Controller indicating that the UE-VBS is available to support the Cell. It provides details such as device ID, and UE-VBS profile including model specifications, capabilities, owner's preferences, and device-specific constraints. This	Device ID, UE-VBS Profile	Registration confirmation

	step ensures that the UE-VBS device is recognized and can be managed within the UE-VBS Computing infrastructure.		
initializeBDIxAgent POST /UE-VBS_Component/device/initializeBDIxAgent	Initializes connection with the BDIx agent on the UE-VBS device. The BDIx agent is responsible for local decision-making and optimization based on real-time data and instructions from the UE-VBS Controller.	None	Agent initialization confirmation
sendDeviceData POST /UE-VBS_Component/data/sendDeviceData	Sends real-time device data to the UE-VBS Controller, including location, resource availability, and operational status. This data is crucial for the UE-VBS Controller to make informed decisions about role assignments and resource allocation.	Device data	Data received confirmation
updateResourceAvailability POST /UE-VBS_Component/data/updateResourceAvailability	Provides updates to the UE-VBS Controller on the current resource availability of the UE-VBS device, including network bandwidth, CPU/GPU usage, and storage capacity. This information helps the UE-VBS Controller to manage resources effectively.	Resource data	Resource update confirmation
sendOperationalStatus POST /UE-VBS_Component/data/sendOperationalStatus	Provides the UE-VBS Controller with the operational status of the UE-VBS device, including its current role, battery level, and health status. This data helps in monitoring and maintaining the health of the network.	Status data	Status update confirmation
receiveRoleAssignment POST /UE-VBS_Component/roles/receiveRoleAssignment	Receives the role assignment (mBS, RS, CSH) from the UE-VBS Controller. The UE-VBS Component device uses this information to configure the Device for the assigned role and to perform the necessary functions.	Role data	Assignment received confirmation
executeRole POST /UE-VBS_Component/roles/executeRole	Executes the assigned role (mBS, RS, CSH) based on the instructions provided by the UE-VBS Controller. This involves configuring the device's	Role data	Execution confirmation

	resources and operations to perform the assigned tasks.		
optimizeLocally POST /UE-VBS_Component/optimization/optimizeLocally	BDIx agents optimize local resource usage and operations based on real-time conditions and feedback from the UE-VBS Controller. This helps in maintaining efficient performance and adapting to changes in the network environment.	Optimization parameters	Optimization confirmation
sendFeedback POST /UE-VBS_Component/feedback/sendFeedback	Sends feedback to the UE-VBS Controller on the effectiveness of local optimizations and current operational status. This feedback helps the UE-VBS Controller to adjust role assignments and resource allocations as needed.	Feedback data	Feedback received confirmation
establishDirectLink POST /UE-VBS_Component/communication/establishDirectLink	Establishes a direct communication link with other UE-VBS devices for creating Virtual Data Tunnels (VDTs) or for other collaborative tasks (i.e., CSP). This link enables high-speed, low-latency data transfer between devices.	Target device ID, link parameters	Link establishment confirmation
dataBackhaul POST /UE-VBS_Component/communication/dataBackhaul	Backhauls data to the gNodeB, ensuring that aggregated data from the UE-VBS devices is transmitted to the central network infrastructure for further processing and distribution.	Data packets	Backhaul confirmation
distributeData POST /UE-VBS_Component/communication/distributeData	Distributes aggregated data received from the gNodeB to the UE-Clients connected to the mBS. This ensures that client devices receive the data intended for them efficiently.	Data packets from gNodeB	Distribution confirmation
manageClientConnections POST /UE-VBS_Component/management/manageClientConnections	Manages connections to UE-Clients, ensuring that each client device can connect, communicate, and receive services from the mBS. This includes handling connection requests, maintaining sessions, and ensuring secure communications.	Client connection data	Connection management confirmation

relayData POST /UE-VBS_Component/relay/relayData	Relays data packets received from one RS to another or to an mBS within the VDT. This ensures efficient data flow and network connectivity.	Data packets, target RS/mBS ID	Relay confirmation
executeCSHTasks POST /UE-VBS_Component/tasks/executeCSHTasks	Executes computational and storage tasks as directed by the UE-VBS Controller, including data caching, processing requests, and storage management. This involves utilizing the device's CPU/GPU and storage capabilities to handle assigned tasks.	Task data	Task execution confirmation
synchWithCSP POST /UE-VBS_Component/synchronization/synchWithCSP	Ensures data synchronization with other CSHs within the CSP, maintaining data consistency and and coordinated task execution across multiple CSHs and enabling collaborative processing. This involves using distributed file systems and synchronization protocols.	Synchronization data	Synchronization confirmation
monitorHealth GET /UE-VBS_Component/health/monitorHealth	Monitors the health and performance of the UE-VBS device, providing updates to the UE-VBS Controller. This includes tracking resource usage, battery level, and task completion status.	None	Health data
adjustResourceUsage POST /UE-VBS_Component/optimization/adjustResourceUsage	Dynamically adjusts resource usage based on real-time conditions and feedback from the UE-VBS Controller. This ensures optimal performance and resource allocation for the assigned role.	Resource parameters	Adjustment confirmation

3.4 Closed-Loop Functions

Closed-loop services are composed of closed-loop functions which share knowledge with the goal of performing an action based on policies and obtained insights. A closed-loop function interacts with other closed-loop functions inside a closed-loop service via MQTT message broker attached to the closed-loop service, configured by the Closed-loop Governance at instantiation. Each function consumes the topic(s) of the related functions, and in turn produces an output on the topic(s) associated with that function. The functions also publish messages relating to events, errors, and updates back to the Closed-loop Governance through the MQTT.

Closed-loop functions also expose interfaces for actions and configurations consumed by the Closed-loop Governance or other actor. Details on these interfaces are given in the following subsections.

3.4.1 Monitoring

The Monitoring function distributes the data using the MQTT broker associated to the closed-loop. This data is then ingested by other relevant functions for inferring the state of the managed entity in relation to the goals set in the closed-loop. The Monitoring function can be dynamically configured/reconfigured by the Closed-loop Governance through an exposed interface, as detailed in Table 3-26.

Table 3-26. Monitoring function APIs.

API Name & Endpoint	Description	Input Parameters	Output (Response)
monitoring-configure GET /api/v1/monitoring-configure/	Retrieves configuration information for the function	No parameters	Function configuration*
interconnect POST /api/v1/monitoring-configure/interconnect	Set/Update messaging configuration	MQTT broker endpoint, MQTT input/output topics	Confirmation of configuration
policy POST /api/v1/monitoring-configure/policy	Set/Update policy information	Policy*	Confirmation on configuration
*Details in text			

3.4.2 Analytics

In the Analytics function, data is received from the monitoring function via the MQTT instance over a topic specific to the data model required by the Analytics function. The Analytics in turn publishes the results of the insights to be used as input by a Decision or Execution function. In addition to using the MQTT topics to communicate with the other closed-loop functions, the Analytics function uses the MQTT to report any actions, errors, or events to the Closed-loop Governance. The input and output data models of the Analytics function are specific to the use case.

The Analytics function can be dynamically configured/reconfigured by the Closed-loop Governance through an exposed interface, as detailed in Table 3-27.

Table 3-27. Analytics functions APIs

API Name & Endpoint	Description	Input Parameters	Output (Response)
analysis-configure GET /api/v1/analysis-configure/	Retrieves configuration information for the function	No parameters	Function configuration*
interconnect POST /api/v1/ analysis-configure/interconnect	Set/Update messaging configuration	MQTT broker endpoint, MQTT input/output topics	Confirmation of configuration
model POST /api/v1/ analysis-configure/model	Set/Update model information (if ML is leveraged)	Model configuration*	Confirmation on configuration
additional POST /api/v1/ analysis-configure/additional	Set/Update additional user defined parameters	Additional configuration*	Confirmation on configuration
policy POST /api/v1/ analysis-configure/policy	Set/Update policy information	Policy*	Confirmation on configuration
*Details in text			

* Additional configuration includes any user defined parameters needed for the analysis algorithm (e.g. data scaling factor), model configuration details include inference url and model signature, messaging configuration includes the MQTT broker address, broker port, credentials, source topic, destination topic, and policy information includes any user-defined rules for the closed-loop function.

3.4.3 Decision Engine

Based on the description of the decision engine provided in Section 2.1.4, the processed data proceeds to the output pre-processing process, which undergoes translation into a format

understandable for external users or actuators (denormalization functional block). Here, a broker or message bus acts as a gateway, facilitating communication between different technical domains and effectively decoupling DE from other technical domains it interacts with. However, it is crucial to elucidate the reference points illustrating communication between generated output/input data and external technical domains (depicted as yellow blocks). These communications are meticulously listed and explained in Table 3-28.

Table 3-28. DE reference points and their associated roles

API Name & Endpoint	Description	Input Parameters	Output (Response)
policy POST /api/v1/configure/ policy/	Establishes guidelines for the exchange of policies between Applications and DE, governing user (or user-representative agent) behaviour, encompassing services and resources. DE is required to acknowledge the policies and information it receives, just as the Application must acknowledge the policies and information it receives.	Eusr_de_pol-Iput policies (initiated by user or operator)	Eusr_de_pol-Output policies (Policies may be defined by the user or operator)
configure GET /api/v1/configure/	Specifies the nature of data and acknowledgments transmitted from other DEs in various technical domains to DE; DE may acknowledge data received from other DEs in the process.	Eoth_de_dat-Orchestrator Input data (Data from other DEs)	Eoth_de_cmd-Orchestrator & output commands (DE's data is contingent upon the operations carried out by DEs)
interconnect POST /api/v1/actuator/ interconnect	Specifies the category of generic data exchanged between actuators and DE, which does not fall under situation- or context-awareness and is distinct from model or knowledge information. DE is expected to acknowledge the data and information it receives.	Eact_de_oth-Other Input data (generic DE data that may benefit the actuator)	Eact_de_oth-Output other data (generic DE data that may benefit the actuator)
model POST	Specifies the exchange of model and/or knowledge information, along with	Eact_de_kno-Knowledge & model data	Eact_de_kno-Output model & Knowledge

/api/v1/model	acknowledgments, between actuators and DE. DE is expected to acknowledge the data and information it receives in this context.	(acknowledgments between actuators and DE)	(acknowledgments between actuators and DE)
interconnect POST /api/v1/actuator/ interconnect	Specifies the exchange of situation- and/or context-aware data and information between actuators and DE. DE is expected to acknowledge the received data and information during this process.	Eact_de_ctx-Situation & context data (input information for DE to determine context)	Eact_de_ctx-output context and situation data (result data from DE for actuators)
interconnect POST /api/v1/analytical-engine/ interconnect	Specifies the data and information transmitted from the AE to DE, with the possibility of acknowledgment by DE for these received data and information.	Eae_de_dat- Input data (data from AE that DE utilizes)	Eae_de_cmd-output commands (acknowledgments from DE to the AE)
interconnect POST /api/v1/monitoring-engine/ interconnect	Specifies the data and acknowledgments transmitted from the MS to DE; DE may acknowledge the received data.	Ems_de_dat- Input data (data from MS that DE utilizes)	Ems_de_cmd-Output commands (recommendations and commands from DE to the MS)

3.4.3.1 MLOPs

The distinctive feature setting the proposed DE in ADROIT6G apart from previous projects lies in the incorporation of MLOps blocks (refer to Figure 2-6), designed to enhance the decision-making process. MLOps, an emerging field, is dedicated to effectively deploying and managing ML in complex environments. Integrating DevOps principles with the specific challenges of ML systems empowers systems to scale and operationalize ML models more efficiently and enhance reliability, scalability, and sustainability in system performance.

The concept of MLOps facilitates DE operations on three distinct levels. Integrating MLOPs with the decision-making functional block streamlines model creation, verification, and management of decisions. Furthermore, its integration with input pre-processing functional blocks simplifies data preparation and management. Additionally, MLOps plays a crucial role in improving the data monitoring process, enabling the system to compare and select data in real-time continuously.

It is important to note that the provided description of the DE engine pertains to a single DE entity. In scenarios with multiple DEs, an orchestrator becomes essential to manage diverse policies and objective functions tailored to specific technical domains.

4 Physical infrastructure

ADROIT6G focuses on advanced network domains, examining numerous state-of-the-art components of contemporary communication technology, as depicted in the lower part of Figure 2-2. The Far-Edge Domain of ADROIT6G utilizes innovative strategies to transform mobile devices into crucial components of the 6G network infrastructure with real-time decision-making capabilities. Moreover, the Edge Domain plays a significant role in bringing processing closer to data sources, resulting in reduced latency and enhanced service delivery in 6G networks, bridging the gap between the Far-Edge devices and the Internet Cloud providers. In addition, we explore NTN and Computing, examining the incorporation of satellite networks into ADROIT6G, and the ways in which various satellite topologies enhance coverage and facilitate low-latency applications. Lastly, we examine the Cloud Domain, highlighting the symbiotic connection between Cloud Radio Access Network (C-RAN) and Mobile Edge Computing (MEC), which offer a versatile and efficient method for network architecture in the context of 6G networks. This involves leveraging BDIx agents as a control unit within the existing ADROIT6G network infrastructure, thereby enhancing the current network infrastructure.

4.1 Far-edge domain

In the context of ADROIT6G, the far-edge domain represents a cutting-edge approach in cellular technology, particularly tailored for 6G networks (Figure 4-1). This domain leverages the capabilities of BDIx agents and other advanced components to create a highly efficient, decentralized, and intelligent cellular ecosystem. The far-edge domain of ADROIT6G is characterized by its innovative use of Mobile Devices, not just as communication tools but as integral components of the cellular network itself. In this domain, each Mobile Device, be it a smartphone or a tablet, is equipped with BDIx agents and evolved into a UE-VBS. These agents are advanced forms of Belief-Desire-Intention agents, now augmented with machine learning capabilities. This enhancement allows them to process data, make autonomous decisions, and optimize network operations in real-time. In this ecosystem, Mobile Devices evolve beyond their traditional roles. Incorporating the concept of UE-VBS (User Equipment as Virtual Base Station) Computing into the far-edge domain of the ADROIT6G framework, further enhances the capabilities and functionality of this advanced cellular network for 6G technology.

UE-VBS Computing represents a transformative approach where individual Mobile Devices are not only consumers of network resources, but also contributors to the Network. This concept is pivotal in realizing the vision of a decentralized, intelligent cellular network as envisaged in ADROIT6G. With UE-VBS Computing, smartphones, tablets, and other UEs take on additional roles such as miniaturised Base Stations, data processing centers, storage units, and network relay points (see Section 4.1.1). In this setup, each mobile device, equipped with BDIx agents, becomes a hub for networking, computational and storage activities. They may become Computing and Storage hubs (CSH), contributing to content caching, storage, and processing of network requests, act as miniaturised Base Stations, extending network density and functioning as relay stations to optimize signal propagation and coverage. This transforms the cellular network into a more dynamic, adaptable, and scalable system.

The incorporation of UE-VBSs into the far-edge domain of ADROIT6G not only makes the network more robust and adaptable but also more cost-effective. By utilizing existing mobile devices as part

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of the network infrastructure, the need for extensive physical base stations and other hardware is reduced. This lowers the operational and infrastructure costs, making advanced cellular solutions more accessible, even for smaller businesses and in areas with limited infrastructure.

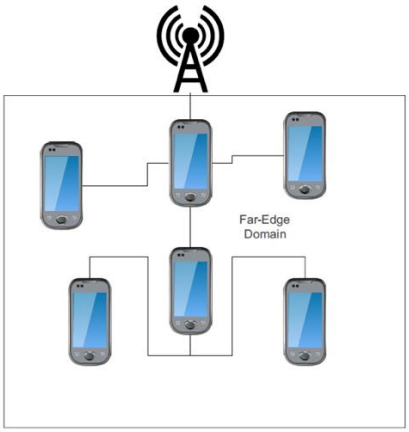

Figure 4-1. Far-Edge Domain.

4.1.1 Mobile Devices Evolved Roles in UE-VBS Computing

The UE-VBS Computing represents a major advancement in the evolution of decentralized cellular networking at the far-edge. It provides a solution that doesn't just involve mobile devices in the network but actively exploits their available resources and multifunctional capabilities. Specifically, the UE-VBS Computing, powered by the DAI Framework with BDIx agents, turns the user device into a multifaceted tool, instrumental in creating a more dynamic, responsive, and robust cellular infrastructure through roles as a **miniaturized Base Station (mBS)**, a **Relay Station (RS)** or **Computing and Storage Hub (CSH)** (Figure 4-2).

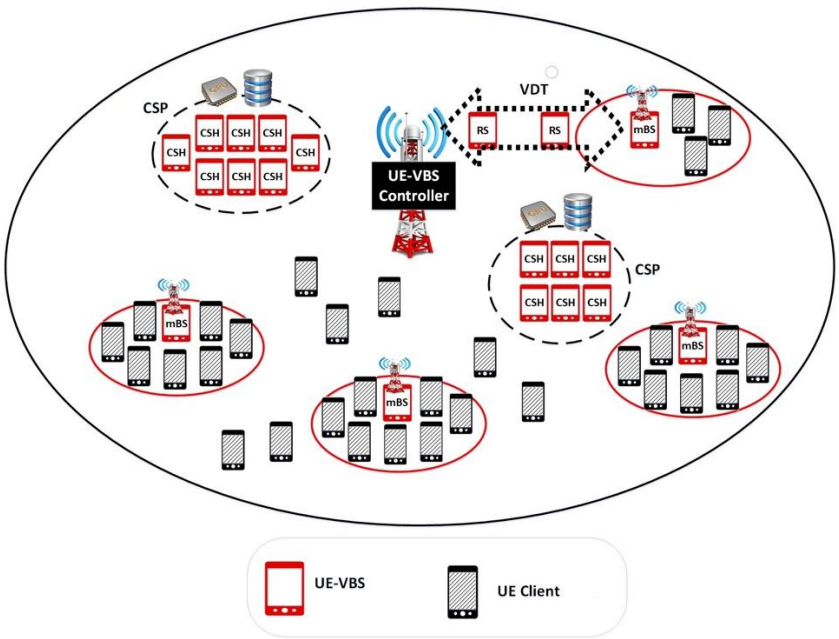

Figure 4-2. The UE-VBS Computing Paradigm at the Far-Edge Domain

4.1.1.1 UE-VBS as miniaturized Base Station (mBS)

When a UE-VBS is designated as a miniaturized Base Station (mBS) within the UE-VBS Computing ecosystem, it undertakes a pivotal role in the network's infrastructure. From the viewpoint of the other Client Mobile Devices in its proximity, the UE-VBS in its mBS role is perceived as a regular gNodeB.

A UE-VBS acting as a mBS collects and aggregates data streams from various Client Mobile Devices (including its own data stream; note that a UE-VBS acting as an mBS, can also be a client and receive mobile services from the network) into a singular, high data rate stream which is then backhaul to the gNobeB. This aggregation causes much less interference in the radio access part since it avoids direct communication between all Mobile Devices and the gNobeB and facilitates a more efficient and reliable channel of communication with the gNodeB. Also, the UE-VBS acting as a mBS and its associated Client Mobile Devices are collectively seen as a single unit by the gNodeB. This unified representation simplifies the network management and enhances the efficiency of data handling.

Furthermore, an interface flexibility for backhauling channel establishment with the gNodeB is offered, since the high-rate data stream from a mBS to the gNodeB can be established through various ways:

- The Uu Interface, providing a direct and efficient link between the mBS and the gNodeB.
- A Virtual Data Tunnel (VDT) formed using other UE-VBSs acting as RSs, especially in scenarios where direct connection is infeasible or less optimal, with the gNodeB. This VDT effectively extends or bridges network coverage.

4.1.1.2 UE-VBS as Relay Station (RS) in a Virtual Data Tunnel (VDT)

The role of a UE-VBS designated as a Relay Station (RS) within the concept of a Virtual Data Tunnel (VDT) is pivotal for enabling effective and efficient data flow and efficient data transmission within the Radio Access Network (RAN). It plays a key role in expanding coverage, bridging coverage gaps, and providing cost-effective backhauling solutions for mobile data traffic.

VDTs are established by utilizing a range of orchestrated access and connectivity technologies such as Millimeter waves, WiFi Direct, LTE Direct, NR, and others. These technologies provide the flexibility needed to establish robust and efficient links, in a sequential or networked manner, between UE-VBSs serving as RSs, forming a bridge to the Gateway (such as a gNodeB), or to other UE-VBSs serving as mBSs. By doing so, VDTs enhance the overall spectral efficiency and reliability of data transmission within the UE-VBS Computing ecosystem, reinforcing the infrastructure's adaptability to varying network demands and conditions, thereby reducing transmission losses, especially in challenging network environments, maintaining high data rates even during peak usage times and also ensuring that high data rates are sustained across various network parts.

