NexaSphere:

NEXGEN 3D NETWORKS SPIN HARMONIES ACROSS 6G, AI, AND UNIFIED TN/NTN

D2.2

System Architecture, Interfaces Specifications, and Preliminary Techno-Economic Analysis

Version 1.0 – Date 31/01/2026

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D2.2: "System Architecture, Interfaces Specifications, and Preliminary Techno-Economic Analysis"

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Responsible Partner	DLR
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Version History

Version	**Date**	**Author**	**Partner**	**Description**
0.1	03.11.2025	Barth	DLR	Initial Version
0.2	11.12.2025	Barth	DLR	Adding of requirements, first version architecture, template system element specification
0.3	12.12.2025	Zombakis	8BELL	Inclusion of Techno-Economic Analysis
0.4	15.12.2025	Barth	DLR	Finalisation of system element specification, update of introduction and executive summary, quality review ready
0.5	14.01.2026	Goratti, Werner, Lyberopoulos	SPI, AER. OTE	Quality review finished
0.6	16.01.2026	All Authors		Comments addressed
1.0	23.01.2026	Barth	DLR	Final editing and conclusion

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Table of contents

This project has received funding from the Horizon Europe research and innovation program under grant agreement No. 101192912

This project has received funding from the Horizon Europe research and innovation program under grant agreement No. 101192912

This project has received funding from the Horizon Europe research and innovation program under grant agreement No. 101192912

List of tables

This project has received funding from the Horizon Europe research and innovation program under grant agreement No. 101192912

List of figures

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Executive summary

This report is the outcome of T2.2 and specifies the preliminary NexaSphere system architecture, preliminary system requirements and interface specification. This task used the use cases and high-level requirements from T2.1, presented in D2.1 [1], as basis for this and derived with the involved experts the necessary system components, interfaces and more detailed requirements. The main aim is to design communication systems for railway, aviation, and automotive based on 3GPP standards where applicable. Non-Terrestrial Networks (NTN) shall be used in combination with terrestrial systems (3GPP, WiFi, LiFi) and legacy solutions (e.g. DVB-S2X). A flexible system is designed with AI management and orchestration features supporting multiple orbits.

The NexaSphere main components include:

- Multi-Connectivity
- Edge-Cloud Continuum
  - Management and Orchestration
  - AI Resource Management
  - Compound AI System
- Antenna
- LiFi
- gNB
- Optical Transceiver
- 5G Core
- Satellite Payload, including On-Board Processing

From these, the general architecture on system and operational level is derived using Capella, an open-source solution for Model Based System Engineering (MBSE). The general architecture supports all use cases and includes several options for deployment that are presented in the document, such as multi-connectivity options, number of mobile network cores, and functional split options. As reference architecture, a full gNB on-board satellite was selected providing Edge Computing services.

Last, the preliminary techno-economic analysis is presented as elaborated in T2.3. Together with the architecture and requirements, they form the basis for the technical activities of NexaSphere in WPs 3-6.

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List of abbreviations and acronyms

5G-NR – 5G New Radio

5GC - 5G Core

A-UPF - Anchor UPF

AF - Application Function

AI - Artificial Intelligence

AMF - Access and Mobility Management Function

ATM – Automotive

ATO - Automatic Train Operation

ATSSS - Access Traffic Steering, Splitting and Switching

AUSF - Authentication Server Function

AVT – Aviation

B5G – Beyond 5G

C-V2X - Cellular Vehicle-to-Everything

CAGR - Compound Annual Growth Rate

CAPEX - Capital Expenditure

COTS – Commercials Of The Shelf

CP - Control Plane

CPE - Customer Premise Equipment

CU - Central Unit

DBFN - Digital Beam Forming Network

DN - Data Networks

DRA - Direct Radiating Array

DU - Distributed Unit

eMBB - Enhanced Mobile Broadband

ETCS - European Train Control System

FIP - Functional Input Ports

RLW - Railway

FOP - Functional Output Ports

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FRMCS - Future Railway Mobile Communication System

GDT - Gate Data Transfer

gNB - 5G base station

HAPS - High-Altitude Platforms

IAB - Integrated Access Backhaul

IFEC - In-Flight Entertainment and Connectivity

ISL - Inter Satellite Links

IVE - In-Vehicle Entertainment

MA - Multi-Access

MANO - Management and Orchestration

MBSE - Model Based System Engineering

MNOs - Mobile Network Operators

NRF - Network Repository Function

NTN - Non-Terrestrial Networks

OBP - On-Board Processor

OCT - Optical Communication Terminal

ODD - Operational Design Domain

OISLs - Optical Intersatellite Links

OPEX - Operational Expenditure

OSM - Open-Source MANO

PCF - Policy Control Function

PER - Packet Error Rate

QoE - Quality of Experience

QoS - Quality of Service

RAT - Radio Access Technology

RAN – Radio Access Network

ROI - Return on Investment

RU - radio unit

Rx – Receive

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SBA - service-based architecture

SerDes - Serializer/De-serializer

SMF - Session Management Function

TN - Terrestrial Networks

TCO - Total Cost of Ownership

Tx – Transmit

UE - User Equipment

UDM - Unified Data Management

UDR - Unified Data Repository

UP - User Plane

UPF - User plane Function

LLC - Low-Latency Communication

VIM - Virtual Infrastructure Manager

VM - Virtual Machine

VNF - virtualized network function

WAB - Wireless Access Backhaul

XPD - Cross-polar Discrimination

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Section 1: Introduction

The preliminary architecture of the NexaSphere System is presented in this document, including the initial set of system requirements and system element specification. The presented system lays the foundation for the technical work packages (WP3, WP4 and WP5) and for the development of the demonstrators (WP6). This work package relation is illustrated in D2.1 [1]. It is a preliminary output of T2.2. This task will continue during the next year of the project and monitor the technical developments for updates to reach the final set of requirements, and the final NexaSphere architecture to be presented in the second issue of this deliverable. This final issue will also further detail the presented preliminary architecture. Furthermore, this document includes a preliminary Techno-Economic and Market Feasibility Analysis that is outcome of T2.3.

The aim is to define a system for connecting cars, airplanes, and railways with main focus on Non-Terrestrial Networks (NTN) but used together with Terrestrial Networks (TN). One of the core requirements is to base the system design on 3GPP specifications where possible which sets, therefore, the foundation of the network architecture; see TS 23.501 [2]. Consequently, for connectivity a User Equipment (UE) connects to a 5G base station (gNB) which is served by a 5G Core (5GC). External services are accessed via Data Networks (DN) that connect to the 5GC. UEs shall be connected directly or via Customer Premise Equipment (CPE). The CPE is a sub-system on-board an airplane or train providing connectivity and other functions to passengers, e.g. via WiFi, LiFi or 3GPP in a relay mode. Passengers in cars typically connect directly. The CPE can be backhauled by different NTN and TNs technologies.

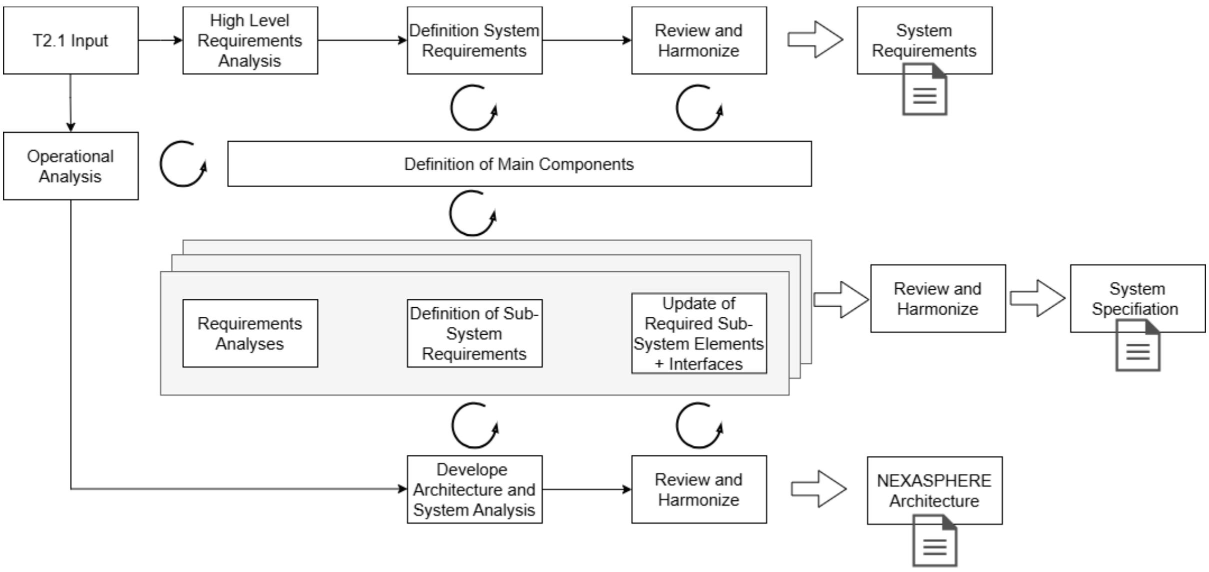

Figure 1-1: System Requirements, specification and architecture definition process implemented

Figure 1-1 depicts the methodology applied in T2.2 to derive the preliminary system requirements, system and sub-system specifications, and the NexaSphere Architecture. Building on the outcomes of T2.1 (use cases' description and high-level requirements as documented in D2.1), a structured a requirement analysis and an operational analysis were carried out, including a contextual analysis of the envisaged system environment. Starting from the high-level requirements, a set of system requirements was derived and documented. Both

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the system requirements and the results of the operational analysis, were used to identify the main components of the NexaSphere system. For each main component, the system requirements were reviewed in detail and decomposed into dedicated sub-system requirements by the respective experts, and were appropriate, with the technical work packages. At this stage, the sub-system elements have already been identified for several components, and the interfaces among the main components have been specified. Based on these elements and the operational analysis, the NexaSphere architecture has been defined using the main components as the architectural building blocks. All the three resulting outputs (the requirements, the interface specifications and the architecture) have been jointly harmonized and reviewed by all partners. Note that all the outputs presented in this document are preliminary and will be further refined and consolidated in subsequent project phases.

The system is designed using Model Based System Engineering (MBSE). We have used the Capella [3] an open-source MBSE tool, as the primary system design environment. The system model is shared among the project partners via a dedicated GitLab instance. For the purposes of this deliverable, selected parts of the model have been semi-automatically transformed into a document, to support the specification of the interfaces presented in Section 4. Capella implements the Arcadia method [4] of which the operational and system analysis layers have been applied within T2.2 as documented in the following.

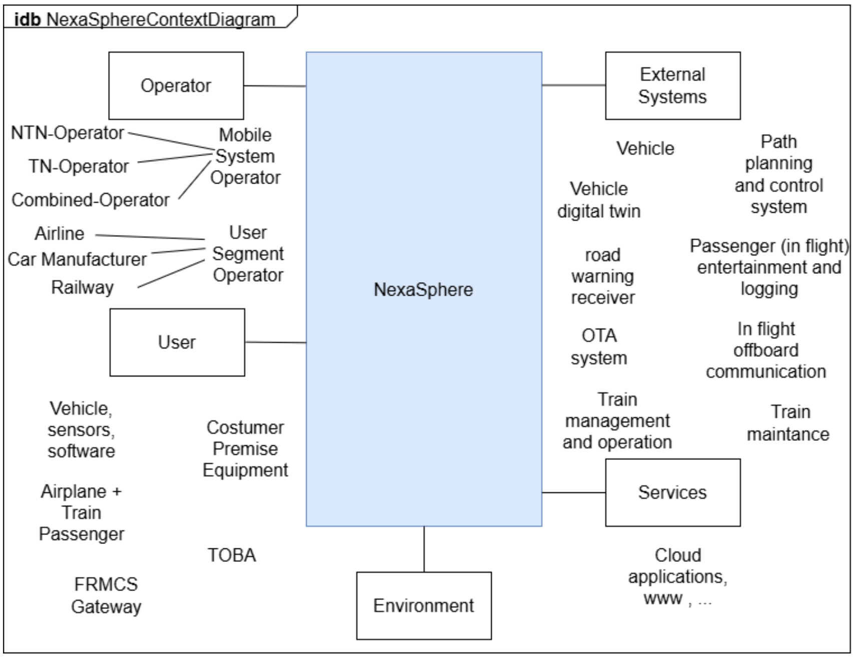

Figure 1-2: Context Analysis Internal Block Diagram

Figure 1-2 presents the internal block diagram resulting from the context analysis. Various relevant users, operators, external systems and services were identified and grouped under the corresponding blocks in the diagram. In alignment with the 3GPP system architecture, the users are abstracted as User Equipment (UE), while the external systems and services are collectively represented as Data Network (DN). In contrast to Mobile Network Operators (MNOs) that manage a whole mobile network, user segment operators (e.g., the vehicle

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manufacturer) manage only the on-board segment deployed within trains, cars and airplanes. Nevertheless, the management of UEs remains under the responsibility of the MNO.

The following main components of the NexaSphere system have been identified:

- Multi-Connectivity
- Edge-cloud Continuum
  - Management and Orchestration
  - AI Resource Management
  - Compound AI System
- Antenna
- LiFi
- gNB
- Optical Transceiver
- 5G Core
- On-Board Processing (OBP) capabilities

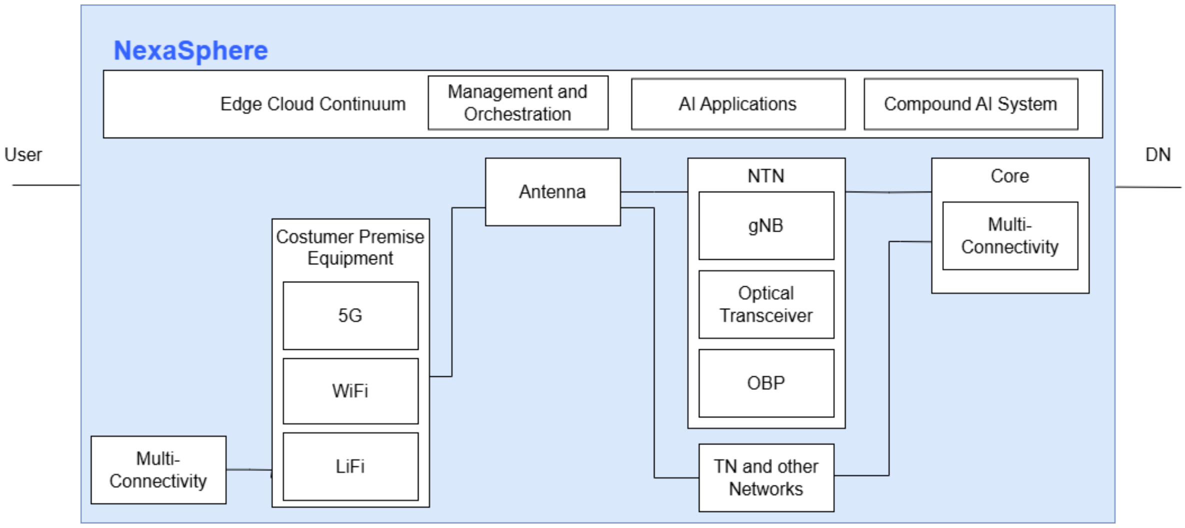

Figure 1-3: NexaSphere main components

These sub-systems are further introduced and specified in the remainder of the deliverable. Figure 1-3 depicts the high-level interconnection of the main building blocks required to deliver services to the user. As mentioned, the user may directly access the system either directly or via the Customer Premises Equipment (CPE). A dedicated multi-connectivity sub-system enables the simultaneous or selective use of multiple access technologies, as required by the service context. Antenna subsystems are required for the wireless links support, associated with the access technologies. Connectivity may be established towards the 5GC or towards other non-3GPP access networks (e.g., WiFi or DVB-S systems) for example through Access Traffic Steering, Splitting and Switching (ATSSS). The core network enables connectivity to external data networks. Overarching the connectivity domain (i.e., UE, CPE, gNB, 5GC and DN) is the edge-cloud continuum which provides distributed processing, storage and advanced service capabilities. It consists of edge cluster nodes, that can be deployed along the communication path, complemented by a management and orchestration (MANO) system, Artificial Intelligence (AI) resource management functions and a compound AI system supporting intelligent end-to-end operation.

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The remainder of the document is organized as follows:

- Section 2: presents the system and subsystem requirements obtained so far;
- Section 3: introduces and specifies on a high level the main sub-systems. The main components will be further detailed in the dedicated technical work packages (WP3, 4 and 5);
- Section 3: provides the preliminary system architecture including the interface specification;
- Section 6: present the Techno-Economic Analysis as preliminary outcome of T2.3;
- Finally, Section 7: concludes the document.

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Section 2: NexaSphere Requirements

In the following, we present an update of the system requirements. The full collection of general NexaSphere system requirements is presented in the Annex, including the initial version that has been presented in D2.1 [1]. New updates are:

- the split of REQ-SYS-80 in REQ-SYS-081 to REQ-SYS-087, since this requirement was covering multiple different topics in one.
- Furthermore, it has been clarified that for REQ-SER-010 is about autonomous functions and not automatic.
- For REQ-SYS-087 it has been added that existing to legacy systems include for instance e.g. DVB-S2X).

The requirements have been updated accordingly as presented in the Annex. The NexaSphere system requirements presented in Table 2-1 have been identified as new requirements, they resulted from an in-depth analysis of the use cases. Requirements for the identified main components of the NexaSphere system are presented that have been derived so far. The system requirements of the antenna systems are presented in Table 2-2; the system requirements of the Core are presented in Table 2-3, the ones from the Edge-Cloud Continuum in Table 2-4; LiFi in Table 2-5, Multi-Connectivity elements are presented in Table 2-6; and finally for the optical transceiver in Table 2-7. The current state of the requirements definition is initial, it comprises a first snapshot of that could be extended and modified in the next version of this deliverable.

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Table 2-1: System Requirements NexaSphere

Requirement Type	Requirement ID	Title	Requirement Description	Applicable to
System Requirement	REQ-SYS-081	NTN GEO	The NexaSphere NTN system shall include GEO satellite(s)	All UCs
System Requirement	REQ-SYS-082	NTN MEO	The NexaSphere NTN system shall include MEO satellites	All UCs
System Requirement	REQ-SYS-083	NTN LEO	The NexaSphere NTN system shall include LEO satellites	All UCs
System Requirement	REQ-SYS-084	NTN HAPS	The NexaSphere system shall include High Altitude platforms	All UCs
System Requirement	REQ-SYS-085	Interoperability legacy satcom	The NexaSphere system shall be interoperable with legacy satellite systems (e.g. DVB-S2X)	All UCs
System Requirement	REQ-SYS-086	interoperability terrestrial networks	The NexaSphere system shall be interoperable with Terrestrial Networks (including spectrum sharing and interference coordination)	All UCs
System Requirement	REQ-SYS-087	Regulation	The NexaSphere system shall comply with regional regulatory compliance	All UCs
System Requirement	REQ-SER-010	**Autonomous** network orchestration	The NexaSphere System shall implement **autonomous** functions for network management and orchestration based on dynamic traffic conditions, mobility, and QoS requirements. Note: such functions may include predictive models, AI-based algorithms, SDNs, etc.	All UCs
System Requirement	EQ-SYS-110	Switch or aggregated access technologies	The NexaSphere system shall switch between or aggregate different user access technologies to optimize content delivery based on real-time link conditions	All UCs
System Requirement	EQ-SYS-120	Power usage on airplane	The NexaSphere system shall optimize the power usage of the communication on-board an airplane	ATM-UC05

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to
System Requirement	EQ-SYS-140	Optimize Resource allocation	The NexaSphere system shall optimize network resource allocation	All UCs
System Requirement	EQ-SYS-150	reduce costs using orchestration and resource management	The NexaSphere system shall Reduce operational costs through real-time network orchestration and automated resource management.	All UCs
System Requirement	EQ-SYS-160	Cross-border transitions	The NexaSphere system shall support seamless cross-border transitions	RLW-UC02
System Requirement	EQ-SYS-170	spectrum reconfigurability	The NexaSphere system shall be able to reconfiguration the used spectrum in real-time to optimize efficiency	RLW-UC02
System Requirement	REQ-SYS-180	Traffic orchestration based on prediction	The NexaSphere System shall be able to manage and orchestrate the traffic using predictive models based on railway historical data to achieve ultra-low latency decision making in high-speed environments.	RLW-UC02
Service Requirement	REQ-SER-060	Passenger connectivity train and airplane	The NexaSphere system shall provide access to passengers on trains and aircraft via both Terrestrial Networks (TN) and Non-Terrestrial Networks (NTN).	All UCs
Service Requirement	REQ-SER-070	3GPP compliant	The NexaSphere System shall be built on existing 3GPP specifications where applicable	All UCs
Service Requirement	REQ-SER-080	3GPP RAN	The NexaSphere System shall provide radio access via 3GPP RAN	All UCs
Service Requirement	REQ-SER-090	3GPP NTN	The NexaSphere System shall provide access via 3GPP NTN	All UCs
Service Requirement	REQ-SER-100	3GPP Terrestrial Networks	The NexaSphere System shall provide access via 3GPP Terrestrial Network	All UCs

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to
Service Requirement	REQ-SER-110	Support non-3GPP access	The NexaSphere System shall allow access via non-3GPP access technologies, i.e. WiFi, LiFi, legacy SatCom	All UCs
Service Requirement	REQ-SER-120	Cabin connection	The NexaSphere system shall provide on-board airplane cabins equipment means to access the network services	AVT-UC03
Service Requirement	REQ-SER-130	Passenger connectivity	The NexaSphere system shall provide access means to passengers on-board trains and airplanes	All AVT+RLW UCs
Service Requirement	REQ-SER-140	UE seamless connectivity	The NexaSphere system shall provide seamless connectivity via the different access technologies directly for the UE	All UCs
Service Requirement	REQ-SER-150	Continuous access	The NexaSphere system shall provide continuous network access for airplanes during their operation	All AVT UCs
Service Requirement	REQ-SER-160	V2N support	The NexaSphere system shall enable V2N connections to support V2X communication	ATM-UC01
Service Requirement	REQ-SER-170	Mission critical service support	The NexaSphere system shall provide mission critical services	RLW-UC01
Service Requirement	REQ-SER-180	Hazardous location warnings	The NexaSphere system shall support the distribution of hazardous location warnings	ATM-UC02
Service Requirement	REQ-SER-190	Simultaneous access	The NexaSphere system shall allow to simultaneously access different access technologies	All UCs
Service Requirement	REQ-SER-200	Simultaneous access NTN and TN	The NexaSphere system shall allow to simultaneously access 3GPP NTN and 3GPP TN	All UCs
Service Requirement	REQ-SER-210	minimize latency	The NexaSphere system shall provide predictive analytics to minimize latency	RLW-UC02

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2.1 System Requirements Antenna

The system requirements of the antenna systems are presented in Table 2-2.

Table 2-2: System Requirements Antenna

Requirement Type	Requirement ID	Title	Requirement Description	Applicable to	Rationale	Comment
System Requirement	REQ-SYS-Ant-020	Aviation Antenna Operational frequency	The aviation antenna shall support the operational frequency in Ku & Ka bands: Ku Rx: 10.7 ÷ 12.7 GHz Ku Tx: 13.7 ÷ 14.5 GHz Ka Rx: 17.5 ÷ 21.2 GHz Ka Tx: 27.5 ÷ 31 GHz			
System Requirement	REQ-SYS-Ant-030	Aviation Antenna Transmit and receive	The aviation antenna shall combine the transmit and receive functionalities in the same aperture			The antenna shall combine in the same aperture both Transmit and Receive functionalities
System Requirement	REQ-SYS-Ant-040	Aviation Antenna Operational scheme	The aviation antenna shall operate in half-duplex or full-duplex			technical aspects and regulatory aspects to be considered
System Requirement	REQ-SYS-Ant-050	Aviation Antenna Duty Cycle	The aviation antenna shall support a duty cycle lower than 75%(TBD)			
System Requirement	REQ-SYS-Ant-060	Aviation Antenna	The aviation antenna shall support an instantaneous bandwidth of 250 MHz (TBC)			

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to	Rationale	Comment
		Instantaneous Bandwidth				
System Requirement	REQ-SYS-Ant-070	Aviation Antenna Polarisation	The aviation antenna shall support RH, LH, and Linear polarization and shall allow a selection			
System Requirement	REQ-SYS-Ant-080	Aviation Antenna EIRP	The aviation antenna shall support the following EIRP: Ka band: 52dBW Broadside 50.2dBW@45° Ku band: 45.7dBW broadside 44.2dBW@45°			
System Requirement	REQ-SYS-Ant-090	Aviation Antenna Cross-polar Discrimination (XPD)	The aviation antenna shall provide a cross-polar discrimination (XPD) better than 15 dB			Over the operating frequency range
System Requirement	REQ-SYS-Ant-100	Aviation Antenna Transmit-Receive Isolation	The aviation antenna shall provide a transmit-receive isolation greater than 45 dB			This aspect will be further analyzed during the development of the antenna

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to	Rationale	Comment
System Requirement	REQ-SYS-Ant-110	Aviation Antenna Tracking accuracy	The aviation antenna shall provide a tracking accuracy smaller than 0.3 degrees @ 45 scanning and smaller than 0.2 degrees @ boresight			
System Requirement	REQ-SYS-Ant-120	Aviation Antenna scanning angle	The aviation antenna shall provide a scanning angle of 360° coverage in Azimuth and 45° in elevation from the boresight			In order to follow a LEO satellite both elevation and azimuth need to be adjusted
System Requirement	REQ-SYS-Ant-130	Aviation Antenna G/T	The aviation antenna shall support the following G/T values: Ka-Band 14.0dB@0° 12.3dB@45 Ku-Band 10.3dB@0° 8.6dB@45			
System Requirement	REQ-SYS-Ant-140	Aviation Antenna Mass	The aviation antenna shall have a mass not greater than 10 Kg (TBC)			including cooling system
System Requirement	REQ-SYS-Ant-150	Aviation Antenna Radiating Aperture Dimensions	The aviation antenna shall a radiation aperture not greater than 700 - 800 mm			
System Requirement	REQ-SYS-Ant-160	Aviation Antenna	The aviation antenna shall have an overall thickness smaller than 100 mm			including, among others, thermal

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to	Rationale	Comment
		Overall Antenna Thickness				management system, electronics, motors and connectors
System Requirement	REQ-SYS-Ant-170	Aviation Antenna RF IN/OUT interface	The aviation antenna shall provide an SMA interfaces for Ku and a 2.92 mm for the Ka-band			
System Requirement	REQ-SYS-ATM-300	Operational frequency	The automotive antenna shall operate in Ka-band and support the operational frequencies of 17.7 to 20.2 GHz for the reception and 27.5 to 30 GHz for transmission			
System Requirement	REQ-SYS-ATM-320	Transmit and receive operation	The automotive antenna shall combine the transmit and receive functionalities in the same aperture			
System Requirement	REQ-SYS-ATM-330	Instantaneous Bandwidth	The automotive antenna shall provide an instantaneous bandwidth of 250 MHz			
System Requirement	REQ-SYS-ATM-340	Polarisation	The automotive antenna shall support circular RHCP polarization			
System Requirement	REQ-SYS-ATM-350	Axial Ratio	The automotive antenna shall have an axial ration smaller than 3dB			
System Requirement	REQ-SYS-ATM-360	EIRP	The automotive antenna shall support am EIRP of 30dBW			

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to	Rationale	Comment
System Requirement	REQ-SYS-ATM-370	Field of view	The automotive antenna shall provide a field of view of 45° elevation and 360° at azimuth			
System Requirement	REQ-SYS-ATM-380	G/T	The automotive antenna shall provide a G/T of the automotive antenna shall -7dB/K at boresight (TBC)			
System Requirement	REQ-SYS-ATM-390	Mass	The automotive antenna shall have a mass smaller than 1Kg (TBC)			
System Requirement	REQ-SYS-ATM-400	Radiating Aperture Dimensions	The automotive antenna shall have a radiation aperture dimension of transmission and reception, each smaller than 10cm			
System Requirement	REQ-SYS-ATM-410	Overall Antenna Thickness	The automotive antenna shall have an overall antenna thickness smaller than 10cm (TBC)			
System Requirement	REQ-SYS-ATM-420	RF IN/OUT interface	The automotive antenna shall provide and 2.92 mm interface			

2.2 System Requirements Core

The system requirements of the Core are presented in Table 2-3.

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Table 2-3: System Requirements Core

Requirement Type	Requirement ID	Title	Requirement Description	Applicable to	Rationale	Comment
System Requirement	REQ-SYS-CN-001	Mobile Core SW	B5G core shall be compliant with/based on 3GPP specification and support the 5QI required by the vertical application	All UCs	To ensure the seamless integration with other 3GPP compliant components (RAN, UE) and support all UCs	
Service Requirement	REQ-SYS-CN-002	Preemption	B5G Core shall support the dynamic resource allocation based on user priority and network resources availability.	All UCs	To ensure the resource availability for the high-priority users which is defined by a use-case	
Service Requirement	REQ-SYS-CN-003	KPI's Monitoring	B5G Core shall expose the performance monitoring metrics at the network level	All UCs	To enable the possibility to monitor the key network metrics	
Service Requirement	REQ-SYS-CN-004	Slicing	B5G Core system shall support the network slicing	All UCs	To ensure the capability to create a network slice with desired QoS tailored to the requirements of a given use case, and ensure its availability to the designated end user	

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to	Rationale	Comment
System Requirement	REQ-SYS-CN-005	Orchestration	B5G Core shall be connected to external third-party components using the standards-defined interfaces	All UCs	To ensure the programmable interaction of the B5G Core with the WP5 orchestrator	
Service Requirement	REQ-SYS-CN-006	Dynamic QoS management	B5G Core shall be capable to managing traffic flows with different QoS	All UCs	To ensure that different traffic flows can be adapted to different UC requirements	
System Requirement	REQ-SYS-CN-007	Support of edge computing	The B5G Core shall support edge-cloud architectural solutions, specifically providing the capability to deploy the UPF at the edge	All UCs	To ensure the reduced latency and optimized data flow "on the edge"	
Performance Requirement	REQ-SYS-CN-008	B5G Core HW (AVT)	The B5G Core physical interfaces shall support the traffic speed of 10 Gbps (may vary for different use-cases)	All AVT UCs	To ensure that DL/UL data rate requirements are satisfied	
Performance Requirement	REQ-SYS-CN-009	B5G Core HW (ATM)	The B5G Core physical interfaces shall support the traffic speed of at least 10 Gbps (may vary for different use-cases)	All ATM UCs	To ensure that DL/UL data rate requirements are satisfied	
Performance Requirement	REQ-SYS-CN-010	B5G Core HW (RLW)	The B5G Core physical interfaces shall support the traffic speed of at least 1 Gbps (may vary for different use-cases)	All RLW UCSs	To ensure that DL/UL data rate requirements are satisfied	

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2.3 System Requirements Edge-Cloud Continuum

The system requirements of the Edge-Cloud Continuum are presented in Table 2-4.

Table 2-4: System Requirements Edge-Cloud Continuum

Requirement Type	Requirement ID	Title	Requirement Description	Applicable to	Rationale	Comment
Service Requirement	REQ-SYS-ECC-001	Network-Level Predictions	Compound AI System shall predict network events including TN/NTN handovers, satellite connectivity and traffic load changes	All UCs	To enable proactive network management through control signals for the underlying network management components	
Service Requirement	REQ-SYS-ECC-002	Application-Level Resource Utilization Prediction	Compound AI System shall predict application-level resource requirements for resource and energy efficient application placement decisions	All UCs	To optimize resource allocation across edge-cloud continuum for various use case applications, with focus on energy efficiency	
Service Requirement	REQ-SYS-ECC-003	Multi-Model Workflow Orchestration	Compound AI System shall orchestrate workflows of specialized AI models, managing data flow between models and aggregating outputs into unified decisions	All UCs	To coordinate and integrate specialized AI models into a unified system providing intelligence capabilities for various NexaSphere components	
Service Requirement	REQ-SYS-ECC-004	Model Selection	Compound AI System shall possess model selection capability for each	All UCs	To enable adaptation to various Use Case requirements and to	

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to	Rationale	Comment
			workload based on Service Level Objective (SLO)requirements		ensure appropriate specialized AI models are selected for each task	
Performance Requirement	REQ-SYS-ECC-005	Resource and Energy Efficiency	Compound AI System shall cause minimal overhead to the NexaSphere system	All UCs	To ensure efficient and sustainable intelligence capabilities	
System Requirement	REQ-SYS-ECC-006	Unified Multi-Domain & Multi-Orbit Orchestration	The MANO system shall natively orchestrate heterogeneous NTN assets across LEO, MEO, GEO, HAPS, and terrestrial domains.	All UCs	6G NTN is inherently multi-domain, and ETSI emphasizes zero-touch automation across domains.	
System Requirement	REQ-SYS-ECC-007	Predictive, AI-Native Resource & Mobility Management	The MANO system shall embed AI/ML-native control loops to handle NTN's time-varying topology	All UCs	NTN introduces high dynamics; deterministic policies are insufficient.	
System Requirement	REQ-SYS-ECC-009	Energy-Efficient, Sustainable Lifecycle Management	The MANO system shall integrate energy-optimization mandates, especially for satellites and aerial platforms	All UCs	NTN nodes have strict power budgets and sustainability is a central 6G requirement.	

2.4 System Requirements LiFi

The system requirements of the LiFi element are presented in Table 2-5.

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Table 2-5: System Requirements LiFi

Requirement Type	Requirement ID	Title	Requirement Text	Derived from	Rationale	Comment
System Requirement	REQ-SYS-Li-001	Multi-antenna LiFi Architecture	The LiFi subsystem shall support a distributed multi-antenna architecture with a central processing unit and multiple optical antennas.	AVT-UC03	Ensures coverage uniformity and scalability in cabin or indoor spaces.	
Performance Requirement	REQ-SYS-Li-002	LiFi System Throughput	The LiFi subsystem shall support a combined user data rate of 100 Mbps or higher at the LiFi central unit.	AVT-UC03	Ensures sufficient system-level throughput	
Performance Requirement	REQ-SYS-Li-003	Coverage Continuity	The LiFi subsystem shall provide continuous coverage in the designated operational area without dead zones.	AVT-UC03	Enhances mobility and user experience.	
Performance Requirement	REQ-SYS-Li-004	Gate Data Transfer Throughput	The optical gate data transfer shall support a data rate up to 10 Gbps for high-speed aircraft–ground transfer.	AVT-UC04	Enables rapid turnaround data operations.	

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Performance Requirement	REQ-SYS-Li-005	Reliable Gate Data Transfer Link	The Gate Data Transfer optical link shall maintain reliable communication over a distance of at least 5 meters without interruption under expected aircraft positioning tolerances.	AVT-UC04	Ensures stable high-speed data exchange despite small aircraft movements or misalignment.	
System Requirement	REQ-SYS-Li-006	SDR Compatibility with 4G/5G PHY/MAC	The LiFi subsystem shall support integration with SDR platforms running standard-compliant 4G/5G PHY and MAC layers (e.g., srsRAN) to enable flexible protocol testing beyond fixed commercial LiFi chipsets.	AVT-UC03	Allows evaluation of scheduling, multi-connectivity, and mobility management concepts.	
System Requirement	REQ-SYS-Li-007	Energy-Efficient FPGA-Based LiFi PHY	The FPGA-based LiFi PHY implementation shall achieve at least 20% improvement in energy efficiency compared to existing commercial LiFi or optical wireless solutions.	AVT-UC05	Ensures the LiFi PHY contributes to reduced energy consumption.	

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2.5 System Requirements Multi-Connectivity

The system requirements of the Multi-Connectivity element are presented in Table 2-6.

Table 2-6: System Requirements Multi-Connectivity

Requirement Type	Requirement ID	Title	Requirement Text	Derived from	Comment
System Requirement	REQ-SYS-MC-003	PDCP timer and buffer management	The NexaSphere system shall support PDCP timer management and buffer handling for both 3GPP TN and NTN accesses when operating under MC	All UCSs	
Performance Requirement	REQ-SYS-MC-004	Handover interrupt time	The NexaSphere system shall ensure short handover interruption time during mobility across terrestrial and non-terrestrial networks under MC	All UCs	
System Requirement	REQ-SYS-MC-005	3GPP + non3Gpp access	The core network must be accessible via at least one 3GPP connection and one non-3GPP connection.	UCs with 5G multi access	
System Requirement	REQ-SYS-MC-006	N3IWF for non3GPP Access	The N3IWF component shall be integrated with the core network to enable access via a non-3GPP connection.	UCs with 5G multi access	
System Requirement	REQ-SYS-MC-007	UE interfaces	The UE shall support enable multipath. One of them shall be 3GPP access	UCs involve UEs	
System Requirement	REQ-SYS-MC-008	CPE interfaces	The CPE shall have at least 2 interfaces at downstream side to be enabled for multipath.	UCs involve CPE	
System Requirement	REQ-SYS-MC-009	UE compatibility release	The UE using a multipath protocol must be compatible with 5G release >= 17 in the case	All UCs	

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Requirement Type	Requirement ID	Title	Requirement Text	Derived from	Comment
		MPTCP-MPQUIC	of MPTCP or 5G release >= 19 in the case of MPQUIC		

2.6 System Requirements Optical Transceiver

The system requirements of the optical transceiver are presented in Table 2-7.