4.1.1.3 UE-VBS as Computing and Storage Hub (CSH)

When viewed individually, the computational and storage strength of a UE-VBS acting as a Computing and Storage Hub (CSH) may seem limited. However, the true strength of the CSH role lies in the joint operation, that when combined and operate in synergy with other CSHs, form a powerful, decentralized Computational & Storage Powerhouse (CSP), highly capable of handling

extensive data storage and processing tasks within the network. This role is essential, not only for offloading and managing the computational and data storage demands that often overwhelm traditional network infrastructures but also for integrating a new level of efficiency and capability in 6G networks. Redistributing these demands across several UE-VBSs dispersed throughout our physical landscape, a decentralized CSP infrastructure with unparalleled scalability and performance is formed, robustly equipped to meet the demanding KPIs set for 6G. Note that this role for UE-VBSs can also be a beacon for a new era in cloud and edge or far-edge computing.

One of the key advantages of the CSH role is its contribution to reducing latency and enhancing data throughput in the network. By processing and storing data locally in a CSH or within a proximate cluster of CHS forming a CSP, the need for transferring large volumes of data to distant cloud servers or centralized data centers can be significantly reduced. This localized approach not only accelerates data access and processing speeds but also contributes to the overall efficiency and resilience of the network.

Furthermore, a CSP can play a crucial role in scenarios where intensive or immediate data processing is essential. For example, in case of holographic rendering, CSPs can provide the necessary computational power (i.e., decompress and render the hologram locally) at the far-edge of the network, close to where data is consumed. This means that instead of sending fully rendered holographic data, which requires significant bandwidth, the network can transmit compressed data formats to the CSP for local decompression and rendering. This approach greatly reduces the bandwidth requirements and latency, making the delivery of high-quality, real-time holographic content more feasible and efficient.

4.2 Edge domain

From the perspective of mobile network operators, edge computing is enabling services to be hosted close to the UE's access point of attachment, efficient service delivery through the reduced end-to-end latency and network load, unlocking the value of IoT, 5/6G, AR/VR, video, AI, analytics and cloud. Edge computing is an architecture leveraging cloud capabilities that locates processing power and storage closer to the source of data generation, seen as a network evolution to EDGE Computing as shown in Figure 4-3.

EDGE computing facility implementation is depending on each use case requirements, as there is no implementation that fits all.

Multi-Access Edge Computing (MEC) encapsulates all the computing domains related to cellular network and offers applications and content providers computing capabilities at the network edge, for a series of services, as described in Figure 4-4.

The MEC system reference architecture is deployed in an NFV environment as VNFs towards ETSI MANO NFV components. The virtualized infrastructure is deployed as NFVI and managed as VIM and the VNFs life cycle management is provided by the platform management and platform orchestrator components. When an application needs more resources, the cloud automatically spins up another instance of that application and removes an instance when load decreases. Such flexible scaling is impossible to achieve when the application is implemented with dedicated hardware.

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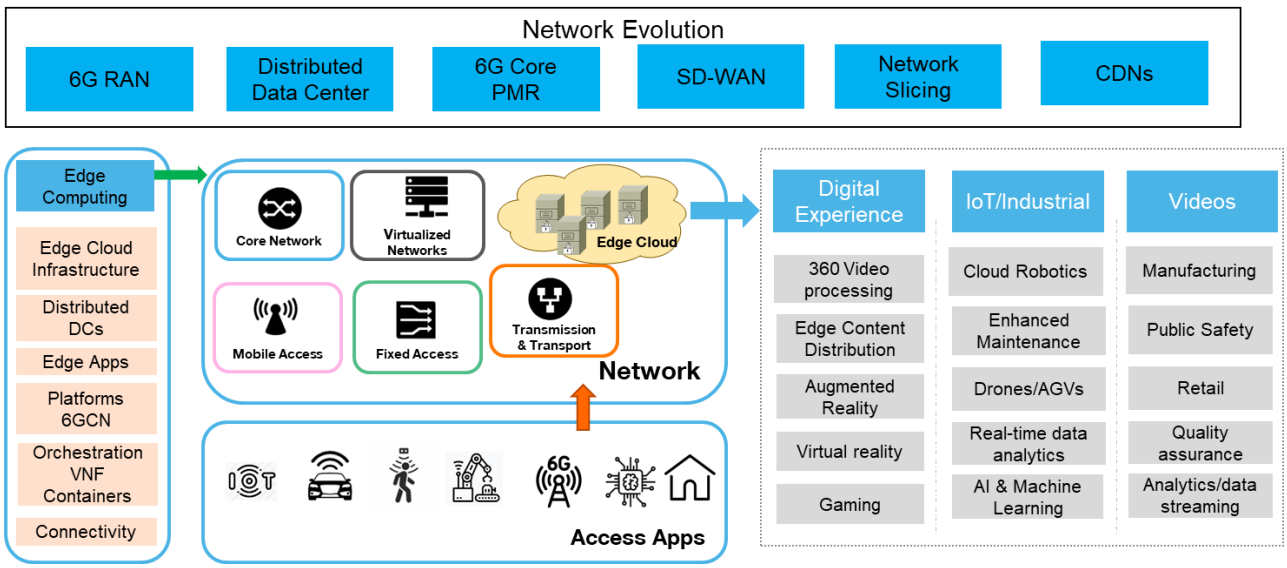

Figure 4-3. Evolution and applications of the edge computing paradigm within 6G networks.

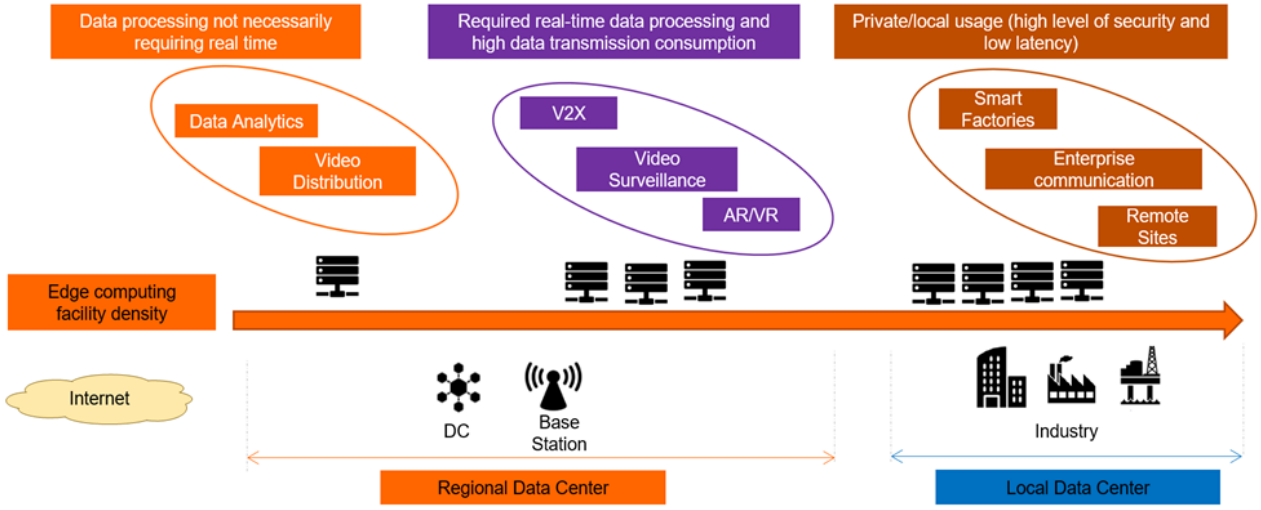

Figure 4-4. Multi-Access Edge Computing (MEC) implementation

The general MEC framework as described in Figure 4-5 consists of several entities described as:

- MEC framework (platform, applications and virtualized infrastructure);
- MEC system management, characterized by Mp and Mm reference point interfaces;
- MEC host management, characterized by Mp and Mm reference point interfaces;
- External network level entities.

In the context of the ADROIT6G project, the edge domain will be represented by the local datacenters that are dedicated to distinct facilities, accommodating the server and network infrastructures needed to host the envisioned applications for such venues, including also specifically provisioned 5G/6G UPF units that would allow for the URLLC slicing promised low-latencies and consumption of critical data on-site.

4.2.1 Satellite Communication and Computing

The ADROIT6G project considers satellite networks as part of its networking infrastructure in a tight integration with its terrestrial counterpart (i.e., the terrestrial 6G network). Satellite networks can then provide space-based connectivity to expand coverage into remote or underserved areas and provide a supplementary link for backup, failover, or resilience purposes. There are three main topologies, as depicted in Figure 4-6: (i) Bent-Pipe (Transparent) topology; (ii) Regenerative Topology; and (iii) Inter-Satellite Link (ISL) topology.

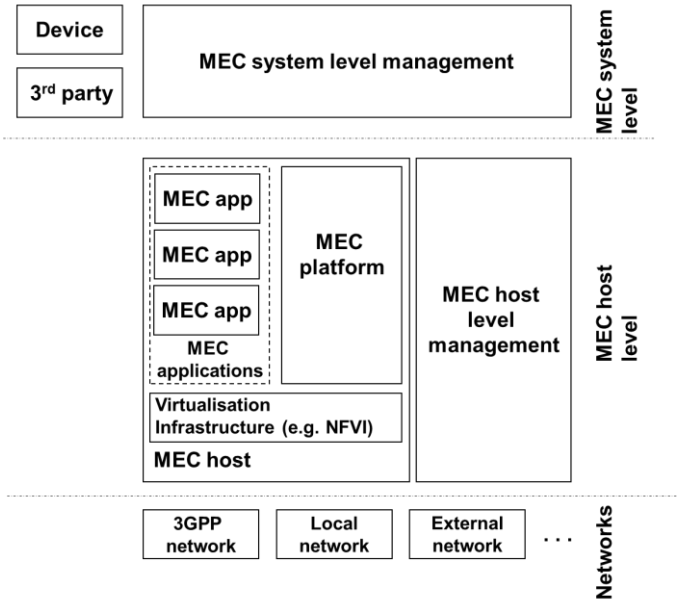

Figure 4-5. MEC computing framework.

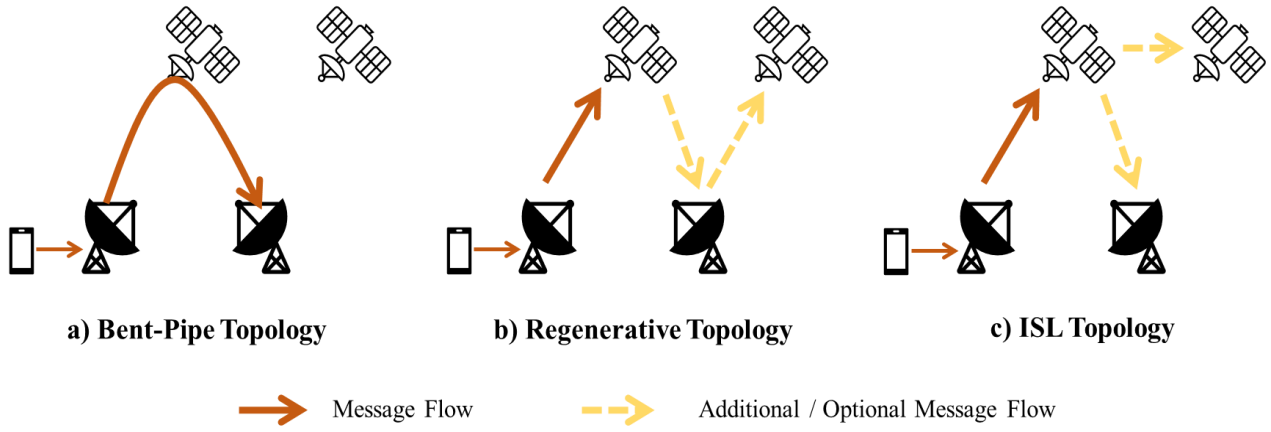

Figure 4-6 - Comparison of Satellite Topologies

In the Bent-Pipe Topology (also referred as transparent model), satellites are just repeaters of received signals, without any control over the data they receive and/or transmit. Each satellite receives signals from a ground station, amplifies them, converts the frequency, and finally retransmits them on a downlink frequency. In turn, in the Regenerative Topology, satellites already have on-board processing capabilities, terminating the protocols up to Layer 3 on-board the satellite. Each satellite receives signals from a ground station, demodulates them to baseband, performs operations like routing or switching, and, finally, (re)modulates the signals to be

transmitted on a downlink back to the ground. For instance, within IP-capable satellite systems, satellites can function as Layer 3 IP routers. Finally, in Inter-Satellite Link Topology, satellites support not only the same capabilities as in the regenerative topologies but also satellite-to-satellite communication, either within the same orbital layer or across different layers. Each satellite can send signals directly to neighbour satellites, if needed, without sending them to a ground station and back up to space.

The abovementioned topologies are equally applicable to Direct-to-Device (D2D) topologies, as depicted in Figure 4-7. In doing so, devices can establish direct communications with satellites without relying on ground stations, further enhancing the efficiency and autonomy of satellite-based communication networks.

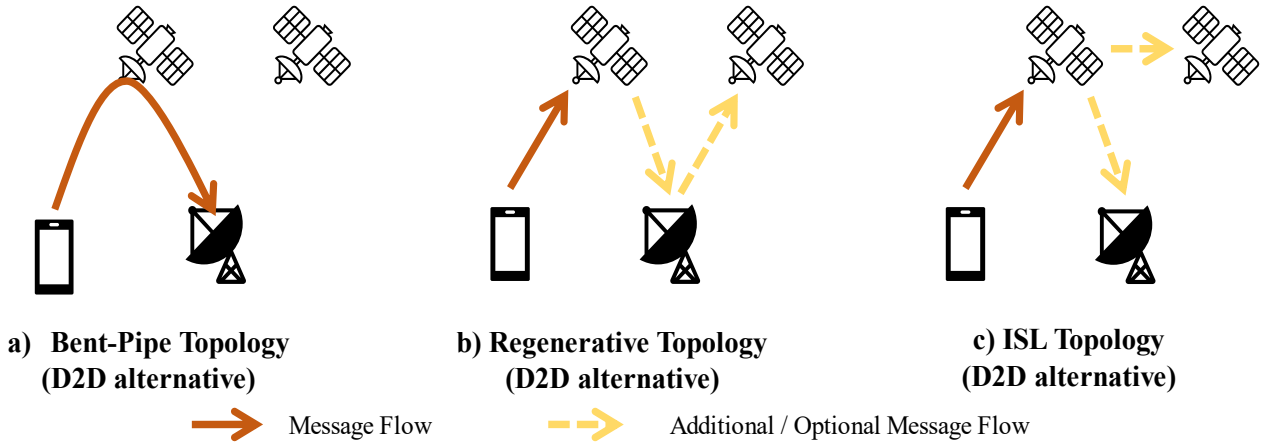

Figure 4-7 - Comparison of Satellite Topologies (Direct to Satellite Alternatives)

Various levels of cooperation between the terrestrial 6G and satellite network can be envisioned which mostly differ in terms of seamless integration, security, trustfulness, and performance. These are depicted in Figure 4-8. Due to the lack of a reference 6G architectural model, these levels are cooperations are identified below from a high-level perspective. In the first option (Option A), satellite networks and terrestrial 6G networks are owned by different operators and, therefore, an interoperability layer that relies either on IP-based communication systems or IP-compatible protocols shall be in place. The former allows both domains to communicate using standard Internet protocols, while the latter uses border gateways that perform protocol conversion. In the second option (Option B), the terrestrial 6G network leverages on the satellite network of a different operator, as an underlay, to provide connectivity to its devices. The third (Option C) and fourth (Option D) already set the terrestrial 6G and the satellite networks under the same operator domain. In this case, both domains can be distinctly managed (but with a higher degree of trust) or fully converge as an interworking and integrated network. Still, one common aspect between all these options is that the terrestrial network would act as the logically centralized point for any Satellite-6G(-Satellite) cooperation. All options enable interconnection scenarios where ground stations around the world are potentially connected to distinct local 6G providers, either via autonomous systems interconnection or via untrusted non-3GPP mechanisms. Additionally, both Options C and D can also consider new integration scenarios, including roaming alike strategies, trusted non-3GPP satellite mechanisms, and even as a Satellite-based RAN.

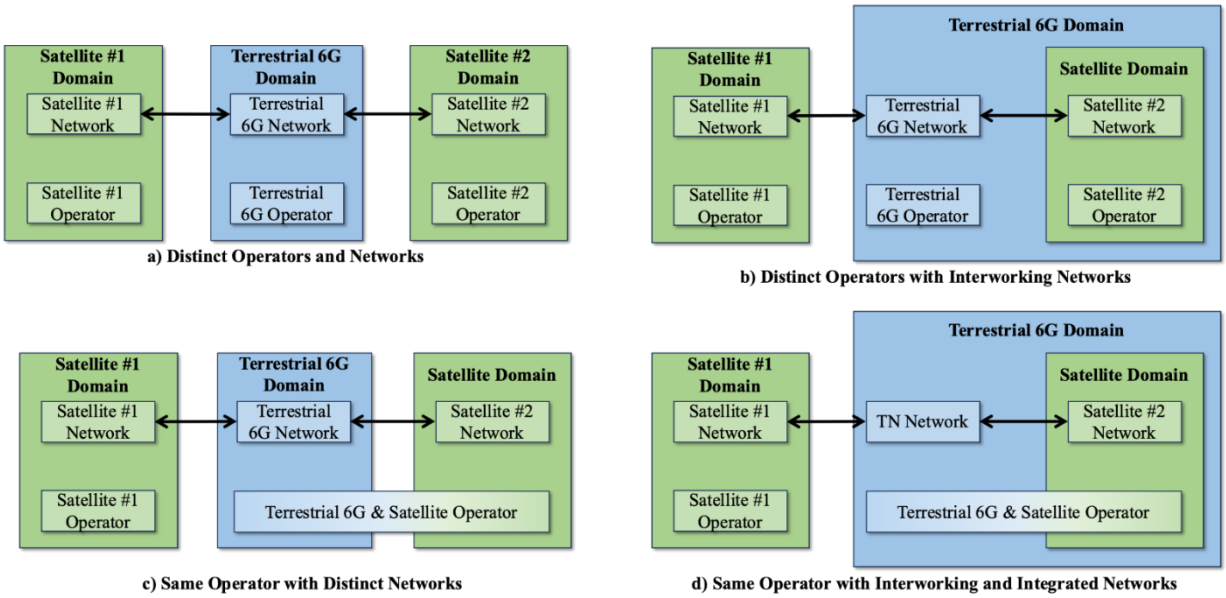

Figure 4-8. High-level cooperation between a terrestrial 6G and satellite networks

In addition to the infrastructure management considerations discussed above, an important aspect of modern NTN infrastructures is that computational satellite hardware has reached a level of maturity suitable for most Edge and Cloud applications, thanks in part to the adoption of COTS components. As such, the possibility of using satellites as Edge nodes in the 6G network, for computational tasks of various kinds, should not be considered as unrealistic anymore. This concept is in general known as *Satellite Computing*, embracing a variety of applications ranging from *Internet of Remote Things* (IoRT) ones to Earth observation, and not necessarily related the orchestration of mobile networks. This new perspective to satellite networks not only considers in-satellite computing resources, but also constraints computer resources in the devices themselves, which may allow short control loops and a reduction of the end-to-end delays. In doing so, ADROIT6G offers not only a true integration of cellular and satellite communications but also a multi-stage network of edge cloud instances spanning from the terrestrial edge to the satellite. Such approach implies that the ADROIT6G framework must support this space-segment, including new routing mechanisms, resource management and scheduling mechanisms that take all constraints of terrestrial and satellite networks into account. The specificities of satellite networks must also be considered like their mobile infrastructure nature with points of attachment moving or appearing and disappearing in brief time windows based on the satellite movement around the Earth. Thus, the ADROIT6G framework shall be able to (re)deploy software components into the Edge Cloud services within satellites, migrating them, if required, to keep a seamless and the expected levels of performance.

Achieving Satellite Computing requires tackling a series of operational challenges, such as the development of ad-hoc orchestration frameworks and algorithms, or the choice of appropriate computing models (e.g., serverless), to deal with the high mobility and energy constraints of satellite hardware. Most of these challenges lie outside of the scope of ADROIT6G – at the same time, the future potential of Satellite Computing, as well as the challenges associated to it, should be kept in mind during the design of the ADROIT6G framework, as an opportunity to improve its novelty and longevity.