Table 2-7: System Requirements Optical Transceiver

Requirement Type	Requirement ID	Title	Requirement Text	Derived from	Rationale	Comment
Performance Requirement	REQ-SYS-OT-011	Optical transceiver throughput	The optical transceiver shall support the required data rate in the backhaul for the use cases (TBD)	All UCs	Prevent optical links becoming bottlenecks in the network	PER based on non-critical train communication reliability of 99.9% = 1 - 1e-3. Depending on architecture, this may include DTE (feeder or CPE-gNB) links as well.
Performance Requirement	REQ-SYS-OT-012	Optical transceiver PER	The optical transceiver shall support the required packet error rate (PER)	All AVT+RLW UCs	Prevent optical links becoming bottlenecks in the network	See comment on throughput
System Requirement	REQ-SYS-OT-013	Optical transceiver variable data-rate	The optical transceiver shall allow trading off data rate for a lower PER	All RLW UCs	Allows to achieve different QoS levels within the network	PER based on critical train communication reliability of 99.9999% = 1 - 1e-6

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Requirement Type	Requirement ID	Title	Requirement Text	Derived from	Rationale	Comment
Performance Requirement	REQ-SYS-OT-014	Optical transceiver latency	The optical transceiver shall be designed in a way that minimizes latency	All UCs	The latency of the transceiver shall be an order of magnitude lower compared to other sources of latency within the system	The maximum processing time depends on required QoS, number of hops, constellation design, system element processing delays

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Section 3: Preliminary NexaSphere Architecture

As mentioned in the introduction, the architecture has been implemented using Capella. In this section, we first present the outcome of the operational analysis. The yellow boxes in Figure 3-1 indicate the high-level functions that have been determined. For the data connection part of the system, this function is mainly data connection. The main function for MANO and AI resource management is to manage the Quality of Service (QoS) and Quality of Experience (QoE), while the Compound AI system's main function is to manage the AI/ML application. It must be noted that the connections in these figures can be one to one, one to multiple or multiple to multiple. As such, we show one 5G-RAN that includes NTN and TN, but generally from the figure it cannot be seen, e.g. how many gNBs are part of the RAN. However, we indicated two gNBs in order to illustrate the satellite hand over and to introduce inter satellite links (ISL).

In the same way, Figure 3-2 presents the system level analyses. Also, here we indicate two satellites for the hand-over and ISLs, but the TN is separated for the NTN in order to analyze the different connections in the system. The architecture shows a reference architecture that has been selected to follow 3GPP release 19 with a full gNB on-board a satellite. Other configurations are also possible, which are discussed in the following section. Similarly, two cores are illustrated; the idea is to have one core for a terrestrial operator and one core for a non-terrestrial one. But also, a single core setup is possible. The architecture developed and presented should be general enough to support both cases, hence it includes two cores, but also a connection from the TN to the first core that connects to the satellite. The different options are discussed later in this section. Furthermore, also for multi-connectivity, there are various options enabled by this architecture that are discussed. In contrast to the operational analysis in this figure, the control plane part has been added as well as several sub-systems that are required to meet the use cases.

The architecture supports both, a direct connection of the user to the RAN (also via a multi-connectivity function), or a connection via a CPE using WiFi, 5G and/or LiFi. The CPE can be backhauled by 5G TN and NTN, or DVB-S2X. The edge cloud continuum includes the components for MANO, AI-based resource management, the compound AI system and the various edge clusters present at CPE, RAN, transport network and DN side. The NTN system is connected via the ground segment. The current figure of the system level analyses includes two cores, there are different options discussed later in the section. Same holds for options for the functional split of gNB functions and options for optical links.

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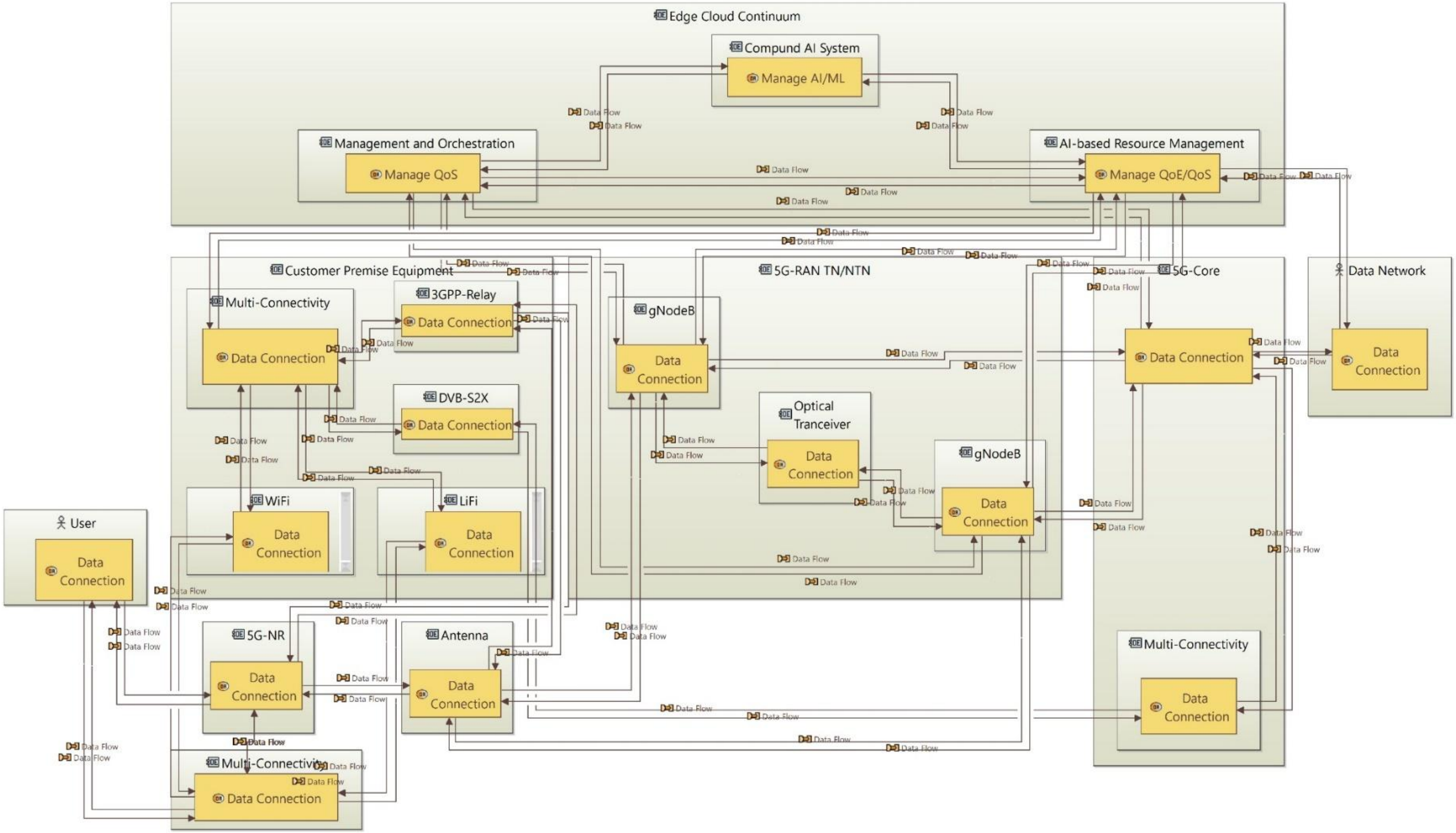

Figure 3-1: NexaSphere Operational Diagram

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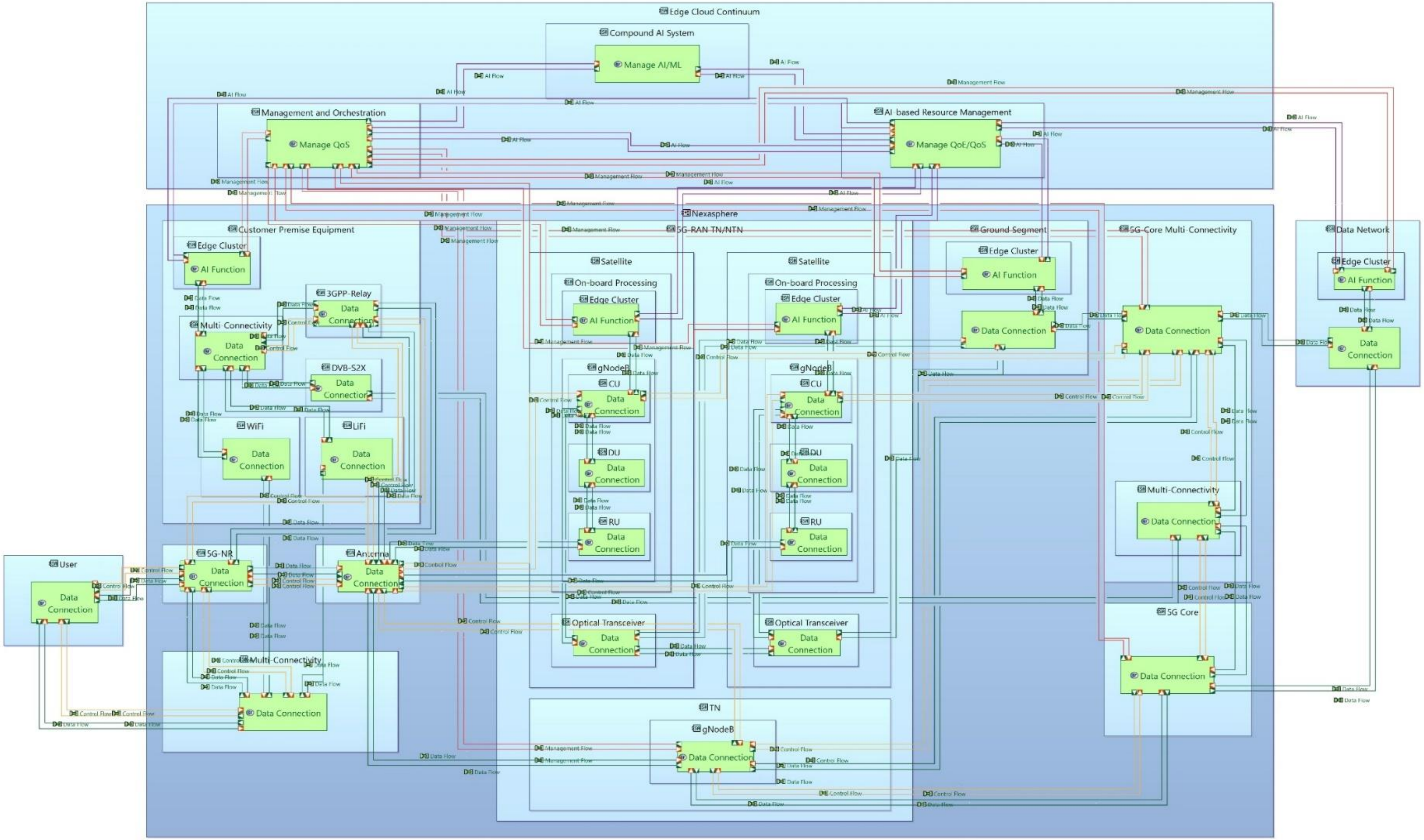

Figure 3-2: NexaSphere System Diagram

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Section 4: System Element Specification

In this section, we describe the main components of the NexaSphere system in the following. The presented tables for the interface specification have been automatically created from the Capella model. This information is generally included by the model as needed for an MBSE approach and can directly be used from there. For delivering purposes we have added the current snapshot in this document. The following section include a description of the main system elements including the interface specification. In the Annex also the interfaces for other blocks are presented. The presents the Functional Output Ports (FOP) and Functional Input Ports (FIP) as is introduced by Capella (and similar to SysMLv1). A system element function can have multiple ports. Typically, system element A has and incoming interface and an outgoing from element B, the incoming is the FIP the outgoing the FOP. Both define the interface between element A and B. The FOP of element A to B should be the FIP of B to A. Furthermore, we specify in the interface tables of each block the data exchanged the type of interface and a description.

4.1 Multi-Connectivity

The Multi-Connectivity block facilitates inter-entity communication through the concurrent use of multiple heterogeneous access links, thereby improving communication robustness, throughput performance and overall service continuity. By abstracting the underlying interfaces, this module coordinates the parallel utilization of distinct network paths and dynamically distributes traffic according to application requirements, service policies and/or network conditions.

The multi-connectivity module may operate in accordance with standardized mechanisms such as 3GPP ATSSS, which provides a unified and interoperable framework for traffic coordination across heterogeneous access technologies. In its standardised form, ATSSS supports the simultaneous use of one 3GPP access (either terrestrial or non-terrestrial, i.e. NR-TN or NR-NTN) in conjunction with one non-3GPP access such as Wi-Fi, Li-Fi or DVB. Through well-defined procedures and policy-based control, ATSSS enables predictable behavior, consistent performance management and seamless mobility support across these domains.

The ATSSS module is implemented in the UE and in the anchor UPF (A-UPF), to manage multi-access (MA) PDU. In terms of functionality, we can isolate the ATSSS module from the above-mentioned elements to better highlight the multi-connectivity setup and integration.

This dual approach allows the NexaSphere system to remain aligned with the 3GPP procedures, while also providing the flexibility to investigate, advanced, non-standard multi-path communication strategies beyond the baseline specifications.

In the overall architecture the multi-connectivity element appears multiple times, as such, although implemented the same functions, the interfaces are slightly different for the user-side, at the core and at the CPE (as shown in Table 4-1, Table 4-2, and Table 4-3, respectively)

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Table 4-1: Interface specification multi-connectivity user

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → User	Data Flow	Socket (ATSSS)	Bytes	From Application Layer, data passes through Socket API (interface to Transport Layer), and then toward IP layer. ATSSS module intercepts data and choses the link in which transmit
FOP 2 → WiFi	Data Flow	IP / Frame 802.11 (WiFi)	IP	Allows connection between UE and CPE via WiFi
FOP 3 → LiFi	Data Flow	IP / Frame 802.11bb (LiFi)	IP	Allows connection between UE and CPE via LiFi
FOP 4 → User	Control Flow	Socket (ATSSS)	Bytes	From Application Layer, data passes through Socket API (interface to Transport Layer), and then toward IP layer. ATSSS module intercepts data and choses the link in which transmit
FOP 5 → 5G-NR	Data Flow	PDU / Uu (5G-NR)	PDU	Allows connection between UE and CPE via NR
FOP 6 → 5G-NR	Control Flow	PDU / Uu (5G-NR)	PDU	Allows connection between UE and CPE via NR
FIP 1 ← User	Data Flow	Socket (ATSSS)	Bytes	From Application Layer, data passes through Socket API (interface to Transport Layer), and then toward IP layer. ATSSS module intercepts data and choses the link in which transmit
FIP 2 ← WiFi	Data Flow	IP / Frame 802.11 (WiFi)	IP	Allows connection between UE and CPE via WiFi
FIP 3 ← LiFi	Data Flow	IP / Frame 802.11bb (LiFi)	IP	Allows connection between UE and CPE via LiFi
FIP 4 ← User	Control Flow	Socket (ATSSS)	Bytes	From Application Layer, data passes through Socket API (interface to Transport Layer), and then toward IP layer. ATSSS

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				module intercepts data and choses the link in which transmit
FIP 5 ← 5G-NR	Data Flow	PDU / Uu (5G-NR)	PDU	Allows connection between UE and CPE via NR
FIP 6 ← 5G-NR	Control Flow	PDU / Uu (5G-NR)	PDU	Allows connection between UE and CPE via NR

Table 4-2: Interface specification multi-connectivity core

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → DVB-S2X	Data Flow	3GPP-ATSSS-N3IWF	UE ID: int	As specified in 3GPP with adaption to handle UE ID
FOP 2 → 5G Core	Data Flow	IP or N9	IP packets	MultiAccess UPF: N9 (ATSSS); Via DN -> IP (Proxy or ATSSS)
FOP 3 → 5G-Core Multi-Connectivity	Data Flow	IP or N9	IP packets	MultiAccess UPF: N9 (ATSSS); Via DN -> IP (Proxy or ATSSS)
FOP 4 → 5G Core	Control Flow	3GPP-N4	N4 Format	Control Plane
FOP 5 → 5G-Core Multi-Connectivity	Control Flow	3GPP-N4	N4 Format	Control Plane
FIP 1 ← DVB-S2X	Data Flow	3GPP-ATSSS-N3IWF	UE ID: int	As specified in 3GPP with adaption to handle UE ID
FIP 2 ← 5G Core	Data Flow	IP or N9	IP packets	MultiAccess UPF: N9 (ATSSS); Via DN -> IP (Proxy or ATSSS)
FIP 3 ← 5G-Core Multi-Connectivity	Data Flow	IP or N9	IP packets	MultiAccess UPF: N9 (ATSSS); Via DN -> IP (Proxy or ATSSS)
FIP 4 ← 5G Core	Control Flow	3GPP-N4	N4 Format	Control Plane
FIP 5 ← 5G-Core Multi-Connectivity	Control Flow	3GPP-N4	N4 Format	Control Plane

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Table 4-3: Interface specification multi-connectivity CPE

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → WiFi	Data Flow	IP / Frame 802.11 (WiFi)	IP	Allows connection between UE and CPE via WiFi
FOP 2 → LiFi	Data Flow	IP / Frame 802.11bb (LiFi)	IP	Allows connection between UE and CPE via LiFi
FOP 3 → DVB-S2X	Data Flow	IP (DVB-S2X)	IP packets	IP packets
FOP 4 → 3GPP-Relay	Data Flow	PDU / Uu (5G-NR)	PDU	with the assumption to be intermediated by a UPF (rebuild IP packets from PDUs)
FOP 5 → 3GPP-Relay	Control Flow	IP (3GPP-Relay)	IP packets	IP packets
FOP 6 → Edge Cluster	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FIP 1 ← WiFi	Data Flow	IP / Frame 802.11 (WiFi)	IP	Allows connection between UE and CPE via WiFi
FIP 2 ← LiFi	Data Flow	IP / Frame 802.11bb (LiFi)	IP	Allows connection between UE and CPE via LiFi
FIP 3 ← DVB-S2X	Data Flow	IP (DVB-S2X)	IP packets	IP packets
FIP 4 ← 3GPP-Relay	Data Flow	PDU / Uu (5G-NR)	PDU	with the assumption to be intermediated by a UPF (rebuild IP packets from PDUs)
FIP 5 ← 3GPP-Relay	Control Flow	IP (3GPP-Relay)	IP packets	IP packets
FIP 6 ← Edge Cluster	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP

4.2 gNB

NexaSphere, will employ an NTN capable gNB from SRS. The gNB is a software-based implementation of L1/L2/L3 layers, deployed on commercial off-the-shelf (COTS) hardware. The gNB implements all layers for both the control and user plane functionalities, while adopting an O-RAN-based architecture in line with the O-RAN Alliance specifications. The implemented solution, as shown in Figure 4-1, features a highly modular architecture, making

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it ideal for both transparent and regenerative scenarios. Towards that end, the architecture incorporates the required 3GPP and O-RAN interfaces to enable disaggregated deployments and interact with third-party solutions:

- F1 interface supporting split 2 - CU/DU separation.
- E2 interface supporting the separation of the CU-UP and CU-CP
- FAPI interface supporting split 6 - MAC/PHY separation (e.g., SoC-based L1 solutions aiming at an embedded/CubeSat gNB implementation).
- (O)FH interface supporting split 7.2x and split 8 - DU/RU or SDR-based radios.