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Each of the approaches described in Figure 4-8 will likely impact the feasibility of a Satellite Computing Edge Cloud infrastructure as part of the Satellite Network. By imposing specific constraints on the data plane configuration, the capability of the 6G network to perform local breakout at the satellite segment also varies. The specific conditions implied: (i) the entirety of gNB functionalities hosted on-board of the satellite; (ii) part of the 5G core hosted on-board of the satellite; or (iii) satellite is used as backhaul. Nevertheless, the same authors argue that very low-latency applications cannot be offered if the data planes need to cross a satellite network, on which the deployment of Edge computing resources and services before the satellite segment can mitigate such limitations. These options are depicted in Figure 4-9.

ADROIT6G expects to take this assumption one step further, and to assess if Edge computing on-board of the satellites can also support such applications by halving the impact of satellite communications E2E path. However, such benefits will depend on the satellite topology in-place and on the capabilities of the satellite links.

4.3 Cloud domain

The integration of the cloud domain into Mobile Network Operators' (MNOs) core networks for 5G and future 6G infrastructures represents a pivotal evolution in telecommunications, positioning the cloud not only as a central element of the network architecture but also as a versatile component of the edge-cloud continuum. This strategic incorporation facilitates a seamless, scalable, and efficient deployment of network functions and services, extending the cloud's utility beyond traditional data center confines to meet the diverse demands of next-generation networks.

The cloud domain's role in the 6G core network is multifaceted, as seen in Figure 4-10, is emphasizing flexibility, scalability, and efficiency. By leveraging virtualization technologies, such as NFV and SDN, MNOs can dynamically allocate resources, automate network operations, and rapidly deploy new services. This agility is crucial for supporting the diverse service requirements of 6G, ranging from high bandwidth consumer applications to ultra-reliable low-latency communications for industrial IoT and mission-critical services. The cloud-based core network also enables more efficient data routing and management, optimizing network performance and reducing operational costs.

In this approach, the edge-cloud continuum concept is important, representing an extension of cloud capabilities to the network edge, offering a distributed computing paradigm that brings processing power closer to the data source or end-users. This architecture is essential for reducing latency, managing bandwidth, and enhancing data privacy and security. In the context of 6G networks, the edge-cloud continuum allows MNOs to deploy applications and services flexibly, depending on their latency, bandwidth, and processing requirements. By intelligently distributing workloads across the continuum, networks can provide tailored services that meet the specific needs of various applications, from IoT devices to high-definition video streaming.

Within this evolved network infrastructure, the cloud domain is ideally positioned to host applications that are not latency-dependent, such as data analytics, video distribution, and large-scale IoT device management. For instance, data analytics platforms can leverage the vast computational resources and storage capacity of the cloud for processing and analysing massive datasets, deriving insights that can enhance operational efficiency, customer experiences, and decision-making processes. Similarly, video distribution platforms can benefit from the cloud's

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scalability to deliver content efficiently to a wide audience, optimizing streaming quality based on network conditions and user preferences.

Moreover, the cloud domain's role extends to supporting the development and deployment of AI and machine learning models, which are integral to optimizing network operations and enabling advanced services in 6G networks. By hosting these applications in the cloud, MNOs can harness powerful computing resources to train and run complex models, facilitating intelligent automation, predictive maintenance, and personalized services at scale.

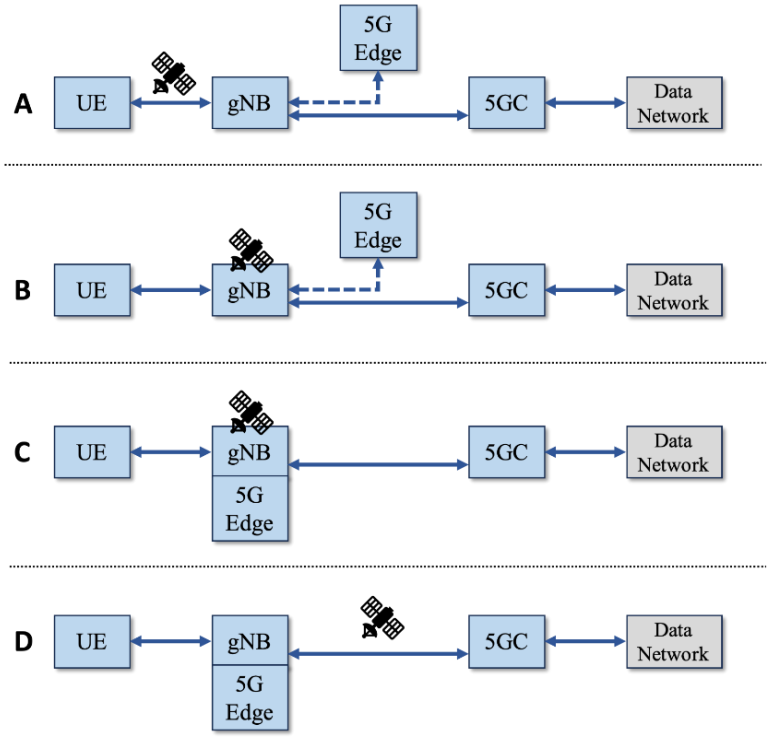

Figure 4-9. Satellite and 5G Edge Possibilities

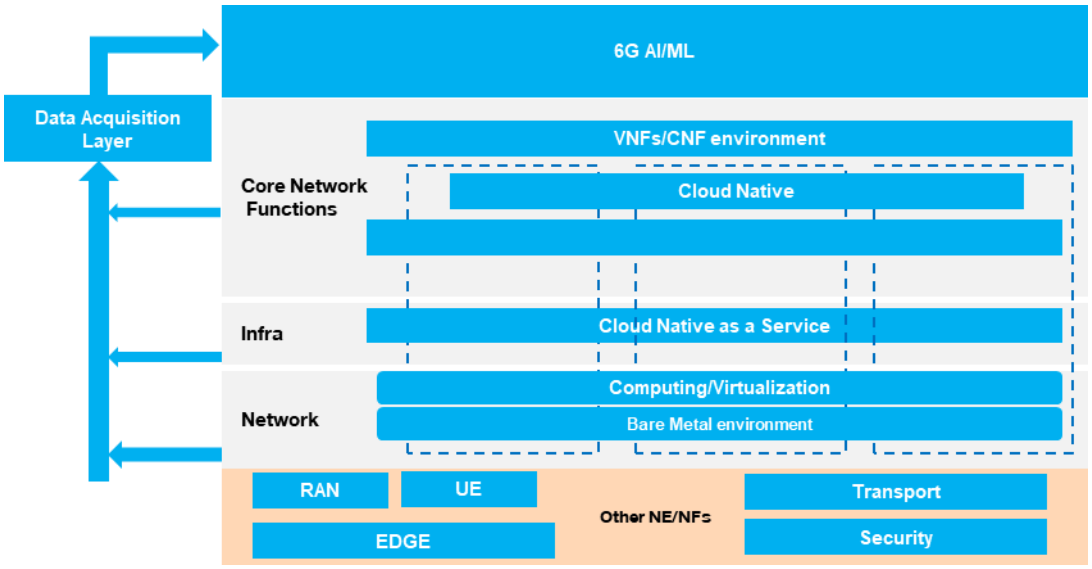

Figure 4-10. 6G Cloud native domain architecture.

5 Related Standards

5.1 ETSI ZSM

The ETSI Zero touch network and Service Management (ZSM) ISG is aiming at defining a new, horizontal and vertical end-to-end operable framework enabling agile, efficient and qualitative management and automation of emerging and future networks and services. ZSM targets a network and service management architecture where all operational processes and tasks (e.g. delivery, deployment, configuration, assurance, and optimization) are executed automatically, ideally with full automation in multi-vendor environments. The existing work from ETSI NFV solves dedicated aspects of network and service management and has defined management capabilities for their respective network function and service virtualization domain. On top of this, ETSI ZSM aims to provide a holistic service management concept which, among others, enables the integration of NFV and edge computing management demands with other relevant service management aspects such as data collection, analytics, intelligence. However, NFV-like architectures are still based on monolithic control and orchestration solutions, mostly dedicated to the management of pipelined network services, where the lack of agility in the service lifecycle and operation is still a clear limitation, especially when it comes to fulfilling heterogeneous service constraints posed by 5G services and beyond.

ZSM goes in the direction of overcoming such limitations, and its reference architecture is built around a set of building blocks that collectively enable construction of more complex management services and management functions. The clear identification and separation of management domains provide means to isolate management duties (possibly referring to very heterogeneous technologies), considering boundaries of different nature (technological, administrative, geographical, etc.). Each management domain provides a set of ZSM management services, realized by functions that expose and/or consume a set of endpoints. An end-to-end service management domain is a special management domain responsible for the cross-domain management and coordination, which glue all of the single domain management services, functions and endpoints.

At the core of the ZSM architecture there are the domain integration fabrics and the cross-domain integration fabric, which facilitate the provision of services and the access to them through the related endpoints across the various domains. It also includes specific services for the communication between management functions, which enable the exchange of management data to consumers. In addition, dedicated domain data services provide the mean to persist data and access it still through the integration fabrics.

According to ZSM principles, management services can be logically grouped according to the functionality offered (such as data collection, analytics, intelligence, orchestration, control). Figure 5-1 depicts the ZSM framework reference architecture. The possibility to flexibly compose management services, together with the exchange of management data provide the foundation of an innovative agile service management that makes easier the integration of the various management aspects (from data collection to orchestration and analysis) enabling the closure of the control loop through network and service optimization processes.

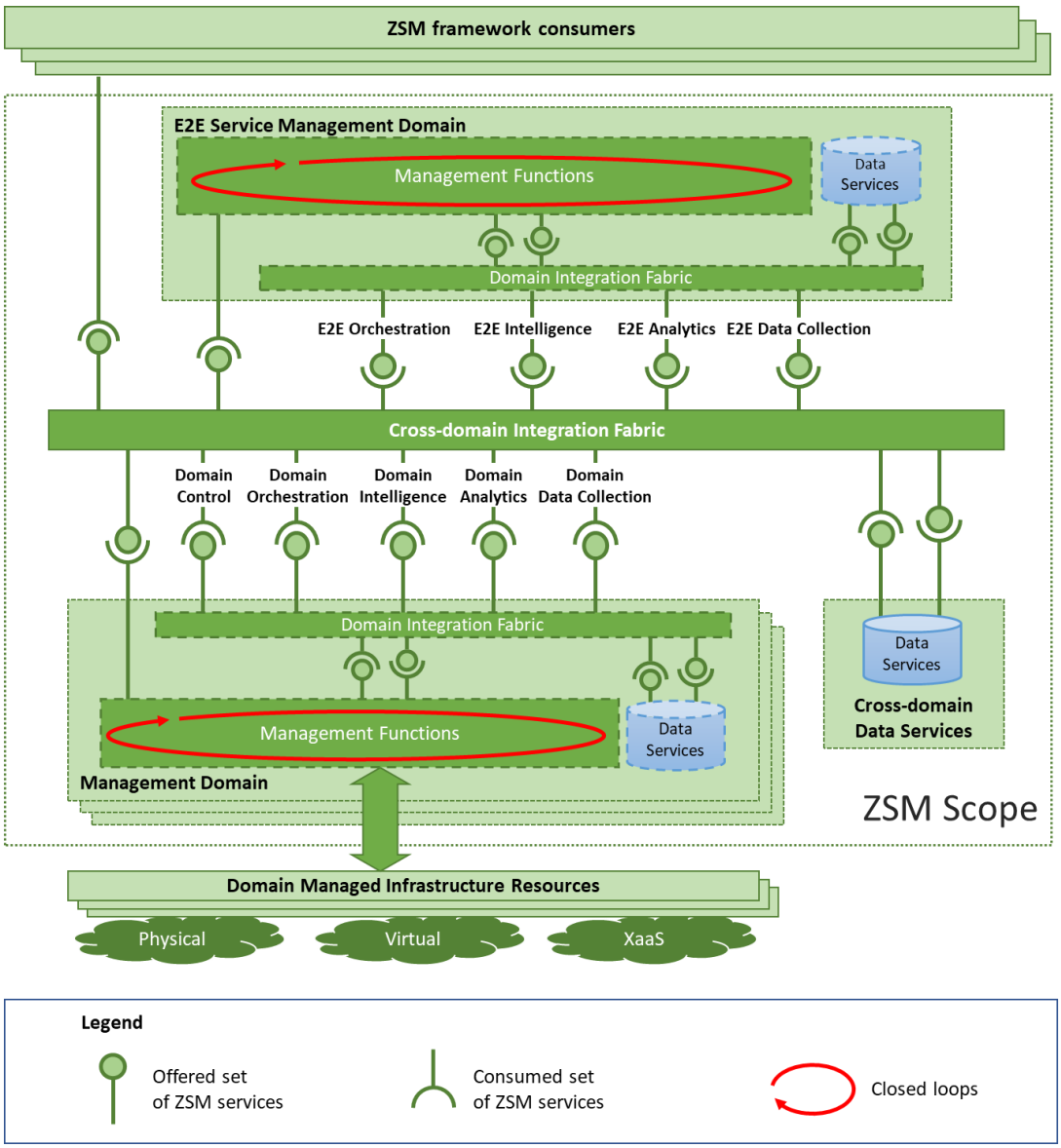

Figure 5-1: ETSI ZSM reference architecture (source: [5])

Based on all the above, the ETSI ZSM approach and principles fits with the requirements and needs of the ADROIT6G system architecture, for what concern an agile framework for composing different AI-enabled vertical and network services under a common agile and flexible architecture, with cooperation of orchestration, data collection and storage, analytics and AI/ML (intelligence) functionalities with decoupled services and functions. ETSI ZSM provides the means to enhance existing management and orchestration capabilities (purely dedicated to lifecycle management of standalone vertical and network services) and enable a comprehensive approach where the runtime service operation is assisted by data analytics and AI/ML tasks, which can be consumed as added value services. This is key to facilitate the implementation of data-driven and AI-enabled solutions for the management of 6G networks and services, capable to fulfil the requirements of heterogenous and demanding 6G use cases.

The ADROIT6G system architecture is conceptually aligned to the ETSI ZSM architecture and principles, as orchestration, control, data analytics and AI/ML services as defined in ETSI ZSM 002

[2] are in line with the capability to provide AI-enabled technical enablers for the realization of 6G networks and services.

Moreover, as said, ETSI ZSM proposes an architecture and a set of enablers to achieve full automation in network and service management, as a way improve the capability of network operators and service providers to deliver, manage and operate their services at scale with reduced operational costs. In this context, ETSI ZSM 005 [3] introduces several means and solutions to automate a set of functionality, operational processes and tasks related to network and service management. The aim of ETSI ZSM is indeed to achieve the realization of autonomous systems through a high degree of automation, combining automatic and adaptive technology enablers and realize cognitive management systems with closed loops. Indeed, most of the means of automation presented in ETSI ZSM 005 [3] (such as policy driven automation, intent-based service orchestration, network governance, network stability) relies on tailored zero-touch closed loops as part of the solution concepts and principles identified to solve the specific automation problem.

5.1.1 Closed Loop Automation

The concept of zero-touch closed loops is indeed considered as one of the main enablers for automation. Being it specifically one of the ETSI ZSM architecture principle (as specified in [2]), it provides a feedback-driven management process that aims at reaching and preserving a set of objectives without any external intervention. Closed loops, which are at the basis of the ADROIT6G system architecture and AI-driven management and orchestration framework, allow self-optimization, improvement of network and resource utilization and automated service assurance and fulfilment.

To achieve closed-loop automation, the ETSI ZSM management framework needs to provide means for the ordered invocation of the steps or phases that realize a closed loop. These are, as specified in ETSI ZSM 009-1 [4] and ETSI ZSM 009-2 [5], and indicated in Figure 5-2, monitoring (responsible for collecting and pre-processing data from managed entities or from external sources), AI-based analytics (responsible for deriving insights from available data from the monitoring stage as well as historical data, possibly leveraging on AI/ML), decision making (responsible for deriving action plans and workflows to be applied from insights provided by the analysis stage), and automated execution actions (responsible for executing the actions and workflows towards the managed entities and resources). An additional knowledge building block (as shown in Figure 5-2) does not represent a real step or stage of the closed loop, but it is rather responsible to maintain and expose to the other closed loop steps the required data to perform its operations. The goal is therefore to realize closed feedback loops that continuously evaluate and adjust network and service attributes and characteristics, according to the specific closed loop and use case goal. In this context, ETSI ZSM 009-2 [5] also identifies the closed loop governance as a set of management capabilities required within the ETSI ZSM framework to management of lifecycle of the closed Loops, configure policies, rules, triggers and priorities of the closed Loops and retrieve status and performance information of the closed loops. ADROIT6G embeds in its AI-driven management and orchestration framework a closed loop governance component, responsible to manage multiple AI-driven closed loop instances and the required interaction with the Crowdsourcing AI/ML framework, with an approach and prototype implementation which is aligned with these ETSI ZSM principles and definitions.

In addition, ETSI ZSM 009-3 [6] addresses advanced closed loop automation topics, such as dynamic composition of closed loops, intent-based closed loops, and cognitive closed loops. Specifically in the area of cognitive closed loops, the ADROIT6G AI-driven closed loop and governance solutions are aligned with the ETSI ZSM proposed approach for using AI/ML techniques and models as part of the closed loop stages/steps operation (e.g. for analysis and decision tasks).

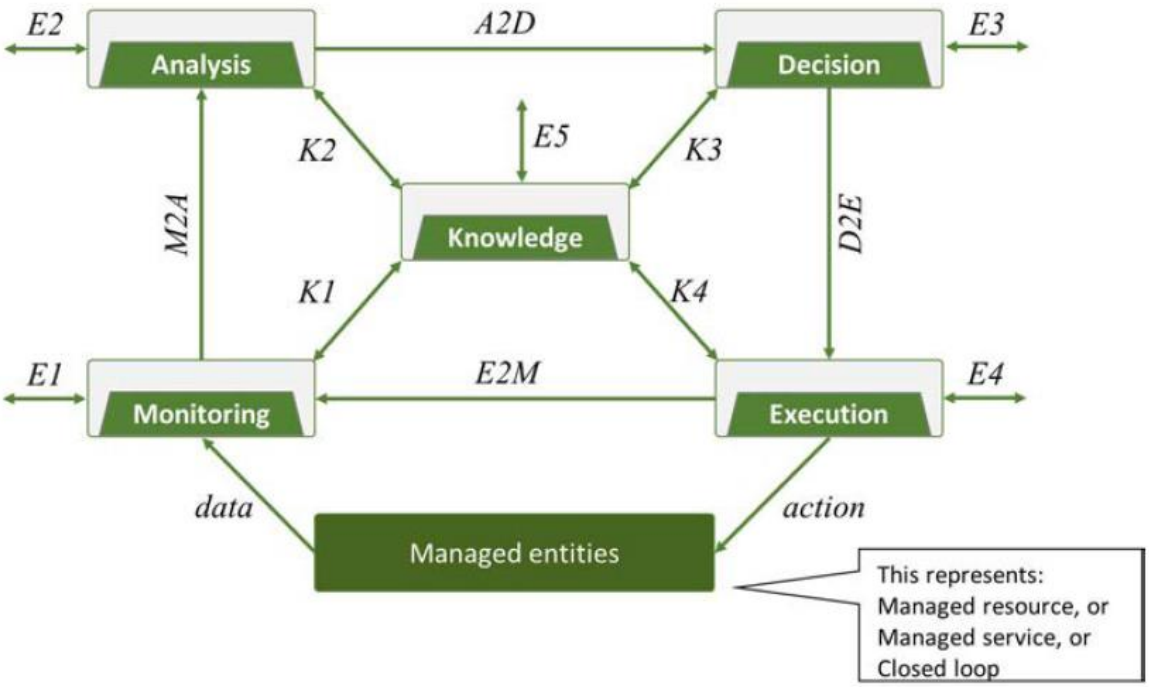

Figure 5-2: Functional view of a Closed Loop

5.2 TM Forum

TM Forum [7] is a global industry association that focuses on digital transformation in the telecommunications, media, and technology sectors. It provides a collaborative platform for industry professionals to share best practices, develop standards, and drive innovation in areas such as 5G, Internet of Things (IoT), cloud computing, and customer experience management, approaching three missions, as seen in Figure 5-3.

Figure 5-3: TMF approaches for telecommunication.

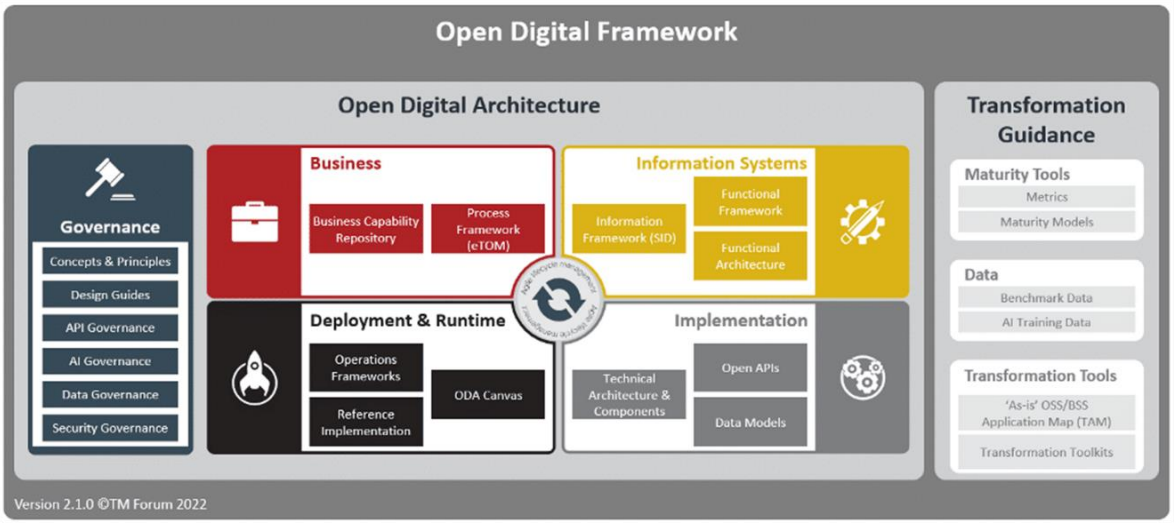

Figure 5-4: TMF Open Digital Architecture.

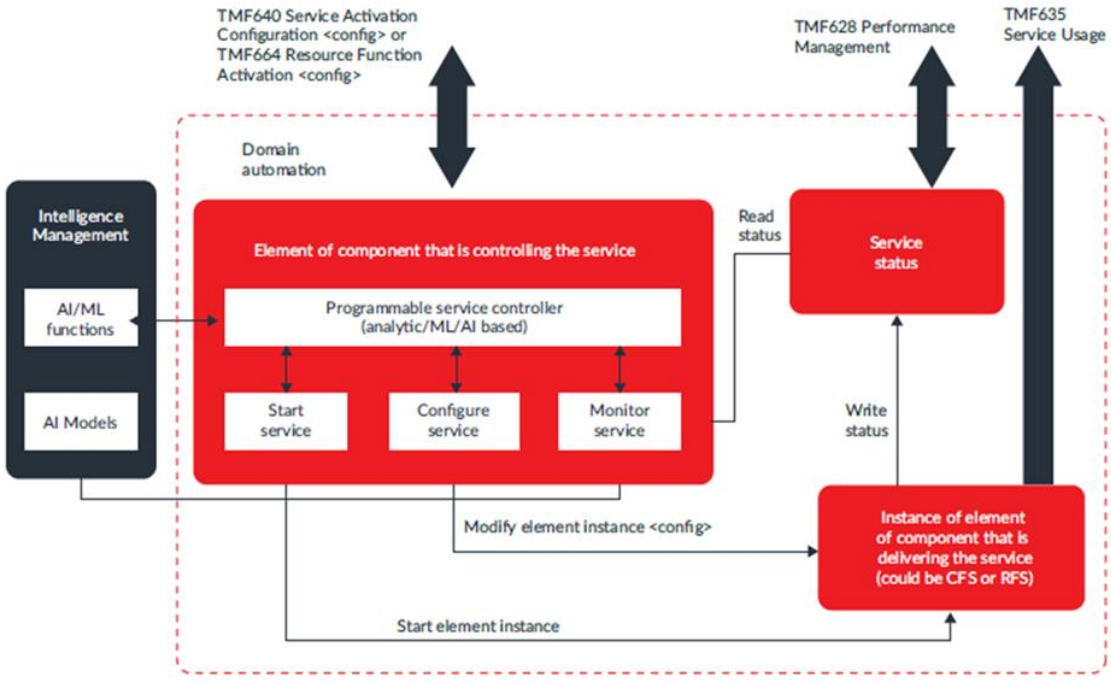

Figure 5-5: TMF autonomous network operation overview.

Composable IT & Ecosystem approach, as summarized by TM Forum's Open Digital Architecture (ODA) is a blueprint for the transformation of telecoms IT and networks, created by our members for the industry, presented in Figure 5-4, the high-level overview of ODA:

- ODA helps telco businesses become nimbler by enabling composable systems and processes - component parts built by the telco and ecosystem partners, connected with Open APIs, plug & play style.
- Telco's can add/remove components and capabilities as technology evolves without escalating costs.

- Composable IT & ecosystems are the cornerstone of a modern-day telco, with the simplicity, automation and modernization required to reduce costs and drive growth.
- Service providers (SPs) need to transition from a traditional telco to being a platform-ready 'digital' telco providing network and/or connectivity as a service.
- CSPs evolve and their services, IT and networks become ever more complex they need a migration path to introduce intelligent operations across all areas of their business so they can become an AI-driven telco.
- Open Digital Architecture (ODA) provides the blueprint.

Autonomous Network Operations (Figure 5-5), describing the TMF operations overview, as:

- Networks are intelligent, native, efficient and reliable, delivering zero-trouble customer experiences
- Fully autonomous, built on open digital architectures, and powered by AI. Moreover, they will leverage Open APIs to drive value through network monetization and enable the delivery of innovative new services
- Autonomous Networks (AN) powered alongside other technologies such as AI, big data, cloud and edge computing
- Fully automated zero wait, zero touch, zero trouble innovative network/ICT services for vertical industries' users and consumers
- Supporting self-configuration, self-healing, self-optimizing and self-evolving telecom network infrastructures for telecom internal users.
- Planning, service/marketing, operations and management.
- AN incorporate a simplified network architecture, autonomous domains and automated intelligent business/network operations for the closed-loop control of digital business, offering the best-possible user experience, full lifecycle operations automation/autonomy and maximum resource utilization.

Data & AI Innovation, digital transformation of new technologies and service rollouts, seen in Figure 5-6:

- AIOps combines big data and machine learning to automate operations processes, including event correlation, anomaly detection and causality determination.
- Digital Telco to the AI-Native telco/AI tools and models.
- AI-Native data architecture, best practices of AI implementation.
- AI/AN framework enables CSPs to unlock new revenue streams, improve their agility and operational efficiency while delivering exceptional customer experience.
- AI Closed Loop Automation Reference Architecture and process flows around key use cases, including the Closed Loop Anomaly Detection and Resolution Automation.
- AI and Automation/ AI in operations (AIOps), AI-assisted or AI-driven automation in network operations.

TM Forum is enabling the industry to explore and understand how to embrace AI, accelerating, de-risking and reducing the costs of applying the technology in their businesses to cut OPEX and grow revenues, Zero-touch is one of the components of TM Forum initiatives, with the programme

Autonomous Networks Project [8], also for future 6G networks implementations, that will be retrieved in the telco's starting with 2030.

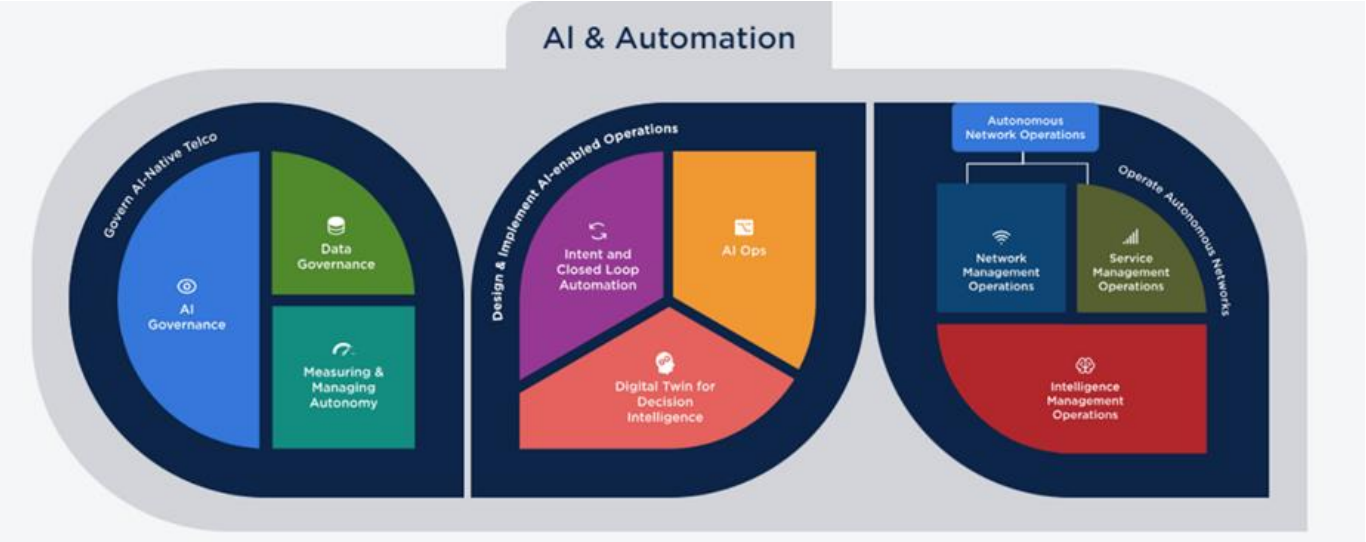

Figure 5-6: TMF Data & AI Innovation and Automation

Open Digital Architecture is introduction to Open APIs ([9]), the TM Forum's Open API program as a global initiative to enable seamless connectivity, interoperability and portability across systems, the forefront of the challenge to find the right mechanism for CSPs and vendors to work together in a faster and more flexible way. Gen5 Open APIs will support the latest event-driven architectures, provide a simpler experience for developers, and enable the intent-based automation which is essential to the efficient operation and management of telecoms IT and networks. The full list of Open API Directory[10] contains Marketing Sales APIs, Product APIs, Service APIs, Customer APIs, Resource APIs, Business Partner APIs and Common APIs, relevant ADROIT6G possible envisioned APIs being listed in Table 5-1. It should be noted that TM Forum principles are linked to ADROIT-6G within few topics like Cloud-Native and Distributive Native-AI driven architecture, zero-touch management and automation goals for network slicing and resource management (Zero-touch Orchestration), the aiming for standardized interfaces and interoperability across different domains and stakeholders interoperability (Open APIs approach).

TMF is supporting the Intent concepts, the formal specification of the expectations, requirements, goals, and constraints, for a technical domain, and is adding specs for intent driven management services for mobile networks. For TMF, the Intent based operation the component of autonomous networks and it includes intent management within autonomous domains through the Open APIs. TMF defines how operators can get a step ahead and deliver future intent-based operations using AI/ML.

Table 5-1: TMF envisioned APIs

API, model, frameworks, Open-Source Solution	Usage and Scope

TMF633 Service Catalog Management API	Service Catalog Management API allows the management of the entire lifecycle of the service catalog elements.
TMF641 Service Ordering API	Create, update & retrieve Service Orders and manages related notifications
TMF639 Resource Inventory Management	Provide the ability to manage Resources.
TMF657 Service Level Specifications	Service Quality Management REST API Specification
TMF655 Change Management API	Standard integration capabilities between external applications and Change Management Application
TMF645 Service Qualification API	Provide service availability to the customer
TMF640 Activation and Configuration API	Allows the user to retrieve, create, update, delete services and retrieve the monitor resource used to monitor the execution of asynchronous requests on specific resource
TMF702 Resource Activation API	Activate Resources, as in the Resource Inventory

5.3 3GPP NTN

3GPP is working on the specification of satellite access in several working groups. 3GPP SA1 is collecting further use cases and potential service requirements for satellite access, that are supposed to be technically specified in Rel-20. The use cases are collected in 3GPP TR 22.887. Satellite use cases related to previous releases are in TR 22.822 and TR 22.865, normative requirements are in 3GPP TS 22.261 [19].

3GPP SA2 has been working on the integration of satellite components into the 5G architecture, the support of NB-IoT/eMTC non-terrestrial networks. Corresponding specifications can be found mainly in TS 23.501 [20], TS 23.502 [21], and TS 23.503 [22].

3GPP SA3 has been working on security and privacy aspects of satellite access, 3GPP SA5 on management and charging aspects.

The RAN working groups are specifying radio-related features for NTNs in different work items (Non-Terrestrial Networks for NR, Internet of Things, Inter-RAT mode mobility support, introduction of different NR NTN bands).

Integration of non-terrestrial networks is a topic of the recently started 6G study in 3GPP SA1 (August 2024). Corresponding stakeholders provided NTN-support and integration, also with respect to satellite-supported positioning, as major area of interest.

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ADROIT6G presents a similar vision for the underlying infrastructure where satellite systems are an integral part of both the communication and computing segments of a 5G/6G network. The aforementioned 3GPP's specifications (including ongoing discussions) are being considered in ADROIT6G mostly from an architectural point of view towards an 5G/6G TN-NTN system, while considering that such converged system shall be administratively managed by different stakeholders. Finally, use cases and their potential service requirements are also being aligned, especially from the transportation vertical domain.

6 Testing & verification methodology

System Under Test (SUT) refers to a system that is being tested for correct operation. In the context of ADROIT6G, a testing and validation procedure will be followed, and robust testing specifications will be defined to ensure that the PoCs will be tested adequately and correctly. The following sections describe this procedure and the PoC specifications.

6.1 Testing and Validation Procedure

The testing and validation procedure is an integral part of the ADROIT6G PoCs and after the definition of the use case or experiment, the end-user will use the scheduling tools, visualization methods, and PoC templates provided by the ADROIT6G platform. Constant experiment monitoring will be also available with detailed performance evaluation on various levels. The exact stages of the ADROIT6G experimentation process are depicted in Figure 6-1 below.

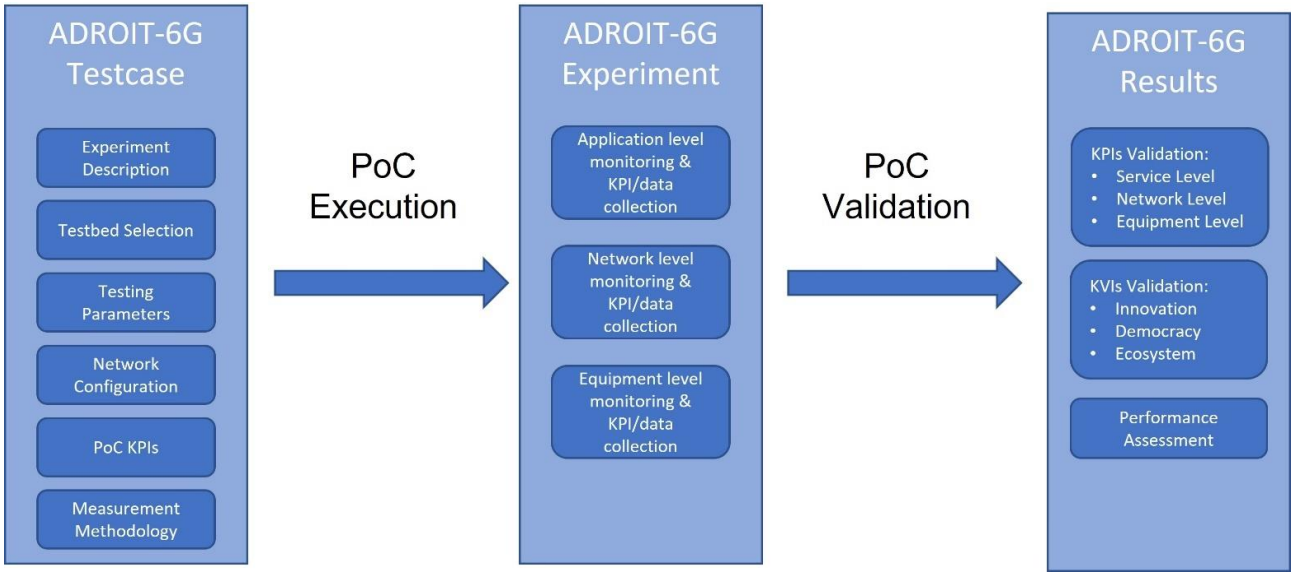

Figure 6-1. ADROIT6G testing and validation procedure.

Step 1 – PoC testcase definition: During this initial step, the testcases for each ADROIT6G PoC will be defined, utilizing the UML diagram which is a diagram based on the UML (Unified Modelling Language) with the purpose of visually representing a system along with its main actors, roles, actions, artifacts or classes, in order to better understand, alter, maintain, or document information about the system. Part of this PoC testcases definition will be all the specifications that are contained on the PoC template and will lay the foundation on how to execute and what to expect from the execution of the testcases.

- **Current Status**: this step is in progress. UML diagrams and PoC templates have been established, and the test case definitions outlined in deliverable D2.2.

Step 2 – Experiment: The second step of the procedure is the actual experiment step. At this step, the defined KPIs are collected as the PoC is executed based on the defined specifications of step 1. Monitoring and KPI collection can be done on a) Application, b) Network, and c) Equipment level.

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- **Current Status:** Monitoring and collecting KPIs is in place; the framework for experiment execution is being implemented. Data collection tools for monitoring KPIs at various levels are being refined, with planned execution on its way.

Step 3- Validation: The last step is the validation of the experiment results. The validation will be done both in terms of KPIs but also in terms of KVIs and general performance assessment. This completes the Testing and Validation Procedure.

- **Current Status:** Validation process outlined. Full implementation and validation of the experiment results are ongoing. The KPIs and KVIs defined according PoCs progress.

6.2 ADROIT6G PoC Testcases' Specifications

PoC Testcases for ADROIT6G have some common characteristics in terms of specifications and it will be beneficial to have a better overview of them to define them early on. Those specifications are relevant to most testcases and will be utilized as part of the PoC template presented in the following section. Test cases UML diagrams are provided in ADROIT6G's deliverable D2.2.

Description: The first specification is for describing the PoC scenario and its specific aim by giving a high-level representation of the target environment and UC/service deployment, identifying the placement of the various components in the testbed and highlighting how they are interconnected to (or through) the 6G network.

- **Current Status:** Definition of POCs established.

Network Environment: This specification is focusing on the 6G network characteristics of the environment where the experiment will be conducted and is broken down into three sub-fields:

- 6G Network settings/configuration: The first subfield describes the 6G Network settings/configuration, in which the experimenters will declare all necessary details regarding the network settings and configurations to make the PoC reproducible.
- Traffic flows: This sub-field describes the PoC traffic flows either in downlink (DL) direction or uplink (UL) direction, specifying their source and destination among the components involved in the experiment.
- Relevant KPIs tested: The third sub-field is for defining the target network KPIs, both in terms of which KPIs are relevant, as well as which are the target values that need to be met at the end of the experiment.

    - **Current Status**: In progress. Network environment specifications defined, with details on traffic flows and network settings. The KPI values and their final validation are still in progress and will be refined through WP5 activities and the execution of the concrete PoCs.

Components and Configuration: This specification is for listing the components of the SUT experiment, either hardware or software and their corresponding configuration, with the following further categorization:

- Components of the SUT: This sub-field is for the experimenters to list the information regarding the hardware components and their corresponding configuration during the experiment.
- Networking components: A list of networking software tools must be completed in this sub-field such as traffic generators, network emulators and network probes, etc.

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- Application-level Configuration: The last sub-field is dedicated to the application-level configuration such as the number of the users and device configuration settings, etc.
    - **Current Status:** Component lists and configurations are being finalized.

Procedure: This specification will provide information for the correct execution of the PoC including a detailed procedure to be repeatable for future re-testing. Included in this are information regarding:

- Test location/route: For indicating the start and the end points of the test.
- Pre-conditions: Pre-conditions that are needed before the execution of the PoC.
- Steps: The actions and procedures that are needed during the different PoC execution steps.
    - **Current Status:** Testing procedure outlined, still subject to possible adjustments for the different POCs.

Measurements: This specification aims to provide the methodology of the experimental measurements and their calculation process. It contains three different sub-fields:

- Methodology: A detailed description of the methodology, such as the acceptable values of the monitoring time, the number of iterations, the monitoring frequency, the formatting of metrics and log files, etc.
- Measurement points: Measurement points where monitoring probes or agents should be placed to perform the required measurements.
- Calculation process: The necessary information on how the calculation process should be conducted.
    - **Current Status:** In progress.

Expected results: The last specification is the description of the Expected Results. This includes results that are potentially outside of the scope of the defined KPIs.