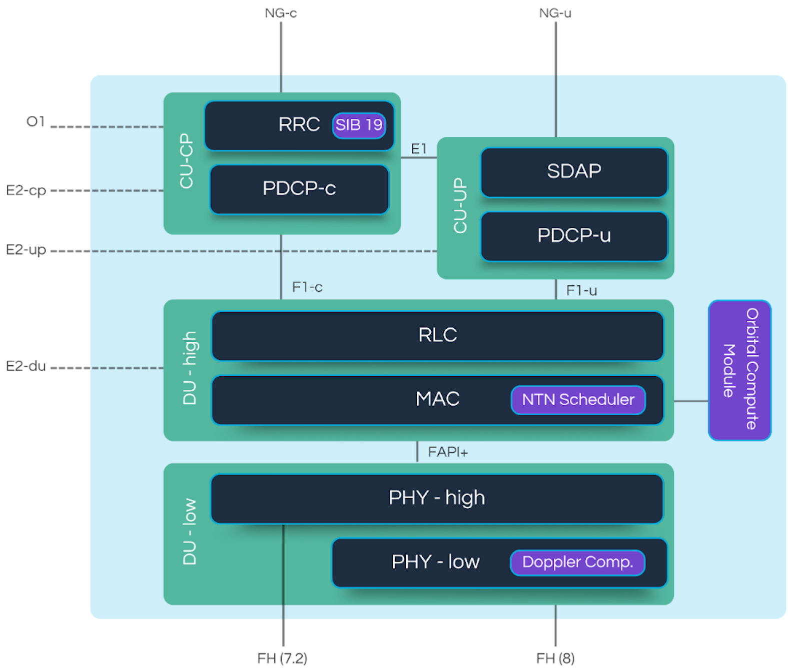

Figure 4-1: gNB ORAN architecture

A list of the most relevant features is presented below:

- FDD, with support for all FR1 bands, including NTN-specific (n254, n255, n256)
- Extended bandwidth support. Although formally, the NTN bands have a maximum specified bandwidth of 20 MHz, the gNB implementation supports:
  - Up to 50 MHz with 15 kHz subcarrier spacing.
  - Up to 100 MHz with 30 kHz subcarrier spacing.
- All physical channels, including PUCCH Format 1 and 2, excluding Sounding-RS.
- All RRC and MAC procedures.
- Handover (intra-DU, intra-CU and inter-CU). 3GPP release 17 NTN-NR-specific features:
  - L2/L3 timer extensions.
  - Extended K-offset up to 1023.
  - High-accuracy SIB19 support.

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- Common TA parameters for the feeder link.
- TLE-defined orbital path generator.
- NTN-enabled scheduler with up to 32 HARQ processes.
- Feeder-link Doppler compensation.

The identified interfaces of the gNB in the NexaSphere system are presented in Table 4-4.

Table 4-4: Interface specification gNB

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → 5G-Core Multi-Connectivity	Data Flow	3GPP-N3	User data packets (e.g., IP packets, voice, video, etc.)	Protocol: GTP-U over UDP/IP
FOP 2 → Antenna	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FOP 3 → Management and Orchestration	Management Flow	HTTP/REST	-	Monitoring metrics (CPU, storage, memory, application/VNF specific metrics)
FOP 4 → 5G-Core Multi-Connectivity	Control Flow	3GPP-N2	Control plane messages	Protocol: NGAP over SCTP/IP
FOP 5 → Antenna	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FOP 6 → 5G Core	Data Flow	3GPP-N3	User data packets (e.g., IP packets, voice, video, etc.)	Protocol: GTP-U over UDP/IP
FOP 7 → 5G Core	Control Flow	3GPP-N2	Control plane messages	Protocol: NGAP over SCTP/IP
FIP 1 ← 5G-Core Multi-Connectivity	Data Flow	3GPP-N3	User data packets (e.g., IP packets,	Protocol: GTP-U over UDP/IP

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			voice, video, etc.)	
FIP 2 ← Antenna	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 3 ← Management and Orchestration	Management Flow	HTTP/REST	-	Provisioning and VNF/Application management (deploy, migrate, scale up-down, etc.)
FIP 4 ← 5G-Core Multi-Connectivity	Control Flow	3GPP-N2	Control plane messages	Protocol: NGAP over SCTP/IP
FIP 5 ← Antenna	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 6 ← 5G Core	Data Flow	3GPP-N3	User data packets (e.g., IP packets, voice, video, etc.)	Protocol: GTP-U over UDP/IP
FIP 7 ← 5G Core	Control Flow	3GPP-N2	Control plane messages	Protocol: NGAP over SCTP/IP

4.3 Core

The 5G Core (5GC) is designed to provide secure, reliable connectivity and network services, such as IP connectivity, mobility management, authentication, authorization, subscriber data and policy management. It separates the control and user planes, enabling flexible deployments and integration with edge resources.

The 5G system architecture for a non-roaming scenario is shown in Figure 4-2, illustrating the network with its primary 5GC distinctly divided into User Plane and Control Plane functions, which may be implemented either as a unified entity or as distinct components.

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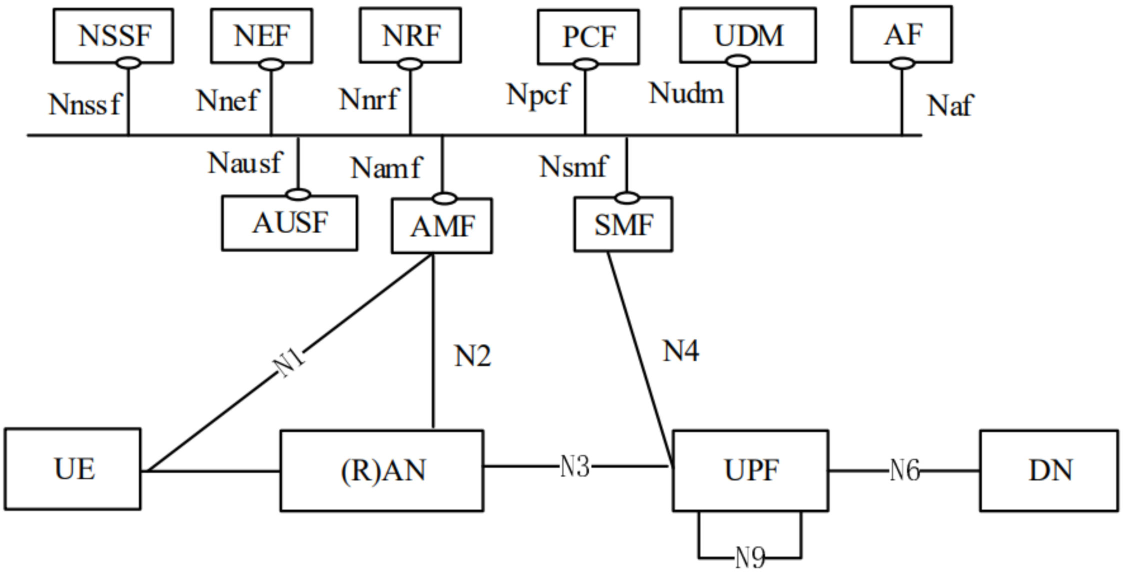

Figure 4-2: 5G-System Architecture (Non-Roaming scenario) [2]

The interactions among control plane functions are implemented according to a service-based architecture (SBA) model. Key functions include Access and Mobility Management Function (AMF), Authentication Server Function (AUSF), Session Management Function (SMF), Network Repository Function (NRF), Unified Data Repository (UDR), Unified Data Management (UDM), Policy Control Function (PCF), Application Function (AF), User plane Function (UPF). The full list of the 5GC network functions is provided in 3GPP 23.501.

To support the NexaSphere use-cases, the 5GC leverages several key features:

Network function virtualization: In 5GC architectures, network functions can be deployed as virtualized network functions (VNFs), enabling flexible and scalable instantiation/deployment across multiple instances. When combined with advanced radio technologies and dynamic resource allocation mechanisms, this approach facilitates the creation of multiple network slices on a shared physical infrastructure. These slices can be provisioned on a per-tenant basis or even tailored for individual services.

Network slicing: A network slice represents a logical segmentation of the network that can be dedicated to a specific customer or vertical and configured to deliver mobile services with predefined Quality of Service (QoS) parameters. This capability is fundamental for supporting diverse vertical industries, each characterized by distinct performance, reliability and latency requirements.

Edge computing: Edge computing brings services closer to end-users, minimizing latency and enhancing overall performance. In 5G networks, edge integration is enabled through Edge Hosting Environments and Edge Application Servers. Features such as traffic steering and local breakout ensure optimized routing for edge-based applications. To support flexible traffic distribution between cloud and edge sites, three connectivity models are defined: (i) distributed anchor point, (ii) session breakout, and (iii) multiple PDU sessions. These models provide adaptable options for managing connectivity across different deployment scenarios.

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5G Core integration into NTN scenarios: NTN extends 5G connectivity to satellites and high-altitude platforms, requiring adaptations in both RAN and Core. Key specifications include TS 23.501 for architecture and TS 23.502 for procedures, updated in 3GPP Release 17/18 for NTN. Integration involves handling registration, PDU sessions and QoS mapping under satellite constraints.

The FOPs and FIPs (i.e., the interfaces) of the core to other NexaSphere system elements are shown in Table 4-5.

Table 4-5: Interface specification B5G-core

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → Data Network	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FOP 2 → Management and Orchestration	Management Flow	3GPP-N5 Management	Control plane messages Management messages	Protocol: RESTful APIs (HTTP/2, JSON) Protocol: RESTful APIs (HTTP/2, JSON)
FOP 3 → gNodeB	Data Flow	3GPP-N3	User data packets (e.g., IP packets, voice, video, etc.)	Protocol: GTP-U over UDP/IP
FOP 4 → CU	Control Flow	3GPP-N2	Control plane messages	Protocol: NGAP over SCTP/IP
FOP 5 → CU	Control Flow	3GPP-N2	Control plane messages	Protocol: NGAP over SCTP/IP
FOP 6 → gNodeB	Control Flow	3GPP-N2	Control plane messages	Protocol: NGAP over SCTP/IP
FOP 7 → Ground Segment	Data Flow	IP (OSL)	IP packets	Carries N2 and N3; Examples: Train with optical terminal, Plane with optical terminal, Terrestrial gNB station with optical terminal
FOP 8 → Multi-Connectivity	Data Flow	IP or N9	IP packets	MultiAccess UPF: N9 (ATSSS); Via DN -> IP (Proxy or ATSSS)
FOP 9 → Multi-Connectivity	Control Flow	3GPP-N4	N4 Format	Control Plane

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FIP 1 ← Data Network	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FIP 2 ← Management and Orchestration	Management Flow	3GPP-N5 Management	Control plane messages Management messages	Protocol: RESTful APIs (HTTP/2, JSON) Protocol: RESTful APIs (HTTP/2, JSON)
FIP 3 ← gNodeB	Data Flow	3GPP-N3	User data packets (e.g., IP packets, voice, video, etc.)	Protocol: GTP-U over UDP/IP
FIP 4 ← CU	Control Flow	3GPP-N2	Control plane messages	Protocol: NGAP over SCTP/IP
FIP 5 ← CU	Control Flow	3GPP-N2	Control plane messages	Protocol: NGAP over SCTP/IP
FIP 6 ← gNodeB	Control Flow	3GPP-N2	Control plane messages	Protocol: NGAP over SCTP/IP
FIP 7 ← Ground Segment	Data Flow	3GPP-N3	User data packets (e.g., IP packets, voice, video, etc.)	Protocol: GTP-U over UDP/IP
FIP 8 ← Multi-Connectivity	Data Flow	IP or N9	IP packets	MultiAccess UPF: N9 (ATSSS); Via DN -> IP (Proxy or ATSSS)
FIP 9 ← Multi-Connectivity	Control Flow	3GPP-N4	N4 Format	Control Plane

4.4 Antenna

Within the scope of the NexaSphere project, two distinct types of antennas are planned for development and validation: (i) a combined Ku/Ka-band antenna for avionics applications, and (ii) a compact Ka-band flat antenna for automotive use.

The avionics antenna concept involves an ultra-wideband panel covering 10.7–31 GHz, complemented by a secondary panel dedicated to polarization selection. The design relies on wideband antennas arranged in sub-arrays, with each element connected to a novel, compact quadruplexer that separates the Ku-RX, Ku-TX, Ka-RX and Ka-TX signals. Following this separation, commercially available core-chip beamformers (COTS) will enable independent scanning of the array at each frequency band. Polarization control is achieved through the programming of these beamforming chips, allowing for flexible selection of any polarization.

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The antenna specifications have been defined under Task 2.2 and are documented in the system requirements.

For the automotive antenna, the primary objectives are to reduce the overall footprint and manufacturing costs while meeting the required throughput performance. To achieve this, different strategies for clustering and sharing radiating elements will be explored, along with alternative fabrication techniques such as planar canonical PCB designs and additive manufacturing. The most promising concepts will then be down selected for further development.

The interfaces of the different antennas are presented in Table 4-6.

Table 4-6: Interface specification antenna

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → 5G-NR	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FOP 2 → 5G-NR	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FOP 3 → gNodeB	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FOP 4 → gNodeB	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FOP 5 → RU	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FOP 6 → CU	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FOP 7 → RU	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite

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				gNodeB can terminate the link directly
FOP 8 → CU	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FOP 9 → 3GPP-Relay	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FOP 10 → 3GPP-Relay	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 1 ← 5G-NR	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 2 ← 5G-NR	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 3 ← gNodeB	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 4 ← gNodeB	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 5 ← RU	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 6 ← CU	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly

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FIP 7 ← RU	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 8 ← CU	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 9 ← 3GPP-Relay	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 10 ← 3GPP-Relay	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly

4.5 LiFi

The LiFi subsystem provides complementary optical wireless access capabilities within the NexaSphere architecture, enabling high-capacity links that operate alongside terrestrial and non-terrestrial links. Two optical communication modalities are considered: (i) a distributed indoor LiFi system for cabin connectivity and (ii) a high-throughput laser-based link for Gate Data Transfer (GDT) during aircraft turnaround. Together, these technologies contribute to the NexaSphere's broader objectives of enabling heterogeneous multi-connectivity and improved spectral efficiency.

For cabin connectivity, the system adopts a distributed multi-antenna architecture designed to improve coverage area and mitigate interference in dense passenger environments. A central processing unit performs baseband functions and aggregates traffic, while multiple compact optical antennas act as remote optical heads responsible for transmission and reception. Target throughput is on the order of 100 Mbps per central unit. The design is intended to be scalable to different cabin layouts and to operate over standard Ethernet transport, allowing IP packets to be exchanged with higher layers without imposing proprietary constraints.

In contrast, the GDT subsystem utilizes a point-to-point laser communication terminal optimized for very high throughput. The link targets multi-gigabit data rates (up to 10 Gbps) to enable rapid synchronization of operational and passenger service data between the aircraft and ground systems. The system is designed to operate in a controlled alignment scenario, complementing 3GPP links that may be capacity-limited or subject to regulatory restrictions. The architecture prioritizes high optical bandwidth, robust link acquisition and fast establishment to minimize turnaround time.

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At system level, both optical subsystems interfaces to the NexaSphere multi-connectivity framework via Ethernet interfaces, exposing IP traffic to the higher layers. This allows LiFi to function as an additional access option within the combined TN/NTN communication stack, while avoiding the need to define specific/specialized interfaces at the architectural level.

Table 4-7 shows the specified interfaces for the LiFi system.

Table 4-7: Interface specification LiFi

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → Multi-Connectivity	Data Flow	IP / Frame 802.11bb (LiFi)	IP	Allows connection between UE and CPE via LiFi
FOP 2 → Multi-Connectivity	Data Flow	IP / Frame 802.11bb (LiFi)	IP	Allows connection between UE and CPE via LiFi
FIP 1 ← Multi-Connectivity	Data Flow	IP / Frame 802.11bb (LiFi)	IP	Allows connection between UE and CPE via LiFi
FIP 2 ← Multi-Connectivity	Data Flow	IP / Frame 802.11bb (LiFi)	IP	Allows connection between UE and CPE via LiFi

4.6 Optical Transceiver

The optical transceiver connects two system elements together, offering high throughput and power efficiency. One transceiver enables both sending and receiving within a single link. Both atmospheric links, including feeder links, and optical intersatellite links (OISLs) are included. The optical links also support multi-orbit scenarios up to GEO. The interfaces of the optical links are IP-based, transparent, and allow for data transport. They are shown in Table 4-8.

Table 4-8: Interface specification optical transceiver

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → CU	Data Flow	IP (OSL)	IP packets	Carries N2 and N3; Examples: Train with optical terminal, Plane with optical terminal, Terrestrial gNB station with optical terminal
FOP 2 → Optical Transceiver	Data Flow	IP (OSL)	IP packets	Carries N2 and N3; Examples: Train with optical terminal, Plane with optical terminal, Terrestrial gNB station with optical terminal

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FOP 3 → Ground Segment	Data Flow	IP (OSL)	IP packets	Carries N2 and N3; Examples: Train with optical terminal, Plane with optical terminal, Terrestrial gNB station with optical terminal
FIP 1 ← CU	Data Flow	IP (OSL)	IP packets	Carries N2 and N3; Examples: Train with optical terminal, Plane with optical terminal, Terrestrial gNB station with optical terminal
FIP 2 ← Optical Transceiver	Data Flow	IP (OSL)	IP packets	Carries N2 and N3; Examples: Train with optical terminal, Plane with optical terminal, Terrestrial gNB station with optical terminal
FIP 3 ← Ground Segment	Data Flow	IP (OSL)	IP packets	Carries N2 and N3; Examples: Train with optical terminal, Plane with optical terminal, Terrestrial gNB station with optical terminal

4.7 Edge-Cloud Continuum

In the context of the NexaSphere, the edge-cloud continuum is conceived not merely as a network connectivity layer, but as a unified, three-dimensional computational fabric. It seamlessly integrates resources across multiple domains such as space-based platforms (e.g., satellites), terrestrial infrastructure (e.g., ground stations) and CPEs (including aviation, automotive and railway units) into a single logical pool of compute and storage resources.

To realize the project's vision of a "Network of Networks", the NexaSphere architecture adheres to the following high-level requirements:

1. Mobility Management: The system must support the orchestration of workloads deployed on mobile nodes that are physically moving (e.g., orbiting satellites or moving users). This requires geo-locality aware scheduling mechanisms to account for time-varying latencies and anticipate for mobility requirements (e/g/. connectivity changes) and resource availability.
2. Hardware Heterogeneity: The infrastructure spans from fully fledged cloud datacenters to low power satellite nodes. The management layer must abstract these differences, while explicitly addressing the specific constraints of space edge nodes, such as the severe power budgets.
3. Unified Execution Plane: The architecture should support the co-location and coordinated execution of Network Functions (e.g. O-RAN CU, UPFs) and general-purpose applications (e.g., AI inference) on the same physical infrastructure. Both containerized workloads and Virtual Machines (VMs) must be supported and must be transparently enabled for the end-users.

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A key architectural decision is the adoption of a cloud native approach across all tiers of the continuum, enabling the deployment of both connectivity and value-added applications as microservices on shared domain (e.g., Kubernetes clusters).

To govern this complex, heterogeneous environment, NexaSphere utilizes ETSI Open-Source Mano (OSM) as the central orchestrator. OSM functions here as a “Manager of Managers” providing complete abstraction of the underlying complexity of the continuum, including service reliability, availability, and healing capabilities. OSM interfaces with diverse Virtual Infrastructure Managers (VIMs) and presents them as a single resource catalogue, providing the desired infrastructure abstraction needed for the service definition as a high-level descriptor that can be automatically instantiated across ground and space nodes of different architectures. By employing OSM, standard compliance is ensured (ETSI NFV-SOL) while gaining the flexibility to manage the unique mix of network and application workloads required for 6G scenarios.

The edge cloud continuum builds on several edge cloud clusters available at the system. The interfaces on different levels are specified in the Annex.

4.7.1 Management and Orchestration

The Management and Orchestration (MANO) framework, i.e., OSM, for Non-Terrestrial Networks (NTN) plays a very important role in enabling the seamless integration, the dynamic adaptation and the efficient operation of 3D connectivity spanning space-, air-, and ground-based infrastructures.