6.3 POC Template

The ADROIT6G PoC template is the document used to outline all necessary details for conducting SUT (System Under Test) experiments. It includes specifications such as inputs, resources (hardware/software), execution steps, and testing procedures, along with mechanisms to monitor KPIs and record experimental results. The template covers various aspects like network environment setup, traffic flows, hardware components, application configurations, and measurement methodologies.

Table 6-1. ADROIT6G PoC template

Topic	PoC	Description
Experimental platform		Platform where the PoC will be executed.
Description		Description of the PoC, and high-level purpose

Network Environment	6G Network settings/configuration	Necessary details regarding the network settings and configurations to make the PoC reproducible
	Traffic flows	Traffic flows included in this UC, along with their flow direction (DL/UL),
	Relevant KPIs tested	Target network KPIs, both in terms of which KPIs are relevant, as well as which are the target values that need to be met at the end of the experiment.
Components and Configuration	SUT (System Under Test)	Hardware components and their corresponding configuration during the experiment.
	Networking	List of network tools required to reproduce specific network conditions or collect network metrics required to execute the experiment in the target environment.
	Application-level	When applicable, application-level configuration parameters.
Procedure	Test location/route	Indicate the start and end point of tests.
	Pre-conditions	Any pre-condition that needs to be met before execution of the PoC.
	Steps	Steps (actions/ procedures) that need to be performed during the execution of the test.
Measurements	Methodology	The methodology to collect and evaluate the measurements.
	Measurements points	Measurement points where monitoring probes or agents should be plaUpdates on ced to perfoADROIT6G rm the required measurements

Framework

	Calculation process	The necessary information on how the calculation process should be conducted
Expected results		Results that are potentially outside of tThe updates of the framework are set bhe scope of the defined KPIs, if those exist.

Current Status. To this end**,** the PoC template has been developed and presented in deliverable D2.1, with initial fields for PoC ID, trial site, and PoC type. It is ready to be used for setting up and executing experiments, actively being used in testing.

7 ADROIT6G KPIs and KVIs

The scope of the present section is to describe and provide the updates on the definitions of relevant target KPIs and KVIs proposed in the literature and in other projects, as well as the international SDOs, and also in the ADROIT6G project. Based on the requirements and needs of the PoCs of the project, the KPIs and KVIs described in this version will set the frame for the validation of the project's PoCs extreme UCs.

The present section aims to provide the complete overview of the 6G network-level KPIs and KVIs within the context of ADROIT6G PoCs. As a result, the scope of the present section is to showcase the definition, the measurement methods, and the verification of technological components of the systems' core 6G network KPIs/KVIs related to the project's PoCs. It is worth mentioning that the outcomes and the proposed methods for KPIs/KVIs framework has been built upon the work described in D2.1 and D2.2. For the purpose of measuring and verifying the results, the KPIs involved and described are defined in:

a) technological network-level for the measurement of the performance of the networks b) application-level for the measurement of the utility of the applications developed within the PoCs

Based on this classification, we provide the final overview of the well-defined set of 6G network-level KPIs and KVIs, with the baseline objectives of the project and set the ground for the target values for each PoC. At this point we need to mention that the process for the development of the framework will be validated within the context of the WP5 activities based on the PoCs idiosyncratic characteristics, the final requirements and the results measured using the KPIs and KVIs to be realistic and relevant for the ADROIT6G's PoCs.

This chapter describes the final set of ADROIT6G on the testing and validation with respect to finalized KPIs and KVIs framework for the project's PoCs. ADROIT6G focuses on the end-to-end validation will be conducted through three heterogenous PoCs for applications with features powered by 6G such as the holographic presence, terrestrial 6G IIoT with extreme mMTC, Rail Automation Support by Non-Terrestrial Networks and Collaborative Construction Robots. With this perspective and given the current restrictions of the 6G enablers, components and that will be evaluated in the results validation.

At this point, it is worth to mention that the 6G commercial networks are expected to be launched around 2030 and currently 6G is in the development phase and standardization is planned to begin within 2025. To this end, in the pre-standardisation phase, the technical KPIs are expected to underperform in comparison with the high speed, low latency and the other major metrics that build the long-run impact of 6G. To this end, as also it is denoted in D5.1, ADROIT6G components and innovations are expected to play a key role on the fulfilment of the PoCs' Key Performance Indicators (KPIs) and Key Value Indicators (KVIs).

To this end, the Key Performance Indicators (KPIs) and Key Value Indicators (KVIs) are defined for the establishment of a holistic methodological assessment framework enabling a uniform and holistic assessment of the four PoCs and the validation of the results and the ADROIT6G architecture.

The core aspect in the KPIs and KVIs collection and analysis will need to be monitored throughout the use of monitoring system of the testbeds. The monitoring system will be a part of the overall framework for the collection of the data from the respective sources, the calculation of the KPIs

defined for each PoC, the collection of the relevant KVIs for each PoC, through the qualitative criteria (relevant for each PoC) and the reporting of the KPIs/KVIs on a dashboard (developed in Grafana).

7.1 ADROIT6G KPIs/KVIs Design Framework

For the set-up of the KPIs/KVIs framework, the present section builds upon the already existing outcomes described analytically in ADROIT6G's deliverables D2.1 and D2.2 and the relevant state-of-the-art results for the emerging issue of measurement of the 6G networks performance and impact.

6G KPIs/KVIs framework builds upon the legacy of 5G/B5G frameworks with the increased performances in terms of the generic network KPIs, enabling new services based on the advanced evolution of networks and its new capabilities. The ADROIT6G framework aims to merge the enhanced capabilities of 5G and the emerging and more advanced capabilities of 6G. In this context, the current deliverable of ADROIT6G identifies the required KPIs to adequately assess the performance of both sets of enhanced and new capabilities based on the measurement standards.

In general, the key indicators are defined in IMT-2020 and IMT-2030, along with some indicative target values for the 6G academic research, focusing on the capabilities of the networks with a decade horizon. At this point, it is worth mentioning that the 6G commercial networks are expected to be launched around 2030 and currently, 6G is in the development phase and standardization is planned to begin within 2025. To this end, in the pre-standardisation phase, the technical KPIs are expected to underperform in comparison to the high speed, low latency and the other major metrics that build the long-run impact of 6G. Consequently, even though the proposed target values of the KPIs follow the definitions of the IMT-2030 recommendations, the KPI validation needs to be performed from the point of view of the project and the specific use cases, using currently available technologies in the testbeds' facilities.

The conceptual framework for the KPIs/KVIs framework is set as described in Figure 7-1. To this end, the framework follows the five main steps as analyzed in [12] that originally describes the implementation of KVIs framework for the case of smart cities.

In the case that further adjustments on the KPIs and KVIs are required based on the capabilities of the 6G networks, with the existing constraints faced, all the appropriate transformations will be made for each PoC in ADROIT6G's deliverable D5.2.

The first step is to set the overall framework at a high level so that we can frame the definitions of the Use Cases or in the ADROIT6G context the PoCs and the scenario analysis required. The next step, concerns the elicitation of the definitions, based on the standards provided by the ETSI, SNS, and other international organizations for the capabilities of the 6G. This step is decomposed into two main needs, firstly the definition of the KPIs/KVIs based on the standards and the breakdown into subsets by category, and secondly gathering the existing research for the estimation of the Key Target Values, based on the State-of-the-Art analysis of the literature and the results of the available research, or the requirements as defined flagship projects.

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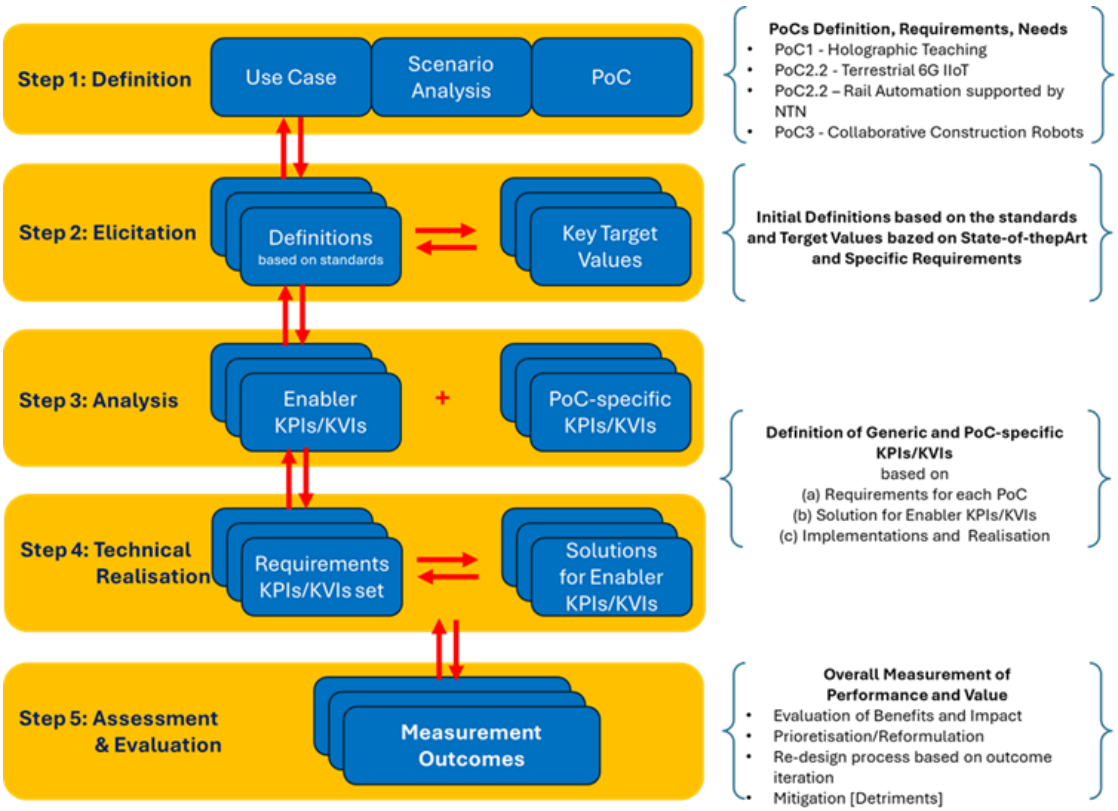

Figure 7-1. KPIs/KVIs definition framework ([13]).

In the third and most crucial step, both the enabler and the PoC-specific KPIs/KVIs will be analyzed in terms of requirements and specifications to assess their expected behavior within the ADROIT6G framework and architecture. Afterward, the requirements set and the solutions for the enabler KPIs/KVIs shall be tested. The last step of the process elaborates on the assessment and evaluation of the end results and the collection of the measurement outcomes. Within ADROIT6G context the measurement of the KPIs concern the network performance, the end-to-end solutions performance, as well as the performance of each component, in the cases that this is feasible. Analytically, the KPIs for each PoC are determined along with their target values in Section 8 of the present deliverable for each PoC, for all the three categories mentioned. In addition, for the long-term impact of the technical developments, the main key values for each PoC are defined, accompanied with the set of quantitative and qualitative measures for the contribution of the technical developments towards the three main categories of key values, Innovation, Democracy and Ecosystem, and the sub-categories as described in the SNS Working Programme 2021-2022.

Within the above-described framework, the present section aims to identify the required KVIs for the overall evaluation of the performance and value of the new capabilities of 6G with respect to the standards accompanying the measurement for 6G networks. To this end, Table 7-1 maps each traffic type of the UCs to its relevant KVIs, for the categories of innovation, democracy and ecosystem. This table can be later altered, as the UCs mature and evolve but an initial approach to those is provided here. Furthermore, Table 7-1 provides a full overview of the KVIs for validation, as well as their relevance, scope and the measurement method implied. Both the table set a complete framework for the UCs performance measurement and validation.

6G can provide diverse benefits in the PoCs concepts, such as data traffic off-loading, improved spectral efficiency, decreased latency, increased throughput, better reliability, and improved energy efficiency. As can be noticed, 6G is expected to have serious impact and provide a series of benefits in terms of speed, latency, efficiency and reliability, while providing more possibilities for real-life implications in several verticals.

For the scope of the PoCs and the validation of the results, selected KPIs and KVIs have been selected for the validation of the 6G network advancements over the 5G/B5G technologies, as well as the improvements in both the performance and longMapping of -term impact of applications developed in the context owithin f the PoCs. In the updated version, new KPIs have been defined for each PoC, in comparison with the two previous iterations of the ADROIT6G architecture. More specifically, for all PoCs the scalability of the systems has been introduced, as well as AI KPIs for measurement of the AI models and algorithms performance (when applicable).

Table 7-1. Network and Service Key Performance Indicators and KVIs of ADROIT6G.

	Poc1	**Poc2a**	**Poc2b**	**Poc3**
Network and Service Key Performance Indicators as defined in the DoA and D2.1				
Peak throughput (Gbps)[1]	√	X	X	X
Experienced upload throughput (Gbps) per device	√	X	X	√
Experienced download throughput (Gbps) per device	√	X	X	√
Maximum bandwidth (GHz)	√	X	X	√
Jitter (μs)	√	√	√	√
Energy efficiency (Tb/J)	√	X	X	√
Device density (devices/m^2)	X	√	√	√
Reliability (packet error rate)	√	√	√	√
Positioning accuracy (cm)	X	X	X	√
End-to-end latency (ms)	√	X	X	√
Visualised user experience	√	X	X	X
QoE (Quality of Experience)[2]	√	√	√	√
AI Model Selection Latency	√	X	X	X
System Scalability	√	√	√	√
Service Recovery Time	√	X	X	X
Orchestration Efficiency	√	X	X	X
Computing power needed per stream rendering (aggregate processing power in CSP)	√	X	X	X
Ram needed per stream rendering	√	X	X	X
Key Value Indicators				
Innovation				
KVI I1: Safety	√	√	√	√
KVI I2: Security	√	√	X	√
KVI I3: Regulation	√	√	√	√
KVI I4: Responsibility	√	X	X	√
Democracy				
KVI D1: Privacy	√	X	X	√
KVI D2: Fairness	√	X	X	√
KVI D3: Digital Inclusion	√	√	√	√

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KVI D4: Trustworthiness	√	√	√	√
Ecosystem				
KVI E1: Sustainability	√	√	√	√
KVI E2: Business Value	X	√	√	√
KVI E3: Economic Growth	X	√	√	√
KVI E4: Open collaboration	√	X	X	√
KVI E5: New Value Chain	X	X	X	√

For the monitoring purposes of the ADROIT6G, the architecture requires the KPIs/KVIs monitoring platform as part of the PoCs framework responsible for the collection of the KPIs/KVIs data from the respective data sources (technical and non-technical) for each testbed. In addition, the monitoring platform functionalities will need to proceed with the required calculations for KPIs and the KVIs as defined by the standards for each Proof-of-Concept. Finally, the platform will need to provide the data for other purposes including a visualization tool for reporting and extracting.

It should be noted that despite the definition of the framework and the complete overview of the available KPIs and KVIs, the final set of measurement indicators for the performance and value of the ADROIT6G PoCs validation and evaluation will be subject to the work performed within the context of WP5 “Integration & Validation” and the related deliverables, that concern the implementation of the ADROIT6G as designed in WP2-WP4, and will be tested and validated in the four concrete PoCs. Within WP5 also, the implementation requirements are described, so that the set of KPIs/KVIs meet the requirements and the needs for each PoC.

To this end, ADROIT6G’s deliverable D5.2 will provide a detailed analysis of the functional requirements from the use cases perspectives (including the definition of relevant KPIs and KVIs to be validated) and the target values, based on technical requirements to be used in the design of the ADROIT6G platform architecture and its components, their detailed low-level design, and the testing and verification methodology containing the definition of test reports format and benchmarking for the validation of the KPIs and KVIs to ensure compatibility as well as future re-usability.

7.2 Key Performance Indicators (KPIs) Final Definitions

As prementioned, the KPIs within the context of ADROIT6G are classified in two categories for capturing the advancements in the performance of the networks, and the upgrade in the PoCs environment, for the end-to-end performance of the application, as described in the following Figure. Given the emphasis on the 6G, which is expected to produce networks with greater speed, reliability, capabilities and energy efficiency, as Quality of Service (QoS) and Quality of Experience (QoE). 6G networks compromise lower latency and faster data transmission, boosting the supported services and applications, providing significant upgrade.

All the technical KPIs are defined in general context so that the framework, facilitate the PoC owners for the evaluation of the Testing Cycles, as depicted in Table 7-2, while the target values have been adjusted based on the initial set of requirements and the capabilities of the systems utilized in testbeds. Within ADROIT6G context the KPIs are classified into three core categories, are it is discussed in Section 8 for each PoC (a) Network KPIs, (b) Service KPIs and (c) KPIs per Component,

which measures the performance contribution of each component in the overall architecture to the Network and Service KPIs, as well as the Technical Objectives KPIs of the project.

7.3 ADROIT6G KVIs Final Definitions and Indicative Target Values

The present section describes an overall mapping for the Key Values and the KVIs for the utilization of the ADROIT6G PoCs. Specifically, an overall mapping of the KVIs and the proposed methodologies for measurement and the indicative target values, are presented in Table 7-2. as stated in the SNS R&I Work Programme 2021-2022, including an explanation of their measurement method. These KVIs will show how ADROIT6G will provide societal impact to vertical sector applications and to European industrial competitiveness and were also formulated through focused group surveys, workshops, webinars, interviews with relevant stakeholders, etc., as they relate to important human and societal key value areas.

The KVIs definitions along with the variables that can technically use for their measurement and the metrics that can be used for each key value are presented below. Given the heterogeneity of the PoCs and the need for different metrics, the target values are provided in Section 8 for each PoC. The KVIs selected for each PoC have been adjusted based on the needs and heterogeneity of each PoC needs and taken into consideration for the determination of the functional and non-functional requirements for all PoCs. The KVIs are both quantitative in the cases that this was feasible and qualitative, when the existence of any alternate metrics was proposed in the SoTA literature, mainly in the case that the service experience is involved.

Table 7-2 includes the definitions for the KVIs, as well as the main metrics and variables that are used broadly for the Key Values, while the initial set of indicative KPIs for Key Values are proposed.

Table 7-2. Definition of the KPIs and Target Values for the PoCs

Key Values	High Level Definitions	Variable for Capturing Definition	Indicative KPIs for Key Values
Innovation			
KVI I1: Safety	Greater protection of vulnerable people, improved feeling safe, and increased operational efficiency for saving lives// Protection of humans, to prevent harm, safer communities.	Greater protection of vulnerable people, improved feeling safe, and increased operational efficiency for saving lives// Protection of humans, to prevent harm, safer communities.	Survey, user and stakeholder perception of personal and community safety resulting from tool use % of actions taken with a device (before vs after) that suggest decrease risk taken by first responders.
KVI I2: Security	Decrease system vulnerabilities	Decrease system vulnerabilities	100% system secured, number of processes that delegate responsibility to appropriate parties and ask them to consider their impact to the wider ecosystem,

			100% personal data protected from unauthorised use.
KVI I3: Regulation	# of Regulatory and Legal Compliance/Standards/Compliance	% of outputs based on such regulatory compliance, standards, certifications etc.	100% ability to be compliant with data, processes etc regulations Survey
KVI I4: Responsibility	Being accountable for (and having control over) system behaviours.	Being accountable for (and having control over) system behaviours.	Number of alternative approaches possible for each system configuration or ratio of system behaviours users can manipulate
KVI I5: Energy efficiency	Reduction in Energy Consumption	Reduction in Energy Consumption	energy consumption per bit >90% ~100% device energy efficiency, 0% energy efficiency degradation due to activity, % improved energy efficiency compared to current status, or % energy from renewable resources, or does not hamper the development and deployment of a low-carbon alternative
Democracy			
KVI D1: Privacy	Confidentiality in of the person	Privacy preservation	>95% privacy concerns of users addressed
KVI D2: Fairness	Impartial and just treatment without discrimination. Outcomes of decisions aimed at avoiding disparate effects on different groups, unless relevant differences cause uneven benefit or burden.	Lack of Bias	Ability to evaluate for bias in algorithms/systems being produced
		Dignity	Survey of users and stakeholder perceptions of the impact of tools on their personal dignity
		Access to participate in DM process	#% users perceive that have better access to active participation in relevant functions regarding 6G and solutions.
KVI D3: Digital Inclusion	Able to support a range of existing	Service Availability	99.9% communication service reliability

	community devices, giving service access to the widest possible range of demographics in a community. Serve the historically under-served; consider broader demographics and ensure they are included in the benefit from the innovation. This include both social and digital inclusion, reducing the digital divide of who has access	Service Availability	Ratio, Increased community access to use services, across all demographics as defined by community authorities
		Embedded devices	# of new embedded devices connected
		Skills Upgrade	# of trainings/trainees offered to marginalised groups
KVI D4: Trustworthiness	Solution deemed trustworthy; stakeholders trust fellow users/governance; trustworthy infrastructures and networks, trusting of other users, public trust in systems and authorities, trust in a behaviour or process, trust in institution.	Dependability	>90% stakeholders deem system dependable for their activities
		Consistency	100% consistent coverage of the network
		Consistency	Comparison of latency of data transmissions (previous vs current).
		Consistency	0% potential bias detected
		Confidence	Reported confidence in sustainable digital devices, systems, and services used in the use-case development and operation.
Ecosystem			
KVI E1: Sustainability	Stakeholder perception and involvement	Reported confidence in sustainable digital devices, systems, and services used in the use-case development and operation.	>80-90% of the users expressing positive evaluation regarding the sustainability of the devices, network, developed applications and services.
	Supply Chain Stakeholders penetration	Supply Chain Stakeholders penetration	Number of involved stakeholders, potential stakeholders, or EoIs for platform adaptation + Diversity of verticals.

	Resource Savings	Resource Savings	>30% CO2 emissions reductions in 6G systems or Quantity of resources saved (money, time, resources like energy consumption) predicted through the use of the tools
	Improved productivity and effectiveness	Improved productivity and effectiveness	% of stakeholder perspectives on their productivity and effectiveness on their activities
KVI E2: Business Value	Inclusive commercial benefit, maintaining and building new market spaces, developing new value chains	Inclusive commercial benefit, maintaining and building new market spaces, developing new value chains	Survey, stakeholder perceptions of problems solved Business growth with financial metrics Survey of users, including quantitative results Number of new customers % cost saved by working with such solutions over defined
KVI E4: Open collaboration	Using methods based on collaboration and knowledge sharing. Include end-users and stakeholders in processes. Work though co-design with local/stakeholder organisations.	Awareness	Survey, Improved awareness among partners and users of stakeholder values, challenges, and needs.
		Participatory processes/methods for community engagement	% of services developed with users and suppliers/ Number of end-users and stakeholders
KVI E5: New Value Chain		Community networks	Increase in community networks (% increase, number total). # of new devices # new verticals

7.4 Remarks on the KPIs/KVIs framework

For the set-up of the KPIs/KVIs framework, the present section builds upon the already existing outcomes described analytically in ADROIT6G's deliverables D2.1 and D2.2 and the relevant state-of-the-art results for the emerging issue of measurement of the 6G networks performance and impact. 6G KPIs/KVIs framework builds upon the legacy of 5G/B5G frameworks with the increased

performances in terms of the generic network KPIs, enabling new services based on the advanced evolution of networks and its new capabilities. The ADROIT6G framework aims to merge the enhanced capabilities of 5G and the emerging and more advanced capabilities of 6G. In this context, the current deliverable of ADROIT6G identifies the required KPIs to adequately assess the performance of both sets of enhanced and new capabilities based on the measurement standards.

For the monitoring purposes of the ADROIT6G, the architecture requires the KPIs/KVIs monitoring platform as part of the PoCs framework responsible for the collection of the KPIs/KVIs data from the respective data sources (technical and non-technical). The measurement of the related KPIs and KVIs will take place within the testbeds, leveraging the monitoring components of each testbed.

It should be noted that despite the definition of the framework and the complete overview of the available KPIs and KVIs, the final set of measurement indicators for the performance and value of the ADROIT6G PoCs validation and evaluation will be subject to the work performed within the context of WP5 “Integration & Validation” and the related deliverables, that concern the implementation of the ADROIT6G as designed in WP2-WP4, and will be tested and validated in the four concrete PoCs. Within WP5 also, the implementation requirements are described, so that the set of KPIs/KVIs meet the requirements and the needs for each PoC. Finally, from an architectural point of view, section 8 of the present deliverable provides a the targeted KPIs and KVIs for each PoC, along with the requirements and the technological enablers from a use cases perspectives, including the target values, based on technical requirements to be used in the design of the ADROIT6G platform architecture and its components.

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8 ADROIT6G PoCs' definition

The ADROIT6G innovative concepts and technologies described above are designed to address various challenges and requirements in the next generation 6G wireless networks. These concepts work in synergy to provide a robust and efficient 6G networking solution able to support the selected innovative use cases and PoCs requiring 6G performance characteristics:

- PoC1: Holographic Teaching
- PoC2: Industrial IoT
  - PoC2a: Terrestrial 6G IIoT
  - PoC2b: Rail Automation supported by NTNs
- PoC 3: Collaborative Construction Robots

In what follows, we present details on the ADROIT6G PoCs, by focusing on their functional and non-functional requirements, their validation criteria, and the considered KPIs per component.

8.1 PoC#1 – Holographic Teaching

PoC.1 will demonstrate a scenario where a teacher delivers a lecture from his/her home, university office, or another remote location. At the same time, students in a physical classroom can watch the teacher's holographic projection delivering the lesson and interact with the teacher by asking questions. The scenario involves **capturing**, **transmitting**, **processing**, **and rendering high-quality 3D holographic content** (point cloud data) in **real-time** using 6G technologies, the ADROIT6G architectural elements and the local UE-VBS computing resources formed by harnessing the networking, storage, and processing resources of mobile devices. In this PoC, these resources can typically be provided by mobile devices that are located on the university campus.

At the teacher's position, a volumetric capture system will be installed to capture his/her activity. For example, the teacher's setup will consist of either three Microsoft Azure Kinect DK depth cameras or the Evercoast Volumetric Capture System, which can be set up with up to 21 depth cameras (Intel RealSense Depth Camera D455). The acquired volumetric data will subsequently be subjected to real-time compression utilizing video coding algorithms to decrease its size for efficient transmission throughout the network. The coded volumetric data, will then be streamed in real-time, through a robust 6G network connection, from the teacher's location directly to the university campus (i.e., to a cluster of UE-VBSs selected to act as CSHs and clustered to form a CSP) for processing and rendering of the 3D holographic data which is then shared with the students in the classroom that will be equipped with AR/VR glasses or XR-compatible smart devices.

Table 8-1 shows the required data rate to transmit the point cloud data recorded from the volumetric capture system to the CSP. The requirements for the transcoding and rendering the holographic data into frames are tabulated in Table 8-2. The data rate requirements for the transmission of the rendered data to the end-devices of the students, based on different resolutions, can be seen in Table 8-3.

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Table 8-1: Data rate requirements for point cloud data captured through volumetric capture systems.

System	Size per frame (MB)	Cameras	Frames per second	Raw Mbps	Compressed Mbps
Evercoast Volumetric Capture	3.2	21	30	16,128	81
Azure Kinect DK	1.4	3	30	1,013	5

Table 8-2: Required computing requirements for holographic rendering device.

	PC[2]	Mobile[3]
Operating System	Windows 10 64-bit version 1909 revision .1350 or higher, or versions 2004 and 20H2 revision .789 or higher	Android 8 or higher SDK 30
Processor	Quad-core Intel or AMD, 2.5 GHz or faster	64-bit Arm-based CPU
Video RAM	16 GB RAM	8 GB RAM
Graphics Card	NVIDIA RTX-2000 series or newer AMD RX-6000 series or newer	Mali T8xx, G71, G72, G76, G77, G78 and G71x series Adreno 5xx, 6xx or 7xx series PowerVR GM9xxx series Xclipse 920
Graphics APIs	DirectX 12 (with Shader Model 6.6 atomics), or Vulkan	OpenGL ES 3.2 Vulkan 1.1 on Android 10 or later devices with compatible drivers
Storage	OS Drive 2 TB M.2 NVMe3	

Table 8-3: Data rate requirements for rendered virtual environment shared with students.

Frame width	Frame height	Frames per second	Raw Mbps	Compressed Mbps

[2] Unreal engine hardware and Software Specifications: https://dev.epicgames.com/documentation/en-us/unreal-engine/hardware-and-software-specifications-for-unreal-engine

[3] Android device specifications for VR content streaming: https://dev.epicgames.com/documentation/en-us/unreal-engine/android-support-for-unreal-engine?application_version=5.3

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3840	2160	90	17,086	85
2560	1440	90	7,594	38
1920	1080	90	4,271	21
1280	720	90	1,898	10

8.1.1 Limitations of 5G in Addressing PoC Challenges

3D holographic teaching is a demanding eMBB application that relies on real-time rendering, seamless interactivity, and the transmission of high-resolution 3D content from one end (i.e., the Teacher) to multiple users (i.e., the Students) simultaneously. This new eMBB application require not only faster data rates, low latency and significant computing power at the far-edge (i.e., for processing and rendering holographic content), but also unparalleled levels of network flexibility, scalability, performance and resource management.

Although, 5G networks provided a substantial advancement in terms of speed, latency and capacity over their predecessors, they are not sufficient to meet the extreme performance requirements of this kind of eMBB use case, due to their inherent architectural limitations.

More specifically, the computational infrastructure of 5G at the far-edge domain is not designed to provide the intense computational power required for rendering 3D holographic content in real time. Rendering 3D holographic content requires substantial computational power to process and generate high-quality visualizations in real-time. In 5G networks (see Figure 8-1) demonstrating how the 3D holographic teaching can be performed using the current 5G technologies), the majority of computational tasks are performed in centralized cloud servers located far from the end-user. This centralized processing introduces significant latency due to the time needed to transmit data (from the Teacher location; step 3) to the cloud, decompress it (step 4) process it, render it, compress it again in a suitable coding format for AR/VR glasses decoding and return the results to the students located at the classroom (steps 5 - 8). For a time-sensitive application like holographic teaching, even slight delays can disrupt the seamless interaction required for a natural and immersive experience. 5G networks provide limited support for far-edge computing at the proximity of the data consumers, which is critical for reducing latency in high-demand applications like holographic teaching. Without substantial far-edge computing integration, 5G networks are inadequate to provide the responsiveness required for this kind of eMBB applications.

Another challenge to realizing extreme immersive XR is the requirement for sufficient wireless capacity. Due to the truly immersive nature of XR, significantly higher data rates and lower latency wireless connectivity is essential to deliver a seamless experience. 3D holographic content consists of large volumes of data, especially when need to be rendered individually for each student (see steps 5 – 8 where there is an individual connection between the AR/VR glasses of the students to the Rendering/Viewer Servers), based on their position in the classroom in relation to the 3D hologram display, and sent as an independent stream from the cloud to the end-user devices (in this case the AR/VR glasses). Transmitting such content, especially when a customized stream is required for each student over long distances in a 5G network consumes significant bandwidth. This results not only in significant delays but also in network congestion during peak usage and potentially causing degraded service for other users (other students, Faculty, Staff, visitors of the university campus) sharing the same infrastructure (i.e., the same fixed Base Station supporting the

coverage where the University Campus is located). To reach this network-level capability there is a pressing need for extensive far-edge computing integration, and a more adaptive, decentralized, and Artificial Intelligence (AI) based network architecture at the far-edge domain that can dynamically allocate resources and optimize performance in real-time.

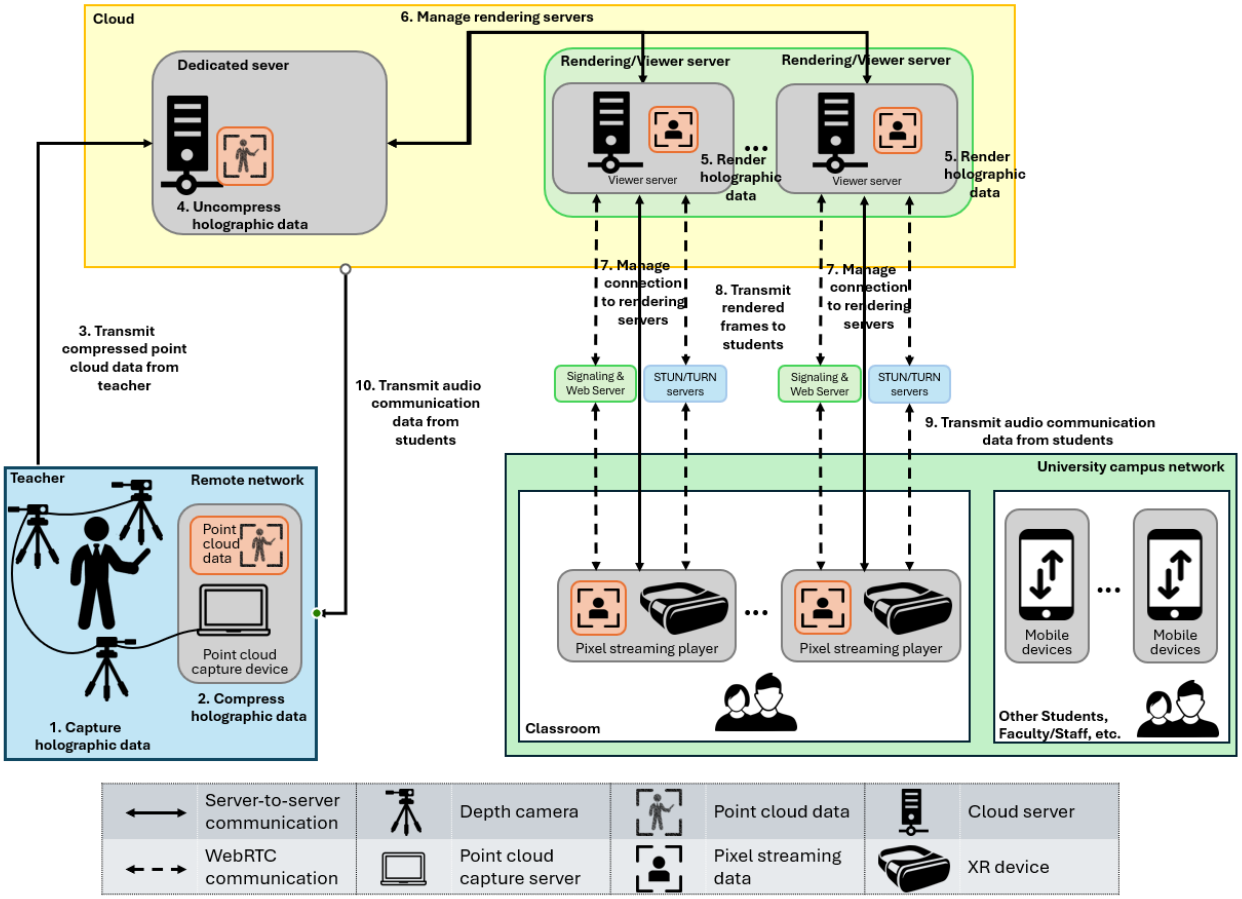

Figure 8-1. Current approach used for capturing, transmitting, processing, and rendering high-quality 3D holographic content – 5G limited support for far-edge computing and reliance on centralized cloud servers

Overall, despite the gains in speed, latency, and capacity achieved by 5G networks, they are inadequate to fulfil the stringent requirements of real-time 3D holographic teaching applications. This kind of application necessitates significant processing resources for real-time processing, rendering, and transmission of high-resolution 3D content from one end (i.e., the Teacher) to multiple users (i.e., the Students) simultaneously, currently beyond the capabilities of 5G networks centralized cloud and fixed networking infrastructure. The additional delay caused by dependence on remote cloud servers and the absence of integrated far-edge computing prevents 5G from attaining the low latency (< 150 - 300 ms) required for providing a seamless interaction between the Teacher's 3D hologram and the Students. Moreover, 5G encounters difficulties in managing the substantial data flow (~85 Mbps per user; see Table 8-3) necessary for transmitting holographic information to the students without encouraging bandwidth congestion, not only to the core network but also to the RAN domain. Furthermore, scalability challenges emerge in cases where a customized stream is required to be rendered and transmitted for each student independently,

based on their position in the classroom in relation to the 3D hologram display. To address these challenges and provide the smooth, scalable, and immersive experience necessary for holographic education, the exploitation of the advanced 6G technologies and components of the ADROIT6G solution including BDIx enabled AI-driven RAN and dynamic resource allocation using the UE-VBS computing is essential.

8.1.2 Functional, Non-Functional Requirements and Specification Table

Table 8-4 provides the list of functional, non-functional requirements and specifications.

Table 8-4. Functional, Non-Functional Requirements and Specification for PoC1.

Requirement Type	Requirement Description	Technical Requirement	Specification	Metric
Functional Requirements				
Real-Time Capture of Teacher's Movements	The system will integrate advanced motion capture technologies to ensure every gesture and nuance of the teacher's movements are recorded accurately, crucial for creating a dynamic and interactive virtual presence in the classroom.	Use advanced motion capture systems like Vicon or Kinect cameras.	Implementation of multiple-camera setups with real-time processing capabilities.	Volumetric capture using at least 3 cameras and recording 30 frames per second.
Real-Time Transmission of Captured Data	The data once captured must be transmitted to the computing infrastructure (i.e., CSP) that will perform merging and reconstruction in real-time, using high-speed network connections enhanced by 6G technology.	Utilize high-speed network connections, potentially leveraging 6G technologies for immediate transmission.	Setup of dedicated network channels and infrastructure to ensure sustained high-speed data transfer.	Have an end-to-end transmission time of no more than 20 ms.
Point Cloud Merging and 3D Reconstruction	The captured data undergoes sophisticated processing where point clouds are merged, and 3D models are	Computing platforms (i.e., UE-VBS computing CSP infrastructure) with high-	Use of scalable computing services with GPU acceleration to handle complex	Point cloud data processed and merged in less than 250ms.

	reconstructed in real-time.	performance GPUs for processing.	computations and data processing.	
Transmission of Holographic Content	High-bandwidth networks and advanced streaming protocols are required to transmit reconstructed holographic content (from CSP) back to the classroom with minimal delay, ensuring a fully immersive experience.	High-bandwidth networks and advanced streaming protocols like WebRTC or HLS for live streaming of 3D content.	Implementation of multicast streaming capabilities to efficiently manage bandwidth and ensure quality of service.	Have an end-to-end transmission time of no more than 10 ms.
Display of 3D Reconstruction to Students	Holographic displays or mixed reality headsets are used to present the reconstructed 3D hologram of the teacher in the classroom, allowing students to interact with the virtual form of their teacher.	Use holographic displays or mixed reality headsets such as Microsoft HoloLens, Magic Leap, or Meta Quest 3.	Deployment of state-of-the-art display technology with high-resolution and real-time tracking features.	Students' application compatible with mixed-reality headsets.
Real-Time Auditory Communication	The system incorporates audio systems with noise-cancelling microphones and speakers, alongside VoIP technology to ensure clear and uninterrupted voice transmission between the teacher and students.	Integrated audio systems with noise-cancelling microphones and speakers; VoIP technology for clear audio transmission.	Installation of high-quality audio interfaces and communication protocols to minimize latency and enhance clarity.	Two-way audio communication between teacher and students.
Display of Content to Teacher	Student-generated content is captured using mobile devices and displayed to the teacher in real-time, enhancing classroom interactivity and allowing for dynamic adaptations based on student engagement.	Mobile devices with microphones and a cloud-based content management system for immediate processing and display on the	Setup of an integrated feedback system that allows real-time sharing and interaction between students and teachers.	Students send questions / events to the teacher.

		teacher's device.		
Non-Functional Requirements				
High Computing Performance	The system must handle the real-time processing and rendering of high-resolution holographic content, managing complex 3D model tasks almost instantaneously after data capture.	High-performance computing solutions for real-time processing.	Utilization of cutting-edge computing hardware and optimized software algorithms to support heavy processing loads.	Capability to process and display complex 3D models within milliseconds of capture.
Low Latency	Minimal delay in communication and data transmission is crucial to maintain the synchronicity of real-world and virtual interactions.	High-speed, low-latency network infrastructure, preferably 6G.	Implementation of optimized network routing and protocols to ensure ultra-low latency communications.	Network latency not exceeding total of 10 milliseconds.
High Bandwidth	Substantial network bandwidth is required to manage the data volume involved in high-definition holographic streaming.	High-capacity network infrastructure.	Provision of broadband network connections with enhanced data throughput capabilities.	Network bandwidth adequate for capacity of at least > 20 Gbps. See also Table 8-1 and Table 8-3.
Usability	System interfaces should be intuitive and easy for non-technical users, to enhance user experience and adoption.	User-friendly software interfaces and training programs.	Design of ergonomic user interfaces and comprehensive user support materials.	User satisfaction ratings above 8 on a scale of 1 to 10.
Reliability	The system must operate consistently without failures during educational activities to maintain continuity.	Robust hardware and software with failover capabilities.	Establishment of redundant systems and regular maintenance schedules to ensure	System uptime of 99.9% during operational hours.

			continuous operation.	
Security	Robust security measures are necessary to protect sensitive data against unauthorized access.	Encryption standards and cybersecurity protocols in place.	Implementation of end-to-end encryption and continuous security audits to safeguard data integrity.	Compliance with industry-standard cybersecurity protocols and encryption standards.
Scalability	The system should accommodate growth, supporting more users and additional classrooms without performance degradation.	Scalable architecture capable of expanding as needed.	Strategic planning of system architecture to allow for modular expansion and integration of new technologies.	Ability to expand to handle 10x the initial load without performance degradation.