Positioned as the central decision-execution layer, MANO interacts continuously with both the AI-based resource management system and the compound AI component of the NTN 3D edge-cloud continuum. The MANO layer also interacts with the edge nodes where the actual workloads are instantiated and executed. Based on optimization insights and recommendations provided by the AI resource manager and the compound AI element, MANO is responsible for enforcing lifecycle management operations -incl. instantiation, scaling, migration and termination- of network functions deployed across satellites, High-Altitude Platforms (HAPS), UAV-based nodes and terrestrial infrastructure.

MANO executes several key functions that are essential for maintaining service continuity within the 3D edge-cloud continuum:

1. Application and network service orchestration across dynamic and mobility-driven NTN topologies.
2. Configuration and re-configuration of Virtualized Network Functions (VNFs) to ensure performance stability under rapidly changing link conditions.
3. Dynamic adaptation of service chains to accommodate variable latency, intermittent coverage and fluctuating bandwidth inherent to NTN environments.

Communication between the AI-based resource manager and the MANO follows a unidirectional REST/HTTP paradigm, ensuring a clear separation between decision-making and execution. MANO receives JSON-formatted recommendations from the AI engine, interprets them as actionable instructions, and enforces them through its orchestration and

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control APIs across all NTN segments. Through these mechanisms, MANO guarantees the optimal operation of the NTN-enabled 3D connectivity fabric, supporting resilient, sustainable and high-performance service delivery across terrestrial and non-terrestrial domains.

The interface specification of the MANO is presented in Table 4-9.

Table 4-9: Interface specification MANO

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → Edge Cluster	Management Flow	HTTP/REST	-	Provisioning and VNF/Application management (deploy, migrate, scale up-down, etc.)
FOP 2 → 5G-Core Multi-Connectivity	Management Flow	3GPP-N5 Management	Control plane messages Management messages	Protocol: RESTful APIs (HTTP/2, JSON) Protocol: RESTful APIs (HTTP/2, JSON)
FOP 4 → gNodeB	Management Flow	HTTP/REST	-	Provisioning and VNF/Application management (deploy, migrate, scale up-down, etc.)
FOP 5 → 5G Core	Management Flow	3GPP-N5 Management	Control plane messages Management messages	Protocol: RESTful APIs (HTTP/2, JSON) Protocol: RESTful APIs (HTTP/2, JSON)
FOP 6 → Compound AI System	AI Flow	HTTP/REST	Infrastructure Resource State (available CPU, memory, storage per node); Node Capabilities (e.g. GPU accelerated)	Compound AI system needs infrastructure state for model selection algorithms and placement decisions. MANO exposes resource availability across the computing continuum.
FOP 10 → AI-based Resource Management	AI Flow	HTTP/REST	JSON {Instructions: string}	Resource management instruction (container scale up/down, migration)
FIP 1 ← Edge Cluster	Management Flow	HTTP/REST	-	Monitoring metrics (CPU, storage, memory,

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				application/VNF specific metrics)
FIP 2 ← 5G-Core Multi-Connectivity	Management Flow	3GPP-N5 Management	Control plane messages Management messages	Protocol: RESTful APIs (HTTP/2, JSON) Protocol: RESTful APIs (HTTP/2, JSON)
FIP 4 ← gNodeB	Management Flow	HTTP/REST	-	Monitoring metrics (CPU, storage, memory, application/VNF specific metrics)
FIP 5 ← 5G Core	Management Flow	3GPP-N5 Management	Control plane messages Management messages	Protocol: RESTful APIs (HTTP/2, JSON) Protocol: RESTful APIs (HTTP/2, JSON)
FIP 6 ← Compound AI System	AI Flow	HTTP/REST	Resource utilization predictions (e.g. predicted storage needed); Application placement recommendations (e.g. recommended node)	Compound AI provides resource predictions to enable intelligent application placement across the ECC. MANO handles actual deployment to clusters.
FIP 10 ← AI-based Resource Management	AI Flow	HTTP/REST	JSON {Instructions: string}	Resource management instruction (container scale up/down, migration)

4.7.2 AI Resource Management

The AI-based resource management element interacts with the edge-clusters, the MANO block, and the core network, analyzing various operational and performance metrics to effectively manage resources across the 3D edge-cloud continuum. It employs optimization algorithms to execute the following key functions:

- Strategic placement and scheduling of workloads aligned with the project's performance and sustainability goals.

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- Resource management for heterogeneous applications operating within the 3D edge-cloud continuum.

The resulting optimization recommendations are communicated to the MANO framework. As the responsible entity, MANO implements the necessary configurations or re-configurations to ensure the optimal operation/performance of the 3D edge-cloud continuum and the seamless provision of the 3D connectivity services. The AI-based resource management supports a unidirectional REST/HTTP interface with edge-clusters, core and MANO. It collects metrics (in a JSON format) from edge-clusters and core and sends recommendations/instructions (in JSON format) to the MANO framework. The interfaces are summarized in Table 4-10.

Table 4-10: Interface specification AI resource management

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → Compound AI System	AI Flow	HTTP/REST	Requested model (e.g. mobility predictions); Requested outputs (e.g. Predicted handovers)	Compound AI aims to utilize various AI capabilities in the NexaSphere system through specialized AI workflow orchestration algorithms.
FOP 2 → Edge Cluster	AI Flow	HTTP/REST	JSON {Monitoring metrics:float}	Monitoring metrics: features extracted from bare metal, container, application, functional, etc.
FOP 7 → Management and Orchestration	AI Flow	HTTP/REST	JSON {Instructions: string}	Resource management instruction (container scale up/down, migration)
FIP 1 ← Compound AI System	AI Flow	HTTP/REST	Requested model (e.g. mobility predictions); Requested outputs (e.g. Predicted handovers)	Compound AI aims to utilize various AI capabilities in the NexaSphere system through specialized AI workflow orchestration algorithms.
FIP 2 ← Edge Cluster	AI Flow	HTTP/REST	JSON {Monitoring metrics:float}	Monitoring metrics: features extracted from bare metal, container, application, functional, etc.

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FIP 7 ← Management and Orchestration	AI Flow	HTTP/REST	JSON {Instructions: string}	Resource management instruction (container scale up/down, migration)

4.7.3 Compound AI System

NexaSphere envisions AI capabilities for efficient resource management and multi-connectivity scheduling across 3D networks and the edge-cloud continuum. However, AI models operating in resource-constrained environments must not cause significant computational or energy overhead to NexaSphere operation. To address this, NexaSphere introduces the Compound AI system element responsible for delivering these AI capabilities in a resource- and energy-efficient manner.

The compound AI system element combines and orchestrates multiple specialized AI/ML models with engineered software components into structured AI workflows. This approach enables control over AI workflow execution, model selection, placement and optimization. In NexaSphere, the compound AI system element orchestrates prediction-drive workflows to ensure sustainable and adaptive connectivity. By coordinating application-level prediction models (compute, storage, content caching) with network-level prediction models (handover timing, satellite link quality), it produces actionable insights for proactive resource management and multi-connectivity scheduling.

To minimize operational overhead while maintaining prediction accuracy, the element incorporates a set of complementary mechanisms:

1. **Model selection**: Activates the prediction models whose task performance, latency and computational costs are aligned with the current system conditions and the requirements of the ongoing task defined by the use case.
2. **Model Scheduling**: Considers factors such as resource availability, latency requirements and network conditions to position models appropriately across the edge-cloud continuum.
3. **Serverless Execution**: Ensures that models consume resources only when actively running, avoiding idle infrastructure overhead and supporting efficient model management.
4. **Model Optimization**: Including techniques such as quantization and distillation, further ensures efficient operation in resource-constrained environments and reduces computational and memory footprint without significant task performance degradation.

Within the NexaSphere architecture, the Compound AI system element exposes its outputs as prediction signals to the resource management and orchestration components and multi-connectivity schedulers, while ensuring that model inference tasks cause minimal overhead to the overall NexaSphere system. In doing so, it enhances the system's ability to perform informed and proactive adaptation across heterogeneous 3D networks.

The compound AI system's interface specification is presented in Table 4-11.

Table 4-11: Interface specification compound AI system

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Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → Management and Orchestration	AI Flow	HTTP/REST	Resource utilization predictions (e.g. predicted storage needed); Application placement recommendations (e.g. recommended node)	Compound AI provides resource predictions to enable intelligent application placement across the ECC. MANO handles actual deployment to clusters.
FOP 2 → AI-based Resource Management	AI Flow	HTTP/REST	Requested model (e.g. mobility predictions); Requested outputs (e.g. Predicted handovers)	Compound AI aims to utilize various AI capabilities in the NexaSphere system through specialized AI workflow orchestration algorithms.
FIP 1 ← Management and Orchestration	AI Flow	HTTP/REST	Infrastructure Resource State (available CPU, memory, storage per node); Node Capabilities (e.g. GPU accelerated)	Compound AI system needs infrastructure state for model selection algorithms and placement decisions. MANO exposes resource availability across the computing continuum.
FIP 2 ← AI-based Resource Management	AI Flow	HTTP/REST	Requested model (e.g. mobility predictions); Requested outputs (e.g. Predicted handovers)	Compound AI aims to utilize various AI capabilities in the NexaSphere system through specialized AI workflow orchestration algorithms.

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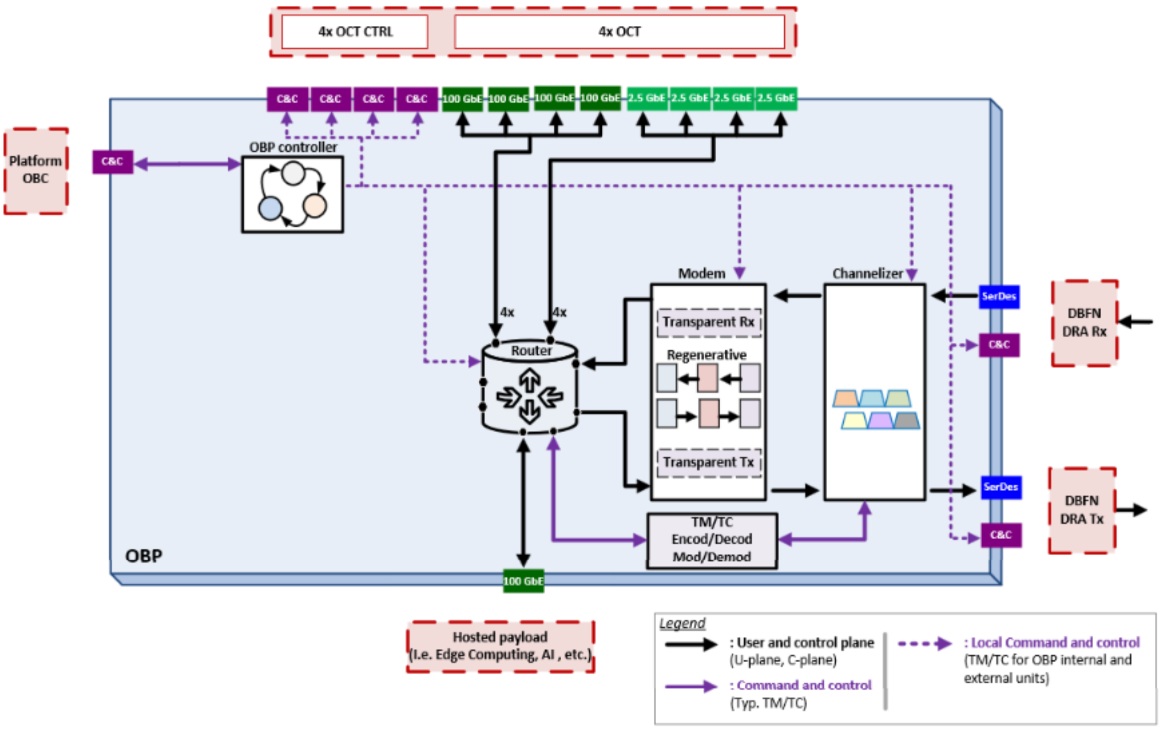
4.8 On-Board Processing

The On-Board Processor (OBP) for the NexaSphere project is defined as a secure, AI-enabled, multi-connectivity edge node designed to integrate terrestrial, non-terrestrial and airborne networks. Leveraging a scalable and reconfigurable architecture, the OBP shall support the following high-level mission functions:

- Enable multi-path connectivity and advanced routing including per-flow steering, bonding, and adaptive mechanisms.
- Provide edge computing and virtualization capabilities allowing network functions and applications to operate locally, orchestrated via the control-plane.
- Enable orchestration through AI-driven automation, telemetry collection and closed-loop control to optimize overall connectivity and Quality of Service (QoS).

Figure 4-3 presents the OBP hardware context diagrams, showing its preliminary high-level interfaces and internal functionality.
The main interfaces between the OBP and other units are as follows:

- Digital Beam Forming Network (DBFN) – Direct Radiating Array (DRA) Receive (Rx)
- Digital Beam Forming Network (DBFN) – Direct Radiating Array (DRA) Transmit (Tx)
- Feeder-Link Reflector Receive (Rx) (optional)
- Feeder-Link Reflector Transmit (Tx) (optional)
- Optical Communication Terminal (OCT) for Optical Inter-Satellite Link (OISL)
- Platform Interfaces (e.g., OBC, etc.)
- Hosted Payload Interfaces (optional)



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The OBP provides the necessary processing to support its hardware connections through Ethernet links, data buses, serial interfaces, and high-speed serializer/deserializer (SerDes) channels. Through these interfaces, the OBP ensures the management of the following subsystem and data flows:

- Operational control of the Rx and Tx beams including beam hoping, satellite and beam handover management via the DFBN control unit.
- General command and control of the payload OCT units.
- Processing and management of all data streams associated with the User Plane (U-Plane), Control Plane (C-Plane), and Management Plane (M-Plane) in alignment with applicable ITU, 5G, and DVB standards, ensuring interoperability and compliance with established communication frameworks.

The operation is enabled by the following core functionality provided by the OBP:

Transparent Data Processing:
- The OBP executes full Layer (L1) protocol stack processing for received and transmitted RF digital spectrum samples originating from the Rx and Tx antennas.
- The OBP can also route RF signals to the channelizer through the optional Feeder Link Reflectors, when the system is configured to support this operational mode.

Regenerative Data Processing:
- The OBP performs Layer 1 (L1) and Layer 2 (L2) processing, including demodulation, decoding, and de-formatting of the digital spectrum originating from the Rx and Tx DRA antennas.
- L1/L2 processing outputs Layer 3 (L3) packets for datagrams compatible with Internet Protocol (IP) Networking, directing the packets to the router for subsequent distribution, including forwarding to the OISL subsystem or retransmission via the RF downlink.
- As in transparent mode, the OBP may route RF signals to the channelizer via the Feeder Link Reflectors when configured for this capability.

Network Router:

The Network Router is implemented using a Software-Defined Networking (SDN) architecture and supports two operational routing modes.

- Conventional Layer 3 (L3) IP routing, supporting IPv4 and IPv6 in accordance with IETF RFC and IEEE 802.x protocol standards.
- Layer 2.5 using Multi-Protocol Label Switching (MPLS), positioned between the Data Link (L2) and Network (L3) layers. MPLS routing, implemented according to ETSI TS 102 856-1 and TS 102 856-2, enables deterministic, label-based forwarding and supports end-to-end MPLS tunnels between ground stations and satellites within the constellation.

The router manages all IP-based input and output data streams within the payload system, providing User-to-User and User-to-Gateway connectivity. Its interfaces include the OISL

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terminals for inter-satellite traffic, the Transparent and Regenerative OBP Processing chains, the platform OBC for TM/TC, and any additional hosted payloads. This central routing function ensures seamless interconnection across all payload and platform communication paths.

Traffic handling is governed by Quality of Service (QoS) mechanisms defined by the communication standards in use and their associated performance requirements, including latency, link quality, availability, and end-to-end delay. To meet these requirements, data flows are channelized and assigned to the distinct operational planes each supporting differentiated priorities, scheduling policies, and queuing mechanisms. This structured approach maximizes overall network reliability, performance, and bandwidth efficiency.

QoS classifications and traffic management principles follow relevant ITU recommendations, which define how IP-based data flows should be categorized and handled to ensure predictable performance required across heterogenous communication environments.

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Section 5: Architecture Options

As introduced in the previous section, the architecture presented is a baseline following 3GPP release 19 with full gNB on-board the satellites and two cores for the connections. In the following we discuss some options not shown in the architecture figure.

5.1 Multi-Connectivity Core Options

The design of a Multi-Connectivity component within a 5G core network can rely on different configuration options, each reflecting a distinct strategy for coordinating traffic across multiple access paths.

Within the standardized 3GPP framework, ATSSS (Access Traffic Steering, Switching, and Splitting) defines the main operational modes used to control how flows are distributed. Steering allows the system to select the most suitable link for a given service based on policies or network conditions; Switching enables the seamless migration of traffic from one access to another in response to failures, congestion, or mobility events; Splitting provides the capability to spread traffic simultaneously across multiple links in order to maximize throughput or balance load. These ATSSS behaviors form the foundation of standardized multi-access integration in the 5G core and ensure consistent handling of flows across heterogeneous access technologies. The realization of ATSSS can rely on multipath transport protocols such as MPTCP or MPQUIC, which provide native support for flow aggregation and seamless failover across multiple paths.

In this standardized configuration, the multi-connectivity component enables the combination of two distinct access technologies for reaching the core network: a 3GPP link, whether terrestrial or non-terrestrial, and a non-3GPP link that, within the previously defined architectural scheme, corresponds to DVB-S2X. This setup allows the component to operate both paths in parallel and to provide effective multi-link transport across heterogeneous technologies.

Beyond the standardized ATSSS approach, a second configuration option adopts a custom proxy-based mode that operates at the transport layer rather than at the access level. Unlike the previous solution, which is constrained by 3GPP specifications and limited to the pairing of one 3GPP and one non-3GPP access, the proxy-based configuration enables the aggregation of an arbitrary number of heterogeneous links, regardless of whether they originate from 3GPP or non-3GPP technologies. This design allows the Multi-Connectivity component to combine multiple transport paths (including, in the context of the previously defined architecture, both the DVB-S2X link and the 5G core network link, also more than one) thereby offering a flexible and highly adaptable multi-link bonding mechanism at the cost of departing from standardization and its associated guarantees of interoperability.

Together, the standardized ATSSS configuration and the custom proxy-based mode enable the multi-connectivity component to cover the full range of use cases that require multi-link operation, from standard-compliant deployment scenarios to advanced, experimental multi-path configurations.

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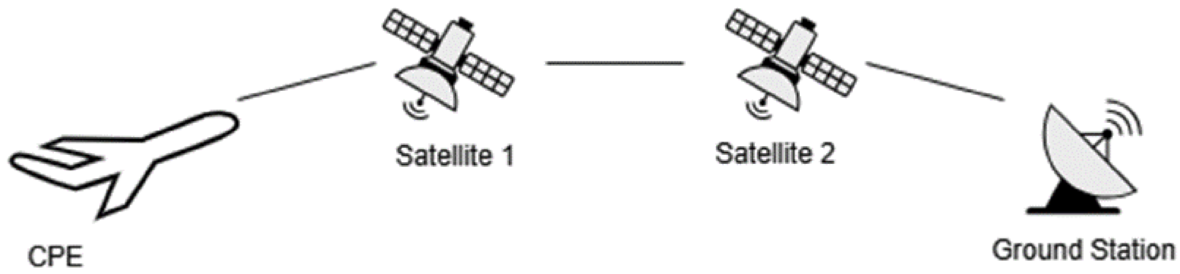
5.2 Functional Split

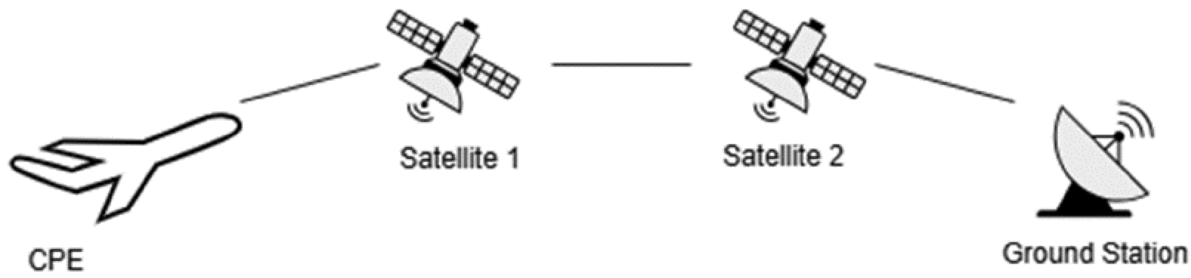
For the functional split, we are referring to the possibility to separately host the different functions from the gNB. A technology which was first introduced to separate the radio unit (RU) from the rest for better maintenance and power access. In general, but especially for NTNs, there are many split options under discussion. As reference, we take the ORAN split in Central Unit (CU), Distributed Unit (DU) and RU. The DU consists of the upper PHY, MAC, and RLC layer. Consequently, the DU includes PDCP and SCAP layers. Together, the CU, DU and RU comprise the full gNB stack. If considering the NexasSphere system architecture, there are different options for the placement of these units. In this report we present the different options; deeper investigations and a selection will be performed in WP3. Considering only the NTN part of the system, the main options for hosting gNB functionality can be narrowed down to the CPE, the satellites, and the ground station. The UE would need to connect either via the CPE or directly to the satellite in transparent or regenerative mode as specified by 3GPP releases 17, 18 and 19. Furthermore, it can be considered that in a LEO/MEO constellation there could be satellites offering different functionalities. We take into account satellite 1 and satellite 2 in the following, but it could be multiple satellites since, generally, a CU can serve multiple DUs. For direct connection of the UE, the CPE can be replaced by the UE in the following descriptions. However, the architectural options are the same, independently whether the CPE or the UE is served. Unless the CPE is serving as part of the base station.



Transparent	gNB	gNB	transparent

Figure 4-1: Reference scenario full gNB on-board satellite with ISL

Figure 4-1 shows the reference architecture with regenerative payload and the full gNB on-board the satellite. Illustrated is the case with ISL, so a hop via the two satellites, but this reference scenario also includes the case that one satellite is serving the CPE. This setup reflects release 19 from 3GPP.



transparent	transparent	transparent	gNB

Figure 4-2: transparent satellite and CPE with gNB on-ground

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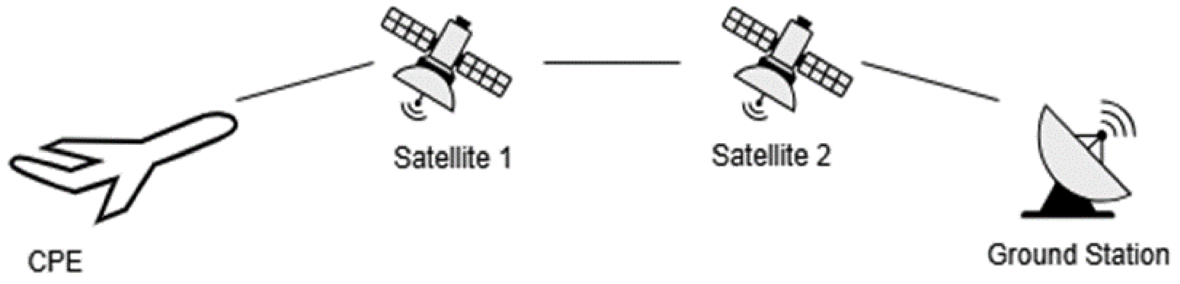
In Figure 4-2 the scenario for transparent satellite and CPE. A UE connecting to the 3GPP-relay on-board will be serviced by a gNB in transparent mode as specified in 3GPP Release 17. The gNB is hosted at the ground station.



DU	CU	transparent	transparent
DU	transparent	transparent	CU
transparent	DU	CU	transparent
transparent	DU	DU	CU
DU + CU (UP) + UPF	transparent	transparent	CU (CP)

Figure 4-3: functional split options

Figure 4-3 shows the various options for functional splits, the left column is dedicated to the option hosted at the CPE, second for satellite 1, third column for satellite 2 and last for the ground station. Each row represents and option for hosting the different functionalities. First is with the DU at the CPE where the CU then could be on-board a satellite (1) or with the ground stations (2). Another option is that the CPE is transparently forwarding the connection and the DU is on-board a satellite, and then, as before, the CU could be on-board a second satellite (3) or at the ground station (4). The last case that we have identified is to have at the CPE the DU and the User Plane (UP) part of the CU but keep the Control Plane (CP) part of the CU at the ground station (5). This enables a UPF on-board for Edge Computing but a shorter connection for the control flow towards the core.

Other options for the CPE 3GPP-relay block are 3GPP's integrated or wireless access backhaul (IAB and WAB).

It should be mentioned that in the case of TN-NTN multi-connectivity there is a parallel path that would allow for other split options. From an architecture perspective, we focus on those where the TN and NTN have a dedicated CU.

5.3 Options for optical links

Optical links can be deployed in a variety of places depending on the architecture as illustrated in Figure 5-1. To start with the user side, optical links may be deployed between CPE and the gNB. A CPE located on an aircraft benefits being above clouds in flight, increasing availability.

Within a gNB in case of a DU/CU split between two satellites, the satellites are connected via an optical link. Space-based gNBs are interconnected via optical links, including multi-orbit constellation scenarios.

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For feeder links between the core network on ground and a gNB on a satellite, optical links may be employed. Availability can be increased using time as well as site diversity, e.g. utilizing a network of ground stations at the cost of latency.

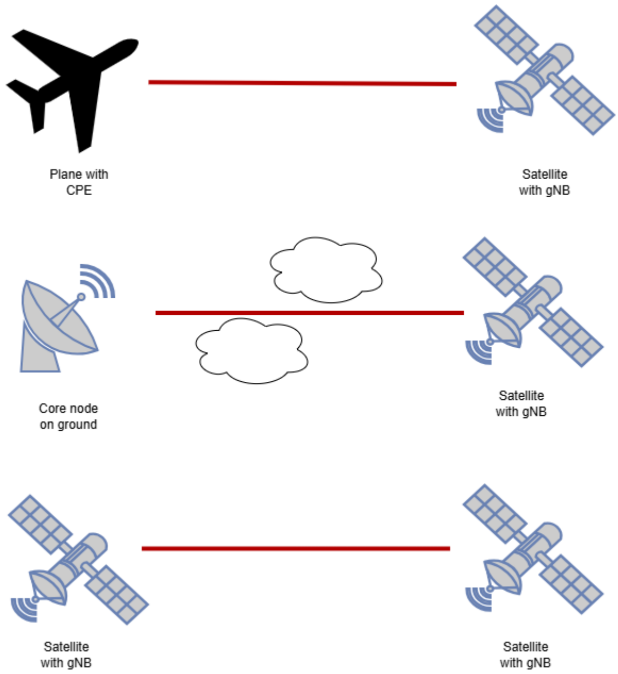

Figure 5-1: options for optical links configurations

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Section 6: Techno-Economic Analysis

The NexaSphere initiative fundamentally defines a requisite technological and architectural framework for advancing the 6G standardization roadmap and addressing the rapidly growing, yet historically unmet, demand for ubiquitous, high-performance network availability in remote geographical areas and dynamic, high-mobility environments [1]. The project's core output, the unified 6G Terrestrial Network (TN) and Non-Terrestrial Network (NTN) architecture, is not an optional luxury but an essential infrastructure convergence [1]. This convergence is mandated by the necessity to simultaneously support two challenging and historically divergent service categories across key European mobility sectors: mission-critical applications (demanding Ultra-Reliable Low-Latency Communication) and high-throughput services (enhanced Mobile Broadband, or eMBB) [5]. The systemic necessity of this TN/NTN unification is validated by its rigorous alignment International Telecommunication Union (ITU) IMT-2030 vision (Rec. ITU-R M.2160-0), which centrally features nine key pillars including ubiquitous connectivity, sustainability, security, resilience, and the critical objective of connecting the unconnected [1]. This framework establishes the foundation for future network evolution, mandating the incorporation of non-terrestrial components to achieve global reach and service continuity [1].The resulting 3D network topology is therefore positioned as a foundational element for future digital economic activity within the transport sector [6].

Quantified Investment

The deployment of a unified, three-dimensional (3D) network infrastructure, incorporating a multi-layered space segment of multi-orbit satellites (LEO, MEO, GEO, HAPS) [7] and multi-Radio Access Technology (RAT) components, inherently requires substantial upfront Capital Expenditure (CAPEX) [1]. However, the overall Total Cost of Ownership (TCO) is strategically mitigated by mandatory architectural efficiencies [1], principally through the adoption of AI-driven network orchestration and enhanced energy-efficiency mechanisms [8]. The long-term justification for this investment is rigorously quantified through the aggregation of anticipated Return on Investment (ROI) across three primary, high-impact economic vectors: first, verifiable safety monetization in the automotive sector (through quantifiable collision reduction) [9]; second, major operational efficiency gains, such as reduced aircraft Turnaround Time (TAT) in aviation and predictive maintenance enabled by ubiquitous IoT in railways [1]; and third, the generation of significant and expanding ancillary revenue from high-throughput passenger services like In-Flight Entertainment and Connectivity (IFEC), a market projected to experience robust Compound Annual Growth Rate (CAGR) [7].

6.1 Key Financial Findings

The platform's proven capability to meet the most stringent technical Key Performance Indicators (KPIs) directly translates into measurable and sustained economic benefits. For instance, successfully enabling reliable Cellular Vehicle-to-Everything (C-V2X) functionality through tight V2V latency control (targeting less than 20 ms in urban scenarios) has been empirically shown to reduce collision risk by up to 26% under conditions of high traffic density [9], yielding substantial societal ROI through avoided accident costs. The European automotive

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V2X market, central to this sector's exploitation, is projected to reach USD 2.0 billion by 2030, reflecting a CAGR of 42.1% [5],[10]. In the railway sector, mandatory compliance with the ≥ 99.999% reliability KPI for mission-critical operations not only satisfies stringent regulatory requirements but critically avoids catastrophic financial and safety incidents that would otherwise result from system failure [11]. The Future Railway Mobile Communication System (FRMCS) market, which the NexaSphere architecture supports, is projected to reach USD 1.45 billion by 2034 [6]. Lastly, the eMBB capabilities enable the system to directly access the rapidly expanding IFEC market, which is forecast to reach between USD 11.65 billion (CAGR 11.36%) and USD 24.2 billion (CAGR 12.5%) by the 2030/2034 period [10], structurally justifying the high-throughput network dimensioning.

6.2 Foundation of the Techno-Economic Model: Translating KPIs to Cost Drivers

This section establishes the analytical methodology for deriving non-linear economic consequences from the stringent technical requirements laid out in the D2.1 document. The techno-economic model is necessarily predicated on classifying NexaSphere's KPIs into standard 3GPP service classes, based on the principle that achieving the highest performance levels directly dictates network dimensioning, capacity costs and architectural complexity.

6.2.1 Performance Tiers in the 6G Ecosystem

NexaSphere's KPI set falls cleanly into two service families, LLC and eMBB each imposing its own engineering burdens and cost implications on a unified 6G design.

Low-Latency Communication (LLC)

LLC underpins mission- and safety-critical operations, from railway signaling (ETCS/ATO) to dense, cooperative driving maneuvers [1]. Meeting these requirements means aiming for exceptionally high assurance, commonly at 99.999% reliability or higher [5]. This reliability target is rigorously positioned within the IMT-2030 vision [7], [10], which mandates reliability levels ranging from $1\text{-}10^{-5}$ to $1\text{-}10^{-7}$ for critical applications. For Railway Critical Services (RLW-UC01), the bar is even clearer: availability and reliability of ≥ 99.999% with end-to-end latency targets of ≤ 100 ms, ultimately pushing toward 10 ms for the most critical traffic [1]. In urban settings, V2V exchanges (ATM-UC01) must stay below 20 ms to support immediate safety decisions [1]. These latency requirements are very challenging or not feasible with NTN delivered by space assets (). As such, delivering this deterministic performance consumes disproportionate resources and, as a result, is the dominant cost driver for the platform's critical domains [5].

Enhanced Mobile Broadband (eMBB)

eMBB speaks directly to high-capacity revenue opportunities in transport. In aviation, Joint Terrestrial–Satellite IFC (AVT-UC01) calls for total downlink rates above 850 Mbps per aircraft [1]. For premium IFE (AVT-UC03), per-user throughput should reach at least 30 Mbps to sustain 4K streams, with aggregate DL targets up to 2.8 Gbps [1]. Hitting those numbers requires resilient multi-link aggregation across heterogeneous layers: terrestrial networks, multi-orbit NTNs and in-cabin, non-3GPP options such as LiFi and Wi-Fi [1].

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6.2.2 The LLC Resource Cost Multiplier

The rigorous pursuit of ultra-high reliability (e.g., 99.999%) and low latency (e.g., 10 ms targets) is an intrinsically expensive engineering endeavor that imposes a non-linear economic penalty across the entire resource dimensioning of the network architecture [5]. To guarantee this level of performance, the system design must incorporate substantial resource over-provisioning and redundancy, frequently employing aggressive techniques such as multi-path transmission, highly granular scheduling (mini-slots) and increased control channel overhead [1].

The deployment of LLC reduces the available capacity for eMBB due to the necessity of reserved resources, frequent control signaling and redundancy inherent to meeting reliability constraints such as 99.999% [1]. Empirical analysis shows that dedicating resource allocation to LLC traffic produces a significant Capacity Reduction Factor (C_RF) for eMBB [1]. Specifically, serving 1 Mbps of LLC traffic can degrade potential eMBB throughput capacity by up to 60 Mbps [1], owing to the stringent timing constraints required to sustain high reliability. This finding indicates that LLC traffic is effectively up to 60 times more costly than traditional best-effort traffic in terms of spectral and capacity utilization, necessitating explicit inclusion of this C_RF parameter in the NexaSphere techno-economic model for accurate resource dimensioning.

6.2.3 Quantifying the Value of Seamless Connectivity and Availability

The economic viability of all high-mobility applications is critically dependent on demonstrating seamless service continuity and high availability. These factors translate directly into quantifiable avoided costs and safeguarded, predictable revenues.

The technical requirement for handovers to occur seamlessly and rapidly (e.g., < 1 s for aviation passenger links and < 1.5 s for railway critical links) is crucial to preventing service disruptions [1]. n railway operations, failure to meet the ≥ 99.999% availability KPI for ETCS/ATO signaling would result in mandatory operational stops, significant financial penalties and unacceptable safety risks [12]. The TN/NTN mobility management system (REQ-SER-020) functions as a critical insurance mechanism, ensuring service continuity across heterogeneous networks, multiple orbital layers (LEO, MEO, GEO) and extreme speed variations.

In the aviation domain, reliable connectivity with minimal interruptions directly underpins high Quality of Experience (QoE), which in turn sustains passenger satisfaction and protects the high-margin ancillary revenue streams associated with IFEC services [1],[5].

6.3 Infrastructure and Operational Cost Framework

Deploying a unified 6G architecture requires substantial investment in complex infrastructure. Its business case rests on cutting ongoing Operational Expenditure (OPEX) through integrated automation, so that the initial Capital Expenditure (CAPEX) is progressively offset by durable efficiency gains.

6.3.1 Unified TN/NTN 3D Architecture: Financial Modeling

NexaSphere relies on a layered space segment, GEO, MEO, LEO and HAPS, to deliver both global reach and low latency [1]. The investment analysis starts with CAPEX, treated as the sum of acquisition and deployment items:

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$$\text{CAPEX} = \text{Sites Costs} + \text{Sites Installation} + \text{Sites Backhaul}$$

In a unified terrestrial/non-terrestrial setup, CAPEX also splits into $\text{CAPEX}_{\text{NTN}}$ (satellites, launch, ground segment) and CAPEX_{TN} (towers, fiber/microwave backhaul). Although single LEO units are relatively inexpensive [1],[6], a very large constellation potentially ~50,000 active satellites, still drives substantial total program CAPEX.

TCO combines initial CAPEX with discounted OPEX over the lifetime TT:

$$\text{TCO} = \text{CAPEX} + \sum_{i=1}^{T} \frac{\text{OPEX}}{(1+r)^i}$$

Here, OPEX is year-i operating cost and r the discount rate. OPEX spans labor, energy, maintenance and facilities.

Net Present Value (NPV) as the Investment Test

Long-run viability is assessed via NPV, discounting projected cash flows (α_i) to present value. A positive Y supports the initial CAPEX:

$$Y = NPV = \sum_{i=1}^{T} \frac{OPEX_i}{(1+r)^i}$$

with $\alpha_i = \text{Revenue}_i - \text{OPEX}_i$ and r the discount factor. Using NTN where TN is cost-ineffective (REQ-SYS-070) elevates Revenue relative to OPEX_i improving the odds of a positive Y [1].

6.3.2 OPEX Optimization via AI-Driven Orchestration

A multi-link, multi-orbit network is operationally complex; intelligent automation (REQ-SER-010) is therefore central. OPEX covers recurring items such as site rent, maintenance, energy and staff.

AI as a TCO Mitigator

The operation of a system involving seamless TN/NTN handover (REQ-SER-020) and dynamic resource allocation across complex transport verticals could be prohibitively expensive [1]. Investment in AI orchestration lowers OPEX directly. Operator spend on AI for network control is projected to reach USD 20 billion by 2028 [8], driven by the push to cut operating costs [5],[6]. These tools automate predictive maintenance, advance network automation and optimize resources in real time [6],[7], simplifying operations and lowering TCO versus proprietary legacy stacks[6],[8]. Furthermore, the reliance on AI-driven orchestration directly supports the IMT-2030 [6],[10], sustainability pillar by minimizing network energy consumption through efficient resource management.

6.3.3 Monetizing Energy Efficiency and Sustainability (REQ-PER-060)

Energy use is both a sustainability goal and a major OPEX lever [7]. NexaSphere targets at least a 20% improvement in energy efficiency (bit/J) for in-cabin access networks (AVT-UC05), directly reducing OPEX (REQ-PER-060) [1]. Gains come from more efficient transceivers, architectural refinements[1] and potentially ultra-low-power neuromorphic AI in the RAN. The

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resulting power savings compound over the system lifetime [8], aligning with the IMT-2030 sustainability pillars.

In rail, the aim is > 5 years of autonomous operation for millions of low-power IoT devices (RLW-UC03), which sharply cuts OPEX by limiting site visits and battery replacements [1].