8.1.3 KPIs per component

The following table provides the list of KPIs per component for PoC1.

Components	Target KPI (ADROIT6G)	Baseline KPI (5G)
Closed-loop Governance	**Provisioning time:** 10min **QoE:** >4.3	**Provisioning time:** few hours to a day QoE: N/A
Service Orchestration & Management	**Provisioning time:** 10min **QoE:** >4.3 **Automated service provisioning:** 3 domains	**Provisioning time:** few hours to a day **QoE:** N/A **Automated service provisioning:** N/A
Resource Orchestration & Management	**Latency:** <10 ms latency	**Latency:** <150 - 300 ms latency
Service/Slice Orchestration & Management	**Latency:** <10 ms latency	**Latency:** <150 - 300 ms latency

	Data rates: downlink rates >20 Gbps and uplink rates >10 Gbps	**Data Rates:** Downlink >1.5 Gbps, Uplink >400 Mbps.
UE-VBS Component	**Messages to Core:** a 50% reduction in data messages exchanged between the core and devices **Data rates:** ensuring downlink rates >20 Gbps and uplink rates >10 Gbps **Device density:** >10 per m^3 - 1000 UEs	**Messages to Core:** Minimum 500 data messages for 100 UEs. **Data Rates:** Downlink >1.5 Gbps, Uplink >400 Mbps. **Device Density:** >2 devices per m^3 (100 UEs under testbed).
BDIx Agents	**Messages to Core:** a 50% reduction in data messages exchanged between the core and devices **Data rates:** ensuring downlink rates >20 Gbps and uplink rates >10 Gbps **Device density:** >10 per m^3	**Messages to Core:** Minimum 500 data messages for 100 UEs. **Data Rates:** Downlink >1 Gbps, Uplink >100 Mbps (aligned with 5G capabilities). **Device Density:** >2 devices per m^3 (100 UEs under testbed).
UE-VBS Controller	**Messages to Core:** a 50% reduction in data messages exchanged between the core and devices **Latency:** <10 ms latency **Device density:** >10 per m^3	**Messages to Core:** Minimum 500 data messages for 100 UEs. **Latency:** <150 - 300 ms latency **Device density:** >2 per m^3
AI/ML Orchestration Manager	**Provisioning time:** 10min	**Provisioning time:** few hours to a day
MERGE	**Energy Efficiency:** 10x **Data transferred: <50%**	Energy Efficiency w.r.t model trained from scratch in a centralized manner, and using FL Data transferred for model trained from scratch in a

		centralized manner, and using FL
Multimodal Latent Diffusion	**Data transmitted**: <50% **Energy Efficiency**: 2x baseline	**Lower usage of TX resources (bandwidth/ energy).**
ML model compression through Quantization	**Energy Efficiency:** ≥30%	**Energy Efficiency:** Federated Learning with Federated Averaging algorithm.

8.1.4 Validation Criteria / Metrics

Table 8-5 provides the list of service KPIs for PoC1, while Table 8-6 provides the list of network KPIs for PoC1. In addition, Table 8-7 provides the list of service KVIs for PoC1, while Table 8-8 provides the list of network KPIs for PoC1.

Table 8-5. Service KPIs for PoC1.

KPI	Description	Target Value
SR-HT-01	End-to-End Latency	< 350 ms
SR-HT-03	Reliability	> 95% uptime
SR-HT-04	System Scalability	Up to 50 devices
SR-HT-05	AI Model Selection Latency	< 100 ms
SR-HT-06	Orchestration Efficiency	< 200 ms
SR-HT-07	Service Recovery Time	< 1 minute
SR-HT-07	Computing power needed per stream rendering (aggregate processing power in CSP)	~30 TFLOPS
SR-HT-08	Ram needed per stream rendering	<32 GB

Table 8-6. Network KPIs for PoC1.

KPI	Description	Target Value
NR-HT-01	Peak Throughput	> 1 Gbps
NR-HT-02	Latency	< 150 ms
NR-HT-03	Jitter	< 5 ms

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NR-HT-04	Reliability	> 95%
NR-HT-05	Orchestration Latency	< 250 ms
NR-HT-06	Resource Utilization Efficiency	> 90% utilization
NR-HT-07	Slice Adaptation Time	< 10 seconds

Table 8-7. Service KVIs for PoC1.

KVI	Description	Values/Scaling
KVI-SR-HT-I1	Safety	User-Centric perception Low / Medium / High
KVI-SR-HT-I2	Security	User-Centric perception Low / Medium / High
KVI-SR-HT-I3	Regulation	User-Centric perception Low / Medium / High
KVI-SR-HT-I4	Responsibility	0 user manipulation incidents
KVI-SR-HT-D1	Privacy	User-Centric perception Low / Medium / High
KVI-SR-HT-D2	Fairness	User-Centric perception Low / Medium / High
KVI-SR-HT-E1	Sustainability	Mean Opinion Score (MOS) of > 4 of the users expressing positive evaluation regarding the sustainability of the devices, network, developed applications and services.

Table 8-8. Network KVIs for PoC1.

KVI	Description	Values
KVI-NR-HT-I1	Energy efficiency	10% improved energy efficiency compared to current status
KVI-NR-HT-D1	Digital Inclusion	50 students with connected devices and 99.9% communication service reliability # trainees from marginalised groups
KVI-NR-HT-D2	Trustworthiness	100% consistent coverage of the network
KVI-NR-HT-E1	Open collaboration	50 connected devices able to interact

8.2 PoC2a: Industrial IoT - Terrestrial 6G IIoT

PoC2a Terrestrial 6G IIoT use case is demonstrating the capabilities of extreme mMTC in a manufacturing process. PoC2a will demonstrate a scenario, driven by CAFA, in which multiple robots (with several IIoT sensors) are operating and collaborating with each other in a production line of an automotive manufacturing process, requiring real-time supply chain optimisation via large scale IIoT sensing and predictive analytics, where a massive number of sensors and actuators is involved (that require also extremely low-latency and extremely high reliability). In such a scenario, several different types of sensors and actuators (i.e., IIoT devices) are involved, communicating with each other, and taking actions in sub-millisecond time intervals, within a confined area, executing different robotic functionalities, such as, for example, metal inert gas welding technique, spot and laser welding techniques, assembly of parts, etc

In a manufacturing environment many robots work side by side with their own control logic and sensors. If each robot has its own enclosed work area, robots may rely on their own inputs. For example, in case the enclosure is breached, or some other fault signal is detected, robot rapidly stops and manufacturing processes halt requiring human intervention. Another approach is to use common control logic for the robots to share space and not to collide. This works to an extent where changes are not frequently made to the robot's operations. Because mobile and reconfigurable robots are more and more involved in manufacturing, increasing flexibility and reducing predictability, more sensors with more sophisticated capabilities are required to cope with increased complexity.

More details about this PoC.2a are presented in previous ADROIT6G deliverables D2.1, D2.2, and D5.1.

8.2.1 Limitations of 5G in Addressing PoC Challenges

The Industrial Internet of Things (IIoT) requires networks capable of supporting ultra-reliable low-latency communication (URLLC), massive machine-type communications (mMTC), and enhanced mobile broadband (eMBB) capable of supporting massive machine-type communications for real-time manufacturing processes. Current 5G networks face several critical limitations in meeting these requirements. These use cases demand not only robust connectivity but also adaptive and decentralized network architectures. While 5G represents a significant leap in connectivity and network performance, it encounters several limitations when addressing the specific requirements of IIoT in industrial environments.

Key Limitations of 5G

- **Limited Coverage and Signal Penetration**
  - Challenge: Industrial IoT environments often involve large factories, warehouses, and outdoor facilities. 5G networks, especially those operating at higher frequency bands (e.g., millimetre waves), struggle with coverage gaps and signal penetration through dense materials such as concrete and metal.
  - Impact: Poor coverage and penetration create unreliable connectivity, leading to potential delays in real-time monitoring, automation, and machine-to-machine communication.
- **Centralized Processing and Latency Constraints**
  - Challenges: Many 5G networks rely on centralized processing, which introduces latency when transmitting data between edge devices and centralized servers. This model is inadequate for industrial applications that require real-time decision-making.
  - End-to-end latency of 10-20ms vs required sub-millisecond for real-time robotics control
  - Connection setup time of 1-2s too high for dynamic manufacturing environments
  - Limited support for massive concurrent connections in confined industrial spaces.
  - Impact: Applications such as autonomous mobile robots and predictive maintenance are adversely affected by the latency, which could lead to safety risks and operational inefficiencies.
- **Centralized Architecture Constraints**
  - Computing bottlenecks with 20 Gbps peak data rates vs required 1 Tbps for next-gen industrial systems
  - Resource allocation delays of 5-10ms vs required sub-millisecond for real-time control

- Limited ability to handle dynamic workload distribution across manufacturing cells.

- **Edge Computing Performance**
  - Processing capacity of 10-20 TOPS insufficient for complex industrial AI/ML workloads
  - Storage limitations affecting local caching capabilities
  - Orchestration delays exceeding 100ms vs required <10ms for dynamic resource management.
- **Potential Solutions in 6G**
  To overcome these challenges, the evolution to 6G networks, as exemplified by the ADROIT6G framework, offers several advancements:
  - Far-Edge Computing: Integration of computational capabilities at the far-edge enables real-time data processing closer to the source, significantly reducing latency.
  - AI-Driven Resource Management: The adoption of AI-enabled systems for dynamic resource allocation ensures optimal performance and QoS across the IIoT network.
  - Enhanced Coverage via NTN Integration: Non-Terrestrial Networks (NTNs) such as satellite-based communications provide robust connectivity in remote and industrial areas.
  - Decentralized Architectures: Decoupling network functions from centralized servers improves scalability and reliability, meeting the demands of dense IIoT environments.

These limitations highlight why current 5G networks cannot fully support the demanding requirements of industrial IoT applications, necessitating the transition to 6G technologies with enhanced capabilities for manufacturing environments.

8.2.2 Functional, Non-Functional Requirements and Specification Table

Table 8-9 revisits requirements from ADROIT6G's deliverable D2.1 to specify metrics of fulfilment and develop KPIs.

Table 8-9: Revision of functional and non-functional requirements of PoC2a

Requirement Type	Requirement Description	Technical Requirement	Specification	Metric
Functional Requirements				
High-Density Device Communication	The ADROIT 6G network must support communication for numerous IIoT sensors and actuators.	Support for extreme mMTC service class.	Consistent data transmission for large device volumes.	Handle thousands of IIoT devices per unit area.
Low-Latency D2D and Device-to-Control Station Communication (D2CS)	Enable low-latency D2D and D2CS and remote-control communication for near real-time interaction.	Ultra-low latency video and sensor data transmission D2D and D2CS.	Real-time, synchronized operation between devices and robots and remote operator control near real time.	Communication delay <10 ms.

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Reliable D2D and Device-to-Control Station Communication (D2CS)	Establish reliable D2D and D2CS communication for coordination and monitoring.	Continuous, high-reliability link between devices and Control Station.	Seamless communication between devices and central control system.	The system shall continue to work even in power outages with SLA 99.95%.
Synchronized Timing Services	Implement timing synchronization for coordinated robot actions indoors.	5G/ 6G network-based time synchronization.	Replace GNSS timing indoors to ensure synchronized actions.	Sub-millisecond synchronization accuracy.
Minimum Data Upload and Download Speed	Ensure minimum data speeds for effective operation and data transfer.	Support upload and download speeds of at least 10 Mbps for each device.	Maintain minimum data rates for seamless operation and real-time data processing.	Upload and download speeds ≥10 Mbps per device.
Non-Functional Requirements				
Energy Efficiency	Use the most energy-efficient transmission and receiver mode for communication.	Use communication only for planned or initiated sessions time.	Adapt network to the planned or initiated sessions to minimize energy consumption.	Decrease energy consumption where is it possible.
Environmental Adaptability and Durability	Ensure robust operation in industrial environments with dust, heat, and vibration.	Design robots and devices to withstand harsh industrial conditions.	Continuous operation under specified conditions.	>95% uptime in harsh conditions without performance issues.
Security and Data Privacy	Protect data integrity and confidentiality of production information.	Implement advanced protocols for data security between devices.	Zero data breaches or unauthorized access incidents.	100% compliance with data security protocols.

8.2.3 Validation Criteria / Metrics

Table 8-10 and Table 8-11 present a revised and summarized version of the KPIs as initially defined in ADROIT6G's deliverables D2.1 and D2.2. Acronym SR marks Service Requirement and number. Acronym NR marks Network requirement.

Table 8-10: Service KPIs for PoC2a

KPI	Description	Values
SR-Poc2a-01	Latency	Communication delay <10 ms
SR- Poc2a -02	Reliability	SLA 99.95%
SR- Poc2a -03	Scalability	Slow degradation for even higher numbers (e.g., >10 devices/m^2)
SR- Poc2a -04	Energy Efficiency	Reduction of energy consumption by >30% compared to legacy

Table 8-11: Network KPIs for PoC2a

KPI	Description	Values
NR- Poc2a -01	Jitter	<1ms
NR- Poc2a -02	Synchronized Timing accuracy	<500 microseconds
NR- Poc2a -03	Upload and download speeds	≥10 Mbps per device.

Table 8-12. KVIs for PoC2a

KVI	Description	Values
KVI-NR- Poc2a-I1	Safety	# of accidents avoided
KVI-NR- Poc2a-I2	Security	Monitoring resources from different providers to identify anomalies and intrusion detection. PoC of anomaly detection in production-grade systems, dealing with the orchestration policies of resources across multiple domains, while maintaining service quality guarantees. Target value > 0.85 The KVI is related to KPIs on Anomaly detection recall and sensitivity
KVI-NR- Poc2a-I3	Regulation	# of standards involved
KVI-NR- Poc2a-D3	Digital Inclusion	Lower latency than current procedures Communication delay <10 ms

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KVI-NR- Poc2a-D4	Trustworthiness	SLA 99.95% and Comparison of latency of data transmissions (previous vs current).
KVI-NR- Poc2a-E1	Sustainability	SR- Poc2a -04 Reduction of energy consumption by >30% compared to legacy
KVI-NR- Poc2a-E2	Business Value	Slow degradation for even higher numbers (e.g., >10 devices/m2) scalability improvement
KVI-NR- Poc2a-E3	Economic Growth	% increase in productivity (target >10%) or % decrease in operational costs (target >10%)

8.2.4 KPIs per component

The following table provides the list of KPIs per component for PoC2a.

Components	Target KPI (ADROIT6G)	Baseline KPI (aka 5G)
Closed-loop Governance	**Provisioning time:** 1min	**Provisioning time:** few hours to a day
Service Orchestration & Management	**Provisioning time:** 1min Delay: Operator to Pod Creation < 1 seconds, Day-2 Operations 2 seconds, Deletion and Clean up 5 seconds.	**Provisioning time:** few hours to a day Delay: Operator to Pod Creation 10 seconds, Day-2 Operations 10 seconds, Deletion and Clean up 1 minute. (OSM O-RAN reference)
Resource Orchestration & Slicing Management	**Latency:** <5 ms latency	**Latency:** <150 - 300 ms latency
UE-VBS Component	**Messages to Core:** a 50% reduction in data messages exchanged between the core and devices **Data rates:** ensuring downlink rates >20 Gbps and uplink rates >10 Gbps **Device density:** >10 per m^3 -1000 UEs	**Messages to Core:** Minimum 500 data messages for 100 UEs. **Data Rates:** Downlink >1.5 Gbps, Uplink >400 Mbps. **Device Density:** >2 devices per m^3 (100 UEs under testbed).
BDIx Agents	**Messages to Core:** a 50% reduction in data messages	**Messages to Core:** Minimum 500 data messages for 100 UEs.

	exchanged between the core and devices **Data rates:** ensuring downlink rates >20 Gbps and uplink rates >10 Gbps **Device density:** >10 per m^3	**Data Rates:** Downlink >1 Gbps, Uplink >100 Mbps (aligned with 5G capabilities). **Device Density:** >2 devices per m^3 (100 UEs under testbed).
ML model compression through Quantization	**Energy Efficiency:** ≥30%	**Energy Efficiency:** Federated Learning with Federated Averaging algorithm.

8.3 POC2b: Rail Automation supported by Non-Terrestrial Networks

Modern railway systems require a strong digitization to achieve maximum safety, best availability at acceptable costs. Rail automation applications and devices shall be enabled to use NTNs (at their different orbital layers) instead of or in addition to today's fixed or cellular solutions. By doing so, connectivity in dead spots can be provided for applications like maintenance/repair, train communication, control and tracking or resilient and high-available control of track-side infrastructure. PoC.2b takes railway automation as an exemplary application, expanding its capabilities towards NTNs (for both communication and computations).

Therefore, ADROIT6G's PoC.2b aims at demonstrating a rail automation scenario supported by NTNs, exploring distinct deployment considerations for the NTN networking segment, which also includes the support of Satellite Computing capabilities. The scenario consists of enabling an interlocking service, thus dealing with reliable control of trains and of the railway infrastructure, as well as on a seamless inter-operation of different subsystems to ensure proper operation of the system. Moreover, the ADROIT6G architectural elements are expected to contribute not only to the fulfilment of its service and network KPIs but also to provide increased flexibility and adaptability for the entire infrastructure and system.

More details about this PoC.2b are presented in previous ADROIT6G's deliverables D2.1, D2.2, and D5.1.

8.3.1 Limitations of 5G in Addressing PoC Challenges

Despite the potential of 5G technologies to offer significant advancements for Rail Automation - to the point of being adopted by the Future Railway Mobile Communication System (FRMCS) to explore its advanced features such as high data rates, low latency and enhanced reliability -, it is already envisioned that several limitations will be faced. Two of those limitations are related to the coverage and cost of infrastructure. 5G networks, particularly those operating in higher frequency bands, have shorter range and are more susceptible to obstacles and weather conditions. Therefore, it necessitates a dense network of base stations along railway tracks, which can be costly and

logistically complex to implement. This is especially true for remote areas around the world so a cost-efficient, yet safe and reliable solution is needed to export products of European rail industries.

According to ongoing initiatives, such as the "Gigabit Innovation Track" (GINT) research project [23] funded by the Federal Ministry for Digital and Transport (BMDV), 5G rail corridors are being designed to deliver reliable mobile broadband connectivity to support the creation of digital railway infrastructure. FRMCS is considering adopting the 3.6 GHz frequency band as a way to offer a good balance between coverage and capacity, meaning we are looking at a new 5G mast every 1-3 kilometres. Just in Germany, rail infrastructure spans across 33464 kilometres in 2023 [24], thus around 20000 new masts will be needed for FRMCS alone [25]. It is without surprise that substantial investments from the private sector as well as support from public institutions are required.

If such investments are needed to meet data rates of up to 5Gbps per train to support telephone and data connections for passengers, the question remains if rail automation use cases (which thrives mainly for reliability, availability, maintainability and safety) also requires such costly deployment. Due to smaller traffic load and a stronger focus on safety compared to passenger experience/infotainment or low-rate infrastructure monitoring, railway automation has the potential to reuse existing infrastructure to expand to areas with no 5G coverage, while also leveraging novel features from the 6G architecture. As this PoC focuses on rail automation as an important example of highly safety and reliability outdoor services, we are expected to answer such question and show innovative solutions to improve and augment 6G NTN services even more by means of space-based edge-cloud based overlay services

6G capabilities, such as a native integration of NTN technologies, are expected to provide a new look on wide-area coverage at a significantly lower infrastructure cost. NTNs utilize satellites, high-altitude platforms and other aerial technologies to provide connectivity, and can cover vast and remote areas more efficiently than terrestrial networks (TN) in regions with challenging geography or sparse populations. In coordination with the terrestrial networks, 6G TN-NTN will become a powerful 3D network that is more resilient, more reliable, and resistant to natural disasters or infrastructure failures that disrupt the ground-based systems. Allied with mechanisms to ensure seamless transition between terrestrial and non-terrestrial connectivity, this hybrid approach ensures continuous service for rail automation services across the entire rail infrastructure.