6.4 Aviation Vertical: High-Throughput Connectivity and Ancillary Revenue

The strategic focus in aviation is the monetization of a superior and resilient passengers' experience, combined with verifiable operational efficiency gains enabled by meeting aggressive eMBB KPIs across all phases of flight.

6.4.1 IFEC Market Sizing and Revenue Potential

The In-Flight Entertainment and Connectivity (IFEC) market represents a major revenue stream and the primary justification for NexaSphere's high-throughput architecture. This sector is expanding rapidly, supported by the projection that global passenger traffic will double by 2040 [6],[9]. The global IFEC market is forecast to reach between USD 11.65 billion (CAGR 11.36%) and USD 24.2 billion (CAGR 12.5%) by the 2030–2034 period [10].

The high-capacity systems developed under NexaSphere, engineered to support 4K video streaming and deliver over 850 Mbps per aircraft (AVT-UC01) [1], are tailored to capture the premium market segment, where passengers' willingness to pay is closely tied to superior Quality of Experience (QoE) [1],[5].

Technical Requirement Justification (eMBB)

To secure this growing market share, the system must provide seamless, high-bandwidth service exceeding conventional connectivity standards. The KPI requirement for a total downlink rate above 850 Mbps per aircraft (AVT-UC01) and a minimum of 30 Mbps per user for 4K streaming (AVT-UC03) is essential to sustaining premium-tier offerings [1]. Passenger willingness to pay for in-flight connectivity correlates directly with the QoE of data-intensive applications [1], [5], making high throughput and uninterrupted service (handover duration < 1 s) prerequisites for premium IFEC monetization and competitive airline differentiation [1],[5].

6.4.2 Value of Seamless Multi-Connectivity (AVT-UC01, AVT-UC02, AVT-UC03)

NexaSphere's aviation advantage is built on architectural resilience through seamless multi-connectivity, an approach that demonstrably outperforms single-LEO architectures [6].

Competitive Differentiation and Resilience

The platform integrates TN, multi-orbit NTN (LEO, MEO, GEO), non-3GPP links (e.g., DVB-S2X) and high-capacity in-cabin LiFi/Wi-Fi aggregation (AVT-UC03).[1] This multi-layered design ensures continuous service (REQ-PER-010) and minimizes interruption, with handover KPIs constrained to less than 1 sec when transitioning between TN and NTN links or between in-cabin technologies [1].

This built-in redundancy guarantees global coverage (REQ-SYS-040) and high availability (> 98%) [1], translating technical resilience into protected ancillary revenue streams and reinforcing a strong competitive market position [1],[9].

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6.4.3 Economic Value of Operational Efficiency (AVT-UC04, AVT-UC05)

Operational efficiency delivers long-term OPEX savings, reduced time on ground and improved fleet utilization. The KPI target of downlink/uplink rates exceeding 10 Gbps when the aircraft is parked at the gate (AVT-UC04) is essential for rapid data transfer, including diagnostics and large-scale software updates [1].

Such high-speed transfer capability directly reduces Aircraft Turnaround Time (TAT), a primary driver of airline profitability and scheduling flexibility. By shortening TAT, airlines can increase fleet availability and operational capacity [1],[9]. Additionally, the targeted 20% increase in energy efficiency (AVT-UC05, REQ-PER-060) reduces the energy costs associated with in-cabin digital systems during long-haul operations, delivering continuous OPEX savings [1],[8].

The strategic focus in aviation is the monetization of superior passenger experience and operational efficiency, enabled by meeting aggressive eMBB KPIs across all phases of flight.

6.5 Automotive Vertical: Safety, Automation and Scalability

Investment in pervasive LLC capabilities underpins the automotive strategy by enabling safer, higher levels of automated driving (SAE L4/L5) and converting technical performance into measurable economic and societal ROI. By delivering deterministic, low-latency communication at scale, LLC supports reliable perception exchange, coordinated maneuvering and fail-operational behavior across diverse traffic conditions, strengthening the case for advanced driver assistance and autonomous mobility services.

6.5.1 C-V2X and Autonomous Driving Market Trajectory

The momentum behind LLC investment is reinforced by the rapid expansion of the Vehicle-to-Everything (V2X) ecosystem. Market projections place the global automotive V2X segment as high as USD 155.17 billion by 2030, propelled by compound growth rates exceeding 40% [1],[10]. Within Europe, NexaSphere's primary geography, the market is expected to reach USD 2.0 billion by 2030, supported by a 42.1% CAGR and underpinned by regulatory alignment, spectrum policy and OEM deployment roadmaps [5][10]. Cellular V2X (C-V2X) remains the leading connectivity path as manufacturers and operators converge on standards-based, scalable platforms that enable automated driving features and enhanced safety functions [1],[10]. NexaSphere is designed to meet this demand with seamless, resilient connectivity that maintains performance across mixed coverage, cross-border mobility and high-density traffic, conditions that typically stress conventional systems [1],[11].

6.5.2 Quantifying the Societal ROI of Safety KPIs (ATM-UC01, ATM-UC02)

The strongest rationale for adopting stringent LLC KPIs is safety monetization: reducing the social and economic burdens of road incidents through dependable, low-latency coordination [1],[6]. Safety-critical applications, such as Cooperative Driving Maneuvers and Connected Automated Passenger Cars (ATM-UC01), require ultra-low and predictable latency to guarantee deterministic actuation and timely hazard response [5]. In urban environments, V2V latency must stay below 20 ms to enable immediate collision-avoidance behaviors, while end-to-end service latency needs to remain under 100 ms even in dense conditions (up to 12,000 vehicles/km^2) [1]. Meeting these thresholds translates into measurable outcomes: empirical studies attribute a 26% reduction in collision risk to C-V2X deployments, alongside a 12% decrease in traffic conflicts [9]. By providing ubiquitous connectivity with reliability above 95%

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[1], NexaSphere converts technical assurance into tangible societal ROI, avoided crashes and medical costs, lower congestion and delay and reduced insurance and enforcement expenditures, effects that compound as penetration rates increase [10].

6.5.3 NTN as an Enabler for Operational Design Domain (ODD) Extension (ATM-UC02, ATM-UC03)

Extending the Operational Design Domain beyond metropolitan cores and major corridors requires continuity of service in locations where terrestrial coverage is sparse or intermittent. Integrating NTN is therefore essential to broaden safe operations into rural and remote areas and along less-served routes [1], [12]. With NTN in place, safety-critical alerts like Hazardous Location Warning (ATM-UC02) and urgent over-the-air software/map updates (ATM-UC03) are delivered consistently, sustaining functional safety and cybersecurity posture throughout the fleet [1]. This universal reliability mandate (REQ-SYS-040) elevates the practical and commercial value of SAE L4 vehicles by ensuring that essential services remain available regardless of geography, weather, or network load, an indispensable differentiator for true L4 autonomy and for scaling autonomous mobility from pilot zones to nationwide coverage [1].

6.5.4 In-Vehicle Entertainment (IVE) Monetization (ATM-UC05)

In-Vehicle Entertainment (IVE) leverages the high-capacity eMBB layer of the integrated TN/NTN architecture to create recurring revenue streams that complement the safety-centric LLC foundation [1]. To satisfy user expectations for immersive media, IVE requires sustained high throughput, at least 100 Mbps downlink per vehicle, with a 1 Gbps goal and moderate latency near 20 ms to support multi-user 4K video, responsive online gaming and VR/XR experiences [1]. This performance envelope supports concurrent, high-quality sessions for up to four occupants in private vehicles and up to thirty passengers in buses and shuttles, ensuring graceful scaling with cabin size and user concurrency [1]. In practice, these capabilities enable tiered bandwidth plans, subscription bundles and content partnerships that increase lifetime revenue per vehicle while reinforcing brand differentiation across trims and service levels.

6.6 Railway Vertical: Mission-Critical Integrity and Digital Transformation

The railway domain is undergoing a decisive modernization wave in which regulatory mandates, long-horizon capital stewardship and day-to-day operational improvement all reinforce one another. At the core of this shift are stringent LLC requirements that dictate how systems are engineered, validated and operated. These technical baselines are not abstract targets: they anchor safety assurance, underpin interoperability across borders and vendors and protect multi-decade investments by ensuring the network can scale in capacity and functionality without repeated rip-and-replace cycles.

6.6.1 FRMCS Rollout: Compliance and Market Size

Across Europe, the mandated transition from GSM-R (2G) to the 5G-based Future Railway Mobile Communication System (FRMCS) is moving from policy to implementation, with national rollouts expected between 2030 and 2032 [6],[8]. This migration constitutes a structured, time-bound market with clear procurement milestones. In value terms, the global FRMCS market is estimated at USD 365 million in 2024 and is projected to reach USD 1.45 billion by 2034, implying a sustained CAGR of 14.8% [7]. Beyond radio access, the program

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catalyzes adjacent upgrades, signaling integration, cybersecurity hardening, life-cycle asset management and hybrid TN/NTN backbones, that collectively raise the reliability bar for critical rail services.

NexaSphere is tightly aligned with 3GPP specifications (REQ-SYS-090) and is positioned to capture this demand through a resilient TN/NTN architecture [5],[7]. The approach emphasizes end-to-end compatibility with railway safety processes while retaining flexibility in vendor selection and deployment phasing. In practice, this means operators can introduce capabilities in measured increments (corridor by corridor, function by function) without jeopardizing interoperability or service continuity.

Technical Justification (LLC)

Safety-critical applications, European Train Control System (ETCS) and Automatic Train Operation (ATO), impose exacting performance thresholds: reliability ≥ 99.999%, availability ≥ 99.999% and end-to-end latency ≤ 100 ms, with a 10 ms ambition for the most critical traffic.[1] The unified TN/NTN design (RLW-UC01) sustains these KPIs through multi-connectivity, deterministic scheduling and rapid failover, maintaining service even at train speeds up to 500 km/h [1]. Consistently hitting these benchmarks is essential not only for regulatory conformity but also for maintaining the operational headroom needed to absorb traffic peaks, service perturbations and maintenance windows without compromising safety [12].

6.6.2 Economic Value of Multi-Connectivity Resilience

From an operator's balance-sheet perspective, resilience converts directly into avoided losses and stabilized service quality. The critical KPI for handover, the ability to switch links in < 1.5 s with no session drop for mission-critical traffic, prevents communication gaps that can cascade into braking interventions, timetable dislocations and penalty exposure [1]. In parallel, consistent connectivity enables centralized traffic management, continuous video/telemetry feeds and remote diagnostics to function as intended, reducing incident duration and recovery costs.

Investment Protection and Standardization

Adherence to 3GPP standards (REQ-SYS-090) [1] is a deliberate hedge against vendor lock-in, a recurrent issue with proprietary stacks [5],[6]. Standards-based interfaces preserve FRMCS CAPEX by ensuring multi-vendor interoperability, fostering competition and enabling incremental upgrades instead of wholesale replacement [5],[6]. This standardization also smooths the path to future enhancements, new radio releases, 6G NTN extensions and AI-assisted orchestration, so operators can evolve capabilities over a 20–30-year asset life while keeping integration risk and cost under control.

6.6.3 ROI of Ubiquitous IoT Integration (RLW-UC03)

Railway infrastructure spans long linear assets, track, catenary, switches, bridges, tunnels and mobile fleets that together demand constant situational awareness. Meeting this need requires ultra-dense sensing: more than 2,000 devices per kilometer of track for real-time diagnostics and condition monitoring [1]. NexaSphere targets autonomous operation beyond five years for low-power NTN/TN IoT nodes, a cornerstone of OPEX reduction (REQ-PER-140) [1]. Longevity

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at the edge drastically cuts truck rolls and battery replacements, the two largest drivers of field maintenance cost.

With these foundations, operators can shift from periodic or reactive maintenance to predictive regimes in which faults are identified early, interventions are precisely timed and asset life is extended. The financial upside is twofold: direct savings (labor, parts, access logistics) and indirect gains (higher availability, fewer service disruptions, better energy usage) [1]. Over time, these effects compound, freeing budget for targeted capacity upgrades and safety enhancements, while preserving compliance and service quality across the network.

6.7 Strategic Conclusions and Exploitation Roadmap

The analysis demonstrates, beyond theoretical argument, that the business case for high-value, mission-critical services hinges on wide-area reach and engineered redundancy. In practice, the ability to deliver LLC for railway safety and automotive autonomy depends on the unified 6G TN/NTN fabric providing ubiquitous coverage and resilient fallback paths [6]. The solution's complexity, spanning multi-orbit assets (LEO/MEO/GEO/HAPS) and coordinated multi-RAT integration, is not an indulgence but a response to the sheer scope and value of the safety and digital markets now converging across the transport sector. By binding these layers into a single, orchestrated platform, the architecture guarantees hyper-connectivity and continuity of service under diverse operating conditions, elevating NTN from a supplemental pathway to an indispensable pillar of the future 6G ecosystem [7].

6.7.1 Addressing the Cost of LLC

LLC's promise carries a real economic weight: delivering deterministic latency and extreme reliability can impose a capacity resource cost multiplier of up to 60× versus best-effort traffic [1]. Left unmanaged, this penalty would erode margins. The platform addresses it on two fronts. First, architectural resilience, multi-connectivity, path diversity and intelligent admission control, reduces over-provisioning by ensuring that resources are applied precisely where and when they are needed. Second, mandated AI-driven orchestration (REQ-SER-010) automates functions such as resource allocation and mobility management [5],[10], trimming OPEX while extracting higher effective spectral efficiency from the same bandwidth footprint, supporting a favorable NPV trajectory over the asset life.

Crucially, the value side of the ledger is both large and demonstrable. Safety outcomes such as a 26% reduction in collisions[6] and ≥ 99.999% reliability for critical train signaling [1] convert directly into avoided losses, fewer incidents, reduced disruption, lower claims and diminished penalty exposure. When these avoided costs are accounted for alongside operational gains, the ROI offsets the high technical barrier inherent to LLC delivery. In parallel, industry investment in AI orchestration, projected to reach roughly USD 20 billion by 2028, signals broad consensus that automation is essential to long-term TCO viability.

6.7.2 Recommendations for Standardization and Policy

Maximizing commercial reach and ensuring durable economics requires a sustained push on standards and policy. Standards bodies (3GPP, UIC, 5GAA) should continue to harden global interoperability and streamline regulatory frameworks so that TN/NTN integration and spectrum sharing proceed without friction (REQ-SYS-080) [5],[7]. Policy guidance ought to prioritize mandatory adoption of 3GPP-compliant systems, including the FRMCS successor to

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GSM-R [1],[7]. to avoid fragmented deployments and to simplify cross-border operation [5],[7]. The project's commitment to 3GPP and IT standards is crucial, as the IMT-2030 vision [6],[10] explicitly requires high interoperability for the successful deployment of a unified 6G ecosystem.

This path is also a hedge against historical pitfalls: strict conformance to open standards protects substantial future CAPEX from proprietary lock-in, ensures multi-vendor competition at procurement time and lowers lifecycle integration risk as networks evolve [5],[6]. The result is a more contestable market with clearer upgrade paths, healthier pricing and faster time-to-value for critical infrastructure.

6.7.3 Exploitation Roadmap

The quantitative technical KPIs, together with the derived financial and market models assembled in this analysis, form the working baseline for subsequent NexaSphere work packages. They will continue to inform the definitive System Architecture and Interface Specification, ensuring that interfaces, performance envelopes and assurance mechanisms align with the economic reality of deployment and operation. In turn, these same metrics will feed the final, comprehensive socio-economic impact assessment (D2.3), which consolidates technical performance, addressable market and cost structures into an integrated justification. The outcome is an evidenced projection of ROI for the unified 6G TN/NTN investment, anchored in measurable KPIs, consistent with standardization roadmaps and aligned with policy objectives.

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Section 7: Conclusion

This deliverable presents the preliminary NEXASPHERE system architecture. It is following the 3GPP system specifications where possible and extends it towards NTN-TN integration. The design should be able to address the use cases from D2.1 on aviation, automotive and railway presented in D2.1 [1]. Passengers can connect directly via 3GPP systems or via the CPE on-board trains and airplanes which provide connectivity and other services. Airplanes, cars and trains are also included as users of the system accessing services directly.

The main elements of the NexaSphere system have been identified including their main functionality. The interfaces among the different elements are specified on a high level. In-depth analyses will continue in the technical work packages and feedback the updates to the architecture. These developments will also reveal if updates are necessary in the second iteration of this deliverable. The second iteration on our MBSE approach more details on the functions are expected to be included and an update of the requirements will be prepared.

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Annex: NexaSphere System Requirements

Table 0-1: NexaSphere System Requirements full collection

Requirement Type	Requirement ID	Title	Requirement Description	Applicable to
System Requirement	REQ-SYS-010	Unified TN/NTN architecture	The NexaSphere System shall integrate Non-Terrestrial Networks (NTN) and Terrestrial Networks (TN) under a unified and standardized architecture	All UCs
Performance Requirement	REQ-SYS-020	NTN European coverage	The NexaSphere NTN shall achieve 100% coverage of European territory	All UCs
Performance Requirement	REQ-SYS-030	NTN European availability	The NexaSphere NTN shall provide 99.9% (TBC) service availability across the European territory for end-user connections.	All UCs
Performance Requirement	REQ-SYS-040	NTN global coverage	The NexaSphere NTN shall achieve 99.9% (TBC) coverage over the full Earth. Note: For aviation use cases	All UCs
Performance Requirement	REQ-SYS-050	NTN global availability	The NexaSphere NTN shall achieve an availability of 99.99% (TBC) over the full Earth	All UCs
System Requirement	REQ-SYS-060	Legacy devices	The NexaSphere Radio Access Network shall be accessible by Legacy devices (smartphones, laptops, etc.) Note: In case of non-radio (e.g. wireless optics) Access Network the legacy device might use external peripherals to access the network.	All UCs
System Requirement	REQ-SYS-070	Multi-Connectivity (TN/NTN) Network Support	Trains and aircrafts within the NexaSphere system shall provide user access via both Terrestrial Networks (TN) and Non-Terrestrial Networks (NTN).	

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to
System Requirement	REQ-SYS-080	System scalability	The NexaSphere System shall be designed to support: -Variable traffic demand in both space and time -A multi-layered space and air segment including GEO, MEO, LEO and HAPS -Interoperability with existing Satellite Systems -Interoperability with Terrestrial Networks (including spectrum sharing and interference coordination) -Regional regulatory compliance	All UCs
System Requirement	REQ-SYS-081	NTN GEO	The NexaSphere NTN system shall include GEO satellite(s)	All UCs
System Requirement	REQ-SYS-082	NTN MEO	The NexaSphere NTN system shall include MEO satellites	All UCs
System Requirement	REQ-SYS-083	NTN LEO	The NexaSphere NTN system shall include LEO satellites	All UCs
System Requirement	REQ-SYS-084	NTN HAPS	The NexaSphere system shall include High Altitude platforms	All UCs
System Requirement	REQ-SYS-085	Interoperability legacy satcom	The NexaSphere system shall be interoperable with legacy satellite systems (e.g. DVB-S2X)	All UCs
System Requirement	REQ-SYS-086	interoperability terrestrial networks	The NexaSphere system shall be interoperable with Terrestrial Networks (including spectrum sharing and interference coordination)	All UCs
System Requirement	REQ-SYS-087	Regulation	The NexaSphere system shall comply with regional regulatory compliance	All UCs
System Requirement	REQ-SYS-090	3GPP interface	The NexaSphere System shall implement 3GPP-compliant interfaces to enable integration with 5G/6G core networks.	