On the one hand, NTNs offer a robust backup and/or parallel link that field-track devices can explore to create additional redundant flows, while enhancing 5G set of possibilities the load-balancing capabilities and efficiently managing network congestion. On the other hand, NTNs can act as a primary link in underserved segments of the rail infrastructure, providing the required connectivity that was not available with 5G (or too costly to be offered). Moreover, in both options 6G NTN-based Computing (e.g., Satellite Edge/Clouds) is expected to be available. It allows for processing NTN-transmitted data in-place, e.g., directly on the satellites rather than transmitting it back to Earth for analysis. In doing so, new possibilities for the deployment of e.g. operations control systems, interlocking logic, and diagnostic systems became available, on which the reduced latency allows for quicker decision-making and responses. At the same time, it allows continuous operation (even if in a restricted state) in case of ground-based disasters since the connectivity to the controlling systems remains active. For example, data storages can become holistic in space and available at one-hop away from the sources / destination.

Another benefit that 6G NTNs bring is related to energy savings within the communication budget. First, less terrestrial infrastructure for the 5G corridors means less energy consumption to provide

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coverage across the entire rail network. Second, the predictive nature of satellite orbits allows more efficient and dynamic algorithms in terms of number of active links, thus also contributing to a reduction of the energy budget in the devices. Third, by enabling data processing within the NTN-based computing, new mechanisms for data compression or filtering can be performed before sending data to devices, thus leading to a reduction of the transmitted information and consequently of the energy consumption. Lastly, space equipment doesn't require active cooling, which can play a major role in energy savings as most user equipment utilizes electric-powered cooling (e.g., fans), not to mention decreasing overall CO2 emissions. And satellites are naturally powered by solar energy.

All in all, 6G allows its expansion to geographical locations that lack any kind of terrestrial communication infrastructure. In addition, 6G TN-NTN (and co-location of Edges/Clouds in the NTN segment) provides higher levels of reliability, availability, robustness which are expected in safety related use cases while contributing to gains in energy efficiency from the communication budget point of view.

8.3.2 Functional, Non-Functional Requirements and Specification Table

Table 8-13 revisits requirements from D2.1 to specify metrics of fulfilment and develop KPIs.

Table 8-13: Revision of functional and non-functional requirements

Requirement Type	Requirement Description	Technical Requirement	Specification	Metric
Functional Requirements				
Support of message priorities	Most of the critical traffic uses messages and probably even a publish-subscribe based messaging middleware.	Make use of a middleware that supports prioritization of urgent messages, both regarding delays and reliability.	Implementation of the field-track elements and background traffic.	The application needs mean to mark priority messages, and the network shall ensure prioritiz0ation and min. bandwidth requirements.
Redundancy support	The system must be as reliable and highly available as possible.	Make use of redundant connections.	Implementation of the field-track elements with TN and NTN connectivity support.	The system shall continue to work, even if one of the connections fails.
Place service components in satellites	Support computing capabilities within the satellites and the	Deploy and manage services,	Deployment of the software elements as	Automated management and

	deployment of user payloads.	containers or VMs in satellites.	containerized payloads.	orchestration of the user containers.
Smooth handover between satellites	Support continuous communication and data transfer with minimal interruption.	Make use of redundant connections.	Implementation of redundancy support to mitigate the downtime during handovers.	The system shall continue to work even during handovers.
Edge Computing must consider the geographical location	The service's payloads running in the Satellite Edge act differently depending on the country where it is flying over, or it may go into a power save mode over the ocean.	The Satellite Computing must know its position and provide such information as a contextual service.	Service's payloads adapt their operation based on the geographical location.	Service's payloads shall adapt their operations based on the location.
Energy Efficiency	Prioritize energy-efficient communication.	Make use of different sleep modes to optimize energy consumption.	Incorporate adaptive measures to maintain the network performance while minimizing energy consumption.	Decrease energy consumption without impacting operations.
Non-Functional Requirements				
Rates around 10Mbps, symmetric	While the concrete numbers depend on the use case, IoT applications typically create many data, so a symmetric bandwidth or even a higher upload rate is needed.	Traffic guarantees for a service, e.g., using slicing or prioritization.	Define traffic prioritization to ensure that the required bandwidth is reserved.	The system shall continue to work, even when background traffic is also present.
Round-trip delays < 100msec	It depends on the application, but this describes the End-to-End delay from on-ground device to a far cloud.	Offload service software components in satellites.	Reduce the E2E latency by placing software components closer to the source. Fast wireless links. Reduced	The system shall ensure that messages arrive within their lifespan.

			buffering in the network.	
High availability	The network must be as reliable and highly available as possible, and concrete numbers depend on what the operator accepts.	Make use of redundant connections.	Implementation of the field-track elements with TN and NTN connectivity support.	The system shall continue to work, even if one of the connections fails.
High security	This must be provided on application layer following zero trust principles, so the network is 'untrusted'. Typically, message integrity is important.	Make use of security protocols and integrity mechanisms.	The middleware components in an edge and the message integrity between the application instances.	The system shall be able to identify tampered messages.

8.3.3 KPIs per component

The following table provides the list of KPIs per component for PoC2b.

Infrastructure	Target KPI	Baseline KPI
Non-Terrestrial Networks (NTN)	Device Density: <10 per m2 Availability: 99.999% Coverage: 100% Message Loss: <5e-6	Device Density: <1 per m2 Availability: 99.999% Coverage: 60-90% Message Loss: <1e-5
Computing capabilities with NTN	Energy efficiency: less 50% Availability: 99.999%	Energy efficiency: Compared to legacy systems in terms of overall energy required for the data transmission. Availability: 99.999%
Components	**Target KPI**	**Baseline KPI**
Closed-loop Governance	Provisioning time: 10min QoE: >4.3	Provisioning time: few hours to a day QoE: N/A
Service Orchestration & Management	Provisioning time: 10min QoE: >4.3	Provisioning time: few hours to a day QoE: N/A

	Automated service provisioning: 3 domains	Automated service provisioning: N/A
UE-VBS Component	Device density: >10 per m3	Device density: >2 per m3 (100 UEs under testbed)
BDIx Agents	Device density: >10 per m3	Device density: >2 per m3 (100 UEs under testbed)
AI/ML Pipeline Manager	Provisioning time: 10min	Provisioning time: few hours to a day
Algorithm	**Target KPI**	**Baseline KPI**
MERGE	Energy Efficiency: 10x Data transferred: <50%	Energy Efficiency: Data transferred Model trained from scratch in a centralized manner, and using FL
ML model compression through Quantization	Energy Efficiency: ≥30%	Energy Efficiency: Federated Learning with Federated Averaging algorithm.
SLA-driven Adaptive	SLA violation rate: =< 0.01 Scalability: Ensure effective scaling up to 50 clients without significant degradation in performance (e.g., Convergence loss).	SLA violation rate: =<0.02 Scalability: Test with 20 Clients
Predictive Monitoring and SLA Offering Solutions	The solution provides models for prediction of monitoring and SLA offerings through AI models. Contribute to provisioning time: 10min (TO 2.1) predictive modeling contributes decision-making for the reduction of reaction time to >50% due to dynamic changes (TO 8.1).	The solution provides models for prediction of monitoring and SLA offerings through AI models. Contribute to provisioning time: 10min (TO 2.1) predictive modeling contributes decision-making for the reduction of reaction time to >50% due to dynamic changes (TO 8.1).

8.3.4 Validation Criteria / Metrics

Table 8-14 and Table 8-15 present a revised and summarized version of the KPIs as initially defined in ADROIT6G's deliverables D2.1 and D2.2.

Table 8-14: Service KPIs

KPI	Description	Values
SR-NTN-01	Service availability	> 99.999% over longer time frames
SR-NTN-02	Reliability	Message loss on application layer $<10^{-5}$
SR-NTN-03	Scalability	Slow degradation for even higher numbers (e.g., >10 devices/m^2)
SR-NTN-04	Energy Efficiency	Reduction of energy consumption by >50% compared to legacy NTNs

Table 8-15: Network KPIs

KPI	Description	Values
NR-NTN-01	Latency / Jitter	<100 milliseconds / < 50miliseconds
NR-NTN-02	Device density	<10 per m2
NR-NTN-03	Packet loss rate	5e-6
NR-NTN-04	QoE	>4.3

Table 8-16: Service KVIs for PoC2b

KVI	Description	Values
KVI-NR- Poc2b-I1	Safety	Monitoring resources from different providers to identify anomalies and intrusion detection. PoC of anomaly detection in production-grade systems, dealing with the orchestration policies of resources across multiple domains, while maintaining service quality guarantees. Target value > 0.85 The KVI is related to KPIs on Anomaly detection recall and sensitivity
KVI-NR- Poc2b-I3	Regulation	# of standards involved
KVI-NR- Poc2b-D3	Digital Inclusion	Lower latency than current procedures Communication delay <10 ms
KVI-NR- Poc2b-D4	Trustworthiness	> 99.999% over longer time frames

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KVI-NR- Poc2b-E1	Sustainability	SR- Poc2b -04 Reduction of energy consumption by >50% compared to legacy NTNs
KVI-NR- Poc2b-E2	Business Value	Slow degradation for even higher numbers (e.g., >10 devices/m^2) and <10 per m^2
KVI-NR- Poc2b-E3	Economic Growth	% decrease in operational costs (target >10%)

8.4 PoC3: Collaborative Construction Robots

In this Collaborative Construction Robots scenario, construction sites are being transformed to robotized thanks to mobile robots and 6G communication technology. Wheeled robots and drones are deployed for efficient transportation and distribution of building materials, reducing manual labor. For connectivity, especially in remote areas, construction companies use a satellite communication to establish a robust internet connection from local 5G/6G network or WLAN.

Automated Ground Vehicles (AGVs) and drones are integrated to enhance operational capabilities. A key innovation is the autonomous coordination between these robots and drones, enabled by 6G technology for precise communication and positioning. This coordination is crucial for synchronizing tasks like lifting, loading, and navigating, ensuring safety and efficiency. More details about this PoC 3 are presented in previous ADROIT6G deliverables D2.1, D2.2, and D5.1.

8.4.1 Limitations of 5G in Addressing PoC Challenges

Collaborative construction robots require highly reliable and low-latency communication to coordinate tasks such as material handling, precision assembly, and real-time monitoring. While 5G networks provide enhancements over previous generations, they encounter several barriers in meeting the stringent requirements of collaborative robotics. Collaborative construction robots require unprecedented levels of coordination and real-time control that push current 5G networks beyond their capabilities. While 5G has enabled basic robotics applications, it faces several critical limitations in supporting advanced construction automation.

Key Limitations of 5G

- **Insufficient Latency Reduction**
  - Challenge: Real-time collaboration between robots and human operators demands ultra-low latency to ensure safety and precision. The latency offered by 5G networks (min 10 ms in ideal conditions) is inadequate for split-second decision-making required in collaborative robotics.
  - Impact: Delays in communication can lead to operational inefficiencies, safety hazards, and reduced productivity.
  - Comparison to 6G: 6G employs ultra-reliable low-latency communication (URLLC) with end-to-end latency reductions to below 1 ms, enabling seamless coordination between robots and operators.
- **Limited Reliability in Dense Environments**
  - Challenge: Construction sites often feature numerous connected devices, heavy machinery, and interference-prone environments. 5G's reliability diminishes under high device density and challenging conditions.

  - Impact: Connectivity interruptions disrupt robot coordination, potentially halting operations and increasing project timelines and costs.
  - Comparison to 6G: 6G integrates AI-enhanced interference mitigation techniques and dynamic frequency allocation, ensuring stable and reliable connections in dense environments.
- **Energy Efficiency Constraints**
  - Challenge: Collaborative robots require energy-efficient communication to maximize operational uptime. Current 5G solutions are not optimized for the energy constraints of battery-powered robotic systems.
  - Impact: Frequent recharging or downtime for robots undermines their utility and cost-effectiveness in construction projects.
  - Comparison to 6G: 6G introduces energy-efficient communication protocols and in-network energy harvesting techniques, significantly reducing power consumption.
- **Scalability Issues**
  - Challenge: Construction sites vary in scale, requiring flexible and scalable network solutions to adapt to changing demands. 5G architectures lack inherent scalability for dynamic environments.
  - Impact: Network rigidity hampers the ability to expand operations seamlessly, limiting the deployment of additional robotic units.
  - Comparison to 6G: 6G's decentralized network architectures and support for self-organizing networks enable seamless scalability to meet evolving site requirements.
- **Network Coverage and Reliability**

Construction sites present unique challenges that expose 5G's limitations in providing consistent coverage and reliability. The dynamic nature of construction environments, with constantly changing physical layouts and moving obstacles, makes it difficult for 5G to maintain stable connections. Traditional 5G networks struggle to adapt to these rapidly evolving conditions while ensuring the ultra-reliable communication needed for robot coordination.

- **Communication Infrastructure**
  Current 5G architecture faces significant constraints in supporting:
  - Real-time coordination between multiple robots and drones
  - Precise positioning and navigation in construction environments
  - Seamless integration of satellite communication for remote sites
- **Edge Computing and Processing**
  5G's edge computing capabilities are insufficient for:
  - Real-time processing of sensor data from multiple robots
  - Complex coordination algorithms for collaborative tasks
  - Dynamic workload distribution across construction sites.
- **Resource Management**
  The centralized resource management approach of 5G becomes a bottleneck when dealing with:
  - Multiple concurrent robot operations
  - Dynamic task allocation between ground vehicles and drones
  - Real-time adaptation to changing construction site conditions.

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These limitations highlight the need for 6G's advanced capabilities in distributed intelligence, integrated satellite communication, and enhanced edge computing to fully support next-generation collaborative construction robotics.

6G Advantages for Construction Robotics

Enhanced Performance

- Sub-10 millisecond latency for real-time control
- 99.999% reliability for safety-critical operations
- Seamless satellite-terrestrial integration
- Terabit-per-second data rates
- Advanced sensing and positioning with sub-decimetre accuracy

Improved Architecture

- Integrated AI/ML processing at network edge
- Distributed intelligence for autonomous operation
- Enhanced satellite communication capabilities
- Dynamic resource allocation
- Zero-interruption handovers

These limitations highlight why current 5G networks cannot fully support the demanding requirements of collaborative construction robots, necessitating the transition to 6G technologies.

8.4.2 Functional, Non-Functional Requirements and Specification Table

Table 8-17 revisits requirements from ADROIT6G's deliverable D2.1 to specify metrics of fulfilment and develop KPIs.

Table 8-17: Revision of functional and non-functional requirements of PoC3

Requirement Type	Requirement Description	Technical Requirement	Specification	Metric
Functional Requirements				
Navigation and Localisation	Robots must navigate the construction site without GNSS signals.	Equipped with navigation algorithms to use 6G positioning functionality.	6G positioning functionality and algorithms.	Localisation accuracy <3 m.
Low-Latency D2D and Device-to-Control	Enable low-latency D2D and D2CS and remote-control	Ultra-low latency video and sensor	Real-time, synchronized operation	Communication delay <10 ms.

Station Communication (D2CS)	communication for near real-time interaction.	data transmission D2D and D2CS.	between devices and robots and remote operator control near real time.	
Reliable D2D and Device-to-Control Station Communication (D2CS)	Establish reliable D2D and D2CS communication for coordination and monitoring.	Continuous, high-reliability link between devices and Control Station.	Seamless communication between devices and central control system.	The system shall continue to work even in power outages with SLA 99.95%.
Safety and Collision Avoidance	Operate safely around humans using sensors and avoid collisions.	Equipped with sensors and safety algorithms for human detection.	Detect humans and obstacles in the path to avoid accidents.	100% obstacles avoided.
Minimum Data Upload and Download Speed	Ensure minimum data speeds for effective operation and data transfer.	Support upload and download speeds of at least 10 Mbps for each device.	Maintain minimum data rates for seamless operation and real-time data processing.	Upload and download speeds ≥10 Mbps per device.
Non-Functional Requirements				
Energy Efficiency	Use the most energy-efficient transmission and receiver mode for communication.	Use communicatio n only for planned or initiated sessions time.	Adapt network to the planned or initiated sessions to minimize energy consumption.	Decrease energy consumption where is it possible.
Environmental Adaptability and Durability	Ensure robust operation in industrial environments with dust, heat, and vibration.	Design robots and devices to withstand harsh industrial conditions.	Continuous operation under specified conditions.	>95% uptime in harsh conditions without performance issues.
Security and Data Privacy	Protect data integrity and confidentiality of production information.	Implement advanced protocols for data security	Zero data breaches or unauthorized access incidents.	100% compliance with data security protocols.

		between devices.		

8.4.3 KPIs per component

The following table presents a list of KPIs per each component from PoC3, detailed for the project target in relation to a baseline defined as 5G standard KPIs.

Components	Target KPI (ADROIT6G)	Baseline KPI
UE-VBS Component	**Energy Efficiency:** 1W or less -> 2x improvement **Peak Data Rate:** > 1.5 Gbps for DL & > 0.4 Gbps for UL **Device density:** > 2 per m3 or 100 devices under 1 BS **Data messages transfers:** < 800 messages	**Data transfers:** 1 traffic unit **Energy Efficiency:** 1 energy unit **Peak Data Rate:** < 20 Gbps for DL & < 10 Gbps for UL **Device density:** > 10 per m3
BDIx Agent	**Data transfers:** < 20ms **Energy Efficiency:** 1W or less -> 2x improvement **Peak Data Rate:** > 1.5 Gbps for DL & > 0.4 Gbps for UL **Device density:** > 2 per m^3	**Data transfers:** 1 traffic unit **Energy Efficiency:** 1 energy unit **Peak Data Rate:** < 20 Gbps for DL & < 10 Gbps for UL **Device density:** > 20 per m^3
Service Instantiation & Orchestration	**Provisioning time:** < 5 min (including slice)	**Provisioning time:** few hours per day
Close-Loop Governance	**Provisioning time:** < 10 min	**Provisioning time:** few hours per day
Component Instantiation	**Provisioning time of each component:** < 1 min	
Co-bots Agent	**Data transfers:** < 30ms **Energy Efficiency:** 1W or less -> 2x improvement **Peak Data Rate:** > 1.5 Gbps for DL & > 0.35 Gbps for UL **Device density:** > 1 per m3	**Provisioning time**: minutes

8.4.4 Validation Criteria / Metrics

Table 8-18 and

Table 8-19 present a revised and summarized version of the KPIs as initially defined in documents D2.1 and D2.2. Acronym SR marks Service Requirement and number. Acronym NR marks Network Requirement. Table 8-20 presents the KVIs for PoC3.

Table 8-18: Service KPIs for PoC3

KPI	Description	Values
SR-Poc3-01	Latency	Communication delay <10 ms
SR-Poc3-02	Reliability	SLA 99.95%
SR-Poc3-03	Energy Efficiency	Reduction of energy consumption by >30% compared to legacy

Table 8-19: Network KPIs for PoC3

KPI	Description	Values
NR-Poc3-01	Jitter of Terrestrial Network	<1ms
NR-Poc3-02	Localisation accuracy using 5G/ 6G network	<3 m
NR-Poc3-03	Upload and download speeds	≥10 Mbps per device
NR-Poc3-04	NTN network latency	<300 ms

Table 8-20: KVIs for PoC3

KPI	Description	Values
KVI-R-HT-I1	Safety	User-Centric perception Low / Medium / High
KVI-R-HT-I2	Security	User-Centric perception Low / Medium / High
KVI-R-HT-I3	Regulation	# Standards used for definitions, requirements etc
KVI-R-HT-I4	Responsibility	0 users manipulation incidences
KVI-R-HT-I5	Energy efficiency	Reduction of energy consumption by >30% compared to legacy
KVI-R-HT-D1	Privacy	User-Centric perception Low / Medium / High

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KVI-R-HT-D2	Fairness	User-Centric perception Low / Medium / High
KVI-R-HT-D3	Digital Inclusion	99.9% communication service reliability
KVI-R-HT-D4	Trustworthiness	100% consistent coverage of the network
KVI-R-HT-E1	Sustainability	Reduction of energy consumption by >30% compared to legacy
KVI-R-HT-E2	Business Value	User-Centric perception Low / Medium / High
KVI-R-HT-E3	Economic Growth	User-Centric perception Low / Medium / High
KVI-R-HT-E4	Open collaboration	Number of Devices connected
KVI-R-HT-E5	New Value Chain	Number of Devices connected

9 Conclusions

This deliverable is the third deliverable of ADROIT6G's WP2, focusing on the presentation of the final approach of the ADROIT6G network architecture. This deliverable is built on the findings of the first two deliverables, D2.1 and D2.2, targeting to fully define the ADROIT6G's PoC requirements. The main contributions of this deliverable are the definition of the interfaces among the different ADROIT6G frameworks, as well as components, as well as the detailed presentation of the KPIs and KVIs per ADROIT6G PoC.

10 References

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