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to
System Requirement	REQ-SYS-100	Edge computing	The NexaSphere System shall support deployment of edge computing functions in both TN and NTN segments to reduce latency and optimize data flow.	All UCs
Service Requirement	REQ-SER-010	Autonomous network orchestration	The NexaSphere System shall implement autonomous functions for network management and orchestration based on dynamic traffic conditions, mobility, and QoS requirements. Note: such functions may include predictive models, AI-based algorithms, SDNs, etc.	All UCs
Service Requirement	REQ-SER-020	Seamless TN/NTN handover	The NexaSphere System shall support unified mobility management (handovers) without service interruption for mobile users between: 1) TN and NTN 2) Multiple elements of the NTN	All UCs
Service Requirement	REQ-SYS-030	Multi-connectivity network support	The NexaSphere System shall support mechanisms that allow the integration of existing satellite waveforms for backhauling.	All UCs
Service Requirement	REQ-SER-040	Service reliability for critical services	The NexaSphere System shall provide a reliability no lower than 99.9999% for Railway Critical Services. Note: Railway Critical Services are specified in 3GPP TS 22.289 V18.0.1	All RLW UCs
Service Requirement	REQ-SER-050	Multi-connectivity (3GPP/non-3GPP) network support for user link	The NexaSphere System shall support mechanisms that allow the use of non-3GPP links (WiFi, LiFi) beside the 3GPP compliant links for the user service link.	All AVT+RLW UCs
Performance Requirement	REQ-PER-010	Aviation applications performances	The NexaSphere System shall provide connectivity to airplanes during all their flight phases ensuring the following performances per single plane: -Total DL > 850 Mbps (aggregated) -Total UL > 85 Mbps (aggregated) Service availability > 98% Service interruption due to handover between TN and/or NTN < 1 sec	All AVT UCs

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to
Performance Requirement	REQ-PER-020	Non-3GPP fallback connectivity	The NexaSphere System shall be able to provide non-3GPP fallback connectivity (e.g. DVB) to aircrafts ensuring a service interruption due to handover no greater than 1 sec with a service availability greater than 98%	All AVT UCs
Performance Requirement	REQ-PER-030	Aviation joint connectivity for on-board entertainment	The NexaSphere System shall be able to deliver on-board entertainment content to users on aircrafts aggregating multiple sources (e.g. WiFi + LiFi) with the following performances per user: -Service Availability > 99% -DL rate > 30 Mbps -UL rate > 10 Mbps -Handover time < 1 sec Note: for aggregated figures assume a total of 450 users, a vehicle load factor of 85% and a take rate of 25%.	ATM-UC03
Performance Requirement	REQ-PER-040	Joint connectivity for gate data transfer	The NexaSphere System shall be able to transfer content from the airport gate to the aircraft CPE aggregating multiple sources (e.g. WiFi + LiFi) achieving the following performances: -Service Availability > 99% -DL/UL rate (when parked) > 10Gbps -DL/UL rate (when un-parked (taxi, landing, take-off)) > 100Mbps	ATM-UC04
Performance Requirement	REQ-PER-060	Resource optimization for in-cabin access networks	The IFC of aircrafts shall be able to orchestrate the in-cabin connectivity parameters for direct user access achieving as a minimum: 20% increase in energy efficiency (bit/Joule) compared to existing solutions (target)	ATM-UC05

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to
Performance Requirement	REQ-PER-070	Support connected automated passenger cars in urban scenario	The NexaSphere System shall provide vehicle connectivity in Urban scenarios considering the following performance requirements: -Vehicle density: 12000 vehicles/km2 -UL rate: 16 Mbps per single vehicle -DL rate: 80 Mbps per single vehicle -Vehicle-to-Vehicle Latency: < 20 ms -End-to-End Service Latency: < 100 ms -Reliability: > 95% at 500 m Note: Unless specific traffic models are available, the capture rate in urban scenario can be estimated as 95% from TN and 5% from NTN with a total vehicle density of 12000 vehicles/km2	ATM-UC01
Performance Requirement	REQ-PER-080	Automotive applications performances in rural and suburban areas	The NexaSphere System shall provide vehicle connectivity in rural and suburban areas ensuring the following performances: -UL rate: 15 Mbps per single vehicle -DL rate: 15 Mbps per single vehicle -Service Latency: < 50 ms -Service Availability > 99.9% Note: Unless specific traffic models are available, it can be assumed a vehicle density of 5000 vehicles/km2 on highways and 9000 vehicles/km2 on rural roads.	

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to
Performance Requirement	REQ-PER-100	Support in-vehicle entertainment (IVE)	The NexaSphere System shall provide vehicle connectivity in rural and suburban areas ensuring the following performances: -UL rate: 40 Mbps per single vehicle -DL rate: 100 Mbps per single vehicle (goal 1 Gbps for 4 simultaneous users in a vehicle) -Service Latency: < 150 ms (goal 20 ms) -Service Availability > 90% (goal 99%) Note: Unless specific traffic models are available, it can be assumed a vehicle density of 5000 vehicles/km2 on highways and 9000 vehicles/km2 on rural roads.	ATM-UC05
Performance Requirement	REQ-PER-110	Railway critical applications performances	The NexaSphere System shall be able to achieve the following performances for railway critical applications (video/voice/data) per train: -Total DL > 2 Mbps -Total UL > 2 Mbps -Reliability > 99.999% -Availability > 99.999% -Latency < 100 ms (goal 10 ms for very critical traffic) -Handover time < 1.5 seconds without session drop Note: Unless specific traffic models are available, it can be assumed a traffic area density of 1 Gbps/km of rail and a train speed of < 500 km/h	RLW-UC01

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to
Performance Requirement	REQ-PER-120	Railway business and performance applications performances	The NexaSphere System shall be able to achieve the following performances for railway business and performance applications per train: -Total DL > 100 Mbps (aggregated) -Total UL > 100 Mbps (aggregated) -Latency < 500 ms -Reliability > 99.9% Service interruption due to handover: tolerant to short disruptions without data loss	RLW-UC01
Performance Requirement	REQ-PER-130	Ultra Low latency decision making for Railway high-speed environments	The NexaSphere System shall be able to manage and orchestrate the traffic using predictive models based on railway historical data to achieve ultra-low latency decision making in high-speed environments.	
Performance Requirement	REQ-PER-150	Railway joint connectivity for on-board entertainment	The NexaSphere System shall be able to deliver on-board entertainment content to users on trains aggregating multiple sources (e.g. WiFi + LiFi) with the following performances: Service Availability > 99% DL rate > 10 Mbps UL rate > 2 Mbps Handover time < 1 sec Note: for aggregated figures assume a total of 450 users, a vehicle load factor of 85% and a take rate of 25%.	ATM-UC04
System Requirement	EQ-SYS-110	Switch or aggregated access technologies	The NexaSphere system shall switch between or aggregate different user access technologies to optimize content delivery based on real-time link conditions	All UCs

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to
System Requirement	EQ-SYS-120	Power usage on airplane	The NexaSphere system shall optimize the power usage of the communication on-board an airplane	ATM-UC05
System Requirement	EQ-SYS-140	Optimize Resource allocation	The NexaSphere system shall optimize network resource allocation	All UCs
System Requirement	EQ-SYS-150	reduce costs using orchestration and resource management	The NexaSphere system shall Reduce operational costs through real-time network orchestration and automated resource management.	All UCs
System Requirement	EQ-SYS-160	Cross-border transitions	The NexaSphere system shall support seamless cross-border transitions	RLW-UC02
System Requirement	EQ-SYS-170	spectrum reconfigurability	The NexaSphere system shall be able to reconfiguration the used spectrum in real-time to optimize efficiency	RLW-UC02
System Requirement	REQ-SYS-180	Traffic orchestration based on prediction	The NexaSphere System shall be able to manage and orchestrate the traffic using predictive models based on railway historical data to achieve ultra-low latency decision making in high-speed environments.	RLW-UC02
Service Requirement	REQ-SER-060	Passenger connectivity train and airplane	The NexaSphere system shall provide access to passengers on trains and aircraft via both Terrestrial Networks (TN) and Non-Terrestrial Networks (NTN).	All UCs
Service Requirement	REQ-SER-070	3GPP compliant	The NexaSphere System shall be built on existing 3GPP specifications where applicable	All UCs
Service Requirement	REQ-SER-080	3GPP RAN	The NexaSphere System shall provide radio access via 3GPP RAN	All UCs
Service Requirement	REQ-SER-090	3GPP NTN	The NexaSphere System shall provide access via 3GPP NTN	All UCs

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to
Service Requirement	REQ-SER-100	3GPP Terrestrial Networks	The NexaSphere System shall provide access via 3GPP Terrestrial Network	All UCs
Service Requirement	REQ-SER-110	Support non-3GPP access	The NexaSphere System shall allow access via non-3GPP access technologies, i.e. WiFi, LiFi, legacy SatCom	All UCs
Service Requirement	REQ-SER-120	Cabin connection	The NexaSphere system shall provide on-board airplane cabins equipment means to access the network services	AVT-UC03
Service Requirement	REQ-SER-130	Passenger connectivity	The NexaSphere system shall provide access means to passengers on-board trains and airplanes	All AVT+RLW UCs
Service Requirement	REQ-SER-140	UE seamless connectivity	The NexaSphere system shall provide seamless connectivity via the different access technologies directly for the UE	All UCs
Service Requirement	REQ-SER-150	Continuous access	The NexaSphere system shall provide continuous network access for airplanes during their operation	All AVT UCs
Service Requirement	REQ-SER-160	V2N support	The NexaSphere system shall enable V2N connections to support V2X communication	ATM-UC01
Service Requirement	REQ-SER-170	Mission critical service support	The NexaSphere system shall provide mission critical services	RLW-UC01
Service Requirement	REQ-SER-180	Hazardous location warnings	The NexaSphere system shall support the distribution of hazardous location warnings	ATM-UC02
Service Requirement	REQ-SER-190	Simultaneous access	The NexaSphere system shall allow to simultaneously access different access technologies	All UCs
Service Requirement	REQ-SER-200	Simultaneous access NTN and TN	The NexaSphere system shall allow to simultaneously access 3GPP NTN and 3GPP TN	All UCs

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Requirement Type	Requirement ID	Title	Requirement Description	Applicable to
Service Requirement	REQ-SER-210	minimize latency	The NexaSphere system shall provide predictive analytics to minimize latency	RLW-UC02

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Annex: Interface Specification

7.1 User

Table 0-1: Interface specification user

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → Multi-Connectivity	Data Flow	Socket (ATSSS)	Bytes	From Application Layer, data passes through Socket API (interface to Transport Layer), and than toward IP layer. ATSSS module intercepts data and choses the link in which transmit
FOP 2 → 5G-NR	Data Flow			
FOP 3 → 5G-NR	Control Flow			
FOP 4 → Multi-Connectivity	Control Flow	Socket (ATSSS)	Bytes	From Application Layer, data passes through Socket API (interface to Transport Layer), and than toward IP layer. ATSSS module intercepts data and choses the link in which transmit
FIP 1 ← Multi-Connectivity	Data Flow	Socket (ATSSS)	Bytes	From Application Layer, data passes through Socket API (interface to Transport Layer), and than toward IP layer. ATSSS module intercepts data and choses the link in which transmit
FIP 2 ← 5G-NR	Data Flow			
FIP 3 ← 5G-NR	Control Flow			
FIP 4 ← Multi-Connectivity	Control Flow	Socket (ATSSS)	Bytes	From Application Layer, data passes through Socket API (interface to Transport Layer), and than toward IP layer. ATSSS module intercepts data and choses the link in which transmit

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7.2 Second B5G Core

Table 0-2: : Interface specification second B5G-core

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → gNodeB	Data Flow	3GPP-N3	User data packets (e.g., IP packets, voice, video, etc.)	Protocol: GTP-U over UDP/IP
FOP 2 → gNodeB	Control Flow	3GPP-N2	Control plane messages	Protocol: NGAP over SCTP/IP
FOP 3 → Data Network	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FOP 4 → Multi-Connectivity	Data Flow	IP or N9	IP packets	MultiAccess UPF: N9 (ATSSS); Via DN -> IP (Proxy or ATSSS)
FOP 5 → Management and Orchestration	Management Flow	3GPP-N5 Management	Control plane messages Management messages	Protocol: RESTful APIs (HTTP/2, JSON) Protocol: RESTful APIs (HTTP/2, JSON)
FOP 6 → Multi-Connectivity	Control Flow	3GPP-N4	N4 Format	Control Plane
FIP 1 ← gNodeB	Data Flow	3GPP-N3	User data packets (e.g., IP packets, voice, video, etc.)	Protocol: GTP-U over UDP/IP
FIP 2 ← gNodeB	Control Flow	3GPP-N2	Control plane messages	Protocol: NGAP over SCTP/IP
FIP 3 ← Data Network	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FIP 4 ← Multi-Connectivity	Data Flow	IP or N9	IP packets	MultiAccess UPF: N9 (ATSSS); Via DN -> IP (Proxy or ATSSS)

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FIP 5 ← Management and Orchestration	Management Flow	3GPP-N5 Management	Control plane messages Management messages	Protocol: RESTful APIs (HTTP/2, JSON) Protocol: RESTful APIs (HTTP/2, JSON)
FIP 6 ← Multi-Connectivity	Control Flow	3GPP-N4	N4 Format	Control Plane

7.3 Data Network

Table 0-3: Interface specification data network

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → 5G-Core Multi-Connectivity	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FOP 2 → 5G Core	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FOP 3 → Edge Cluster	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FIP 1 ← 5G-Core Multi-Connectivity	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FIP 2 ← 5G Core	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FIP 3 ← Edge Cluster	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP

7.4 5G-NR

Table 0-4: Interface specification 5G-NR

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → Antenna	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly

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FOP 2 → Antenna	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FOP 3 → Multi-Connectivity	Data Flow	PDU / Uu (5G-NR)	PDU	Allows connection between UE and CPE via NR
FOP 4 → 3GPP-Relay	Data Flow			
FOP 5 → Multi-Connectivity	Control Flow	PDU / Uu (5G-NR)	PDU	Allows connection between UE and CPE via NR
FOP 6 → 3GPP-Relay	Control Flow			
FOP 7 → User	Data Flow			
FOP 8 → User	Control Flow			
FIP 1 ← Antenna	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 2 ← Antenna	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 3 ← Multi-Connectivity	Data Flow	PDU / Uu (5G-NR)	PDU	Allows connection between UE and CPE via NR
FIP 4 ← 3GPP-Relay	Data Flow			
FIP 5 ← Multi-Connectivity	Control Flow	PDU / Uu (5G-NR)	PDU	Allows connection between UE and CPE via NR
FIP 6 ← 3GPP-Relay	Control Flow			
FIP 7 ← User	Data Flow			
FIP 8 ← User	Control Flow			

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7.5 Edge Cluster

7.5.1 Edge Cluster DN

Table 0-5: Interface specification edge cluster DN

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → AI-based Resource Management	AI Flow	HTTP/REST	JSON {Monitoring metrics:float}	Monitoring metrics: features extracted from bare metal, container, application, functional, etc.
FOP 2 → Data Network	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FOP 3 → Management and Orchestration	Management Flow	HTTP/REST	-	Monitoring metrics (CPU, storage, memory, application/VNF specific metrics)
FIP 1 ← AI-based Resource Management	AI Flow	HTTP/REST	JSON {Monitoring metrics:float}	Monitoring metrics: features extracted from bare metal, container, application, functional, etc.
FIP 2 ← Data Network	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FIP 3 ← Management and Orchestration	Management Flow	HTTP/REST	-	Provisioning and VNF/Application management (deploy, migrate, scale up-down, etc.)

7.5.2 Edge Cluster RAN

Table 0-6: Interface specification edge cluster RAN

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → AI-based Resource Management	AI Flow	HTTP/REST	JSON {Monitoring metrics:float}	Monitoring metrics: features extracted from bare metal, container, application, functional, etc.
FOP 2 → CU	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP

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FOP 3 → Management and Orchestration	Management Flow	HTTP/REST	-	Monitoring metrics (CPU, storage, memory, application/VNF specific metrics)
FIP 1 ← AI-based Resource Management	AI Flow	HTTP/REST	JSON {Monitoring metrics:float}	Monitoring metrics: features extracted from bare metal, container, application, functional, etc.
FIP 2 ← CU	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FIP 3 ← Management and Orchestration	Management Flow	HTTP/REST	-	Provisioning and VNF/Application management (deploy, migrate, scale up-down, etc.)

7.5.3 Edge Cluster CPE

Table 0-7: Interface specification edge cluster CPE

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → AI-based Resource Management	AI Flow	HTTP/REST	JSON {Monitoring metrics:float}	Monitoring metrics: features extracted from bare metal, container, application, functional, etc.
FOP 2 → Multi-Connectivity	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FOP 3 → Management and Orchestration	Management Flow	HTTP/REST	-	Monitoring metrics (CPU, storage, memory, application/VNF specific metrics)
FIP 1 ← AI-based Resource Management	AI Flow	HTTP/REST	JSON {Monitoring metrics:float}	Monitoring metrics: features extracted from bare metal, container, application, functional, etc.
FIP 2 ← Multi-Connectivity	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FIP 3 ← Management	Management Flow	HTTP/REST	-	Provisioning and VNF/Application management

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and Orchestration				(deploy, migrate, scale up-down, etc.)

7.5.4 Edge Cluster Ground Segment

Table 0-8: Interface specification edge cluster ground segment

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → AI-based Resource Management	AI Flow	HTTP/REST	JSON {Monitoring metrics:float}	Monitoring metrics: features extracted from bare metal, container, application, functional, etc.
FOP 2 → Ground Segment	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FOP 3 → Management and Orchestration	Management Flow	HTTP/REST	-	Monitoring metrics (CPU, storage, memory, application/VNF specific metrics)
FIP 1 ← AI-based Resource Management	AI Flow	HTTP/REST	JSON {Monitoring metrics:float}	Monitoring metrics: features extracted from bare metal, container, application, functional, etc.
FIP 2 ← Ground Segment	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FIP 3 ← Management and Orchestration	Management Flow	HTTP/REST	-	Provisioning and VNF/Application management (deploy, migrate, scale up-down, etc.)

7.6 WiFi

Table 0-9: Interface specification WiFI

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → Multi-Connectivity	Data Flow	IP / Frame 802.11 (WiFi)	IP	Allows connection between UE and CPE via WiFi

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FOP 2 → Multi-Connectivity	Data Flow	IP / Frame 802.11 (WiFi)	IP	Allows connection between UE and CPE via WiFi
FIP 1 ← Multi-Connectivity	Data Flow	IP / Frame 802.11 (WiFi)	IP	Allows connection between UE and CPE via WiFi
FIP 2 ← Multi-Connectivity	Data Flow	IP / Frame 802.11 (WiFi)	IP	Allows connection between UE and CPE via WiFi

7.7 DVB-S2X

Table 0-10: Interface specification DVB-S2X

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → Multi-Connectivity	Data Flow	IP (DVB-S2X)	IP packets	IP packets
FOP 2 → Multi-Connectivity	Data Flow	3GPP-ATSSS-N3IWF	UE ID: int	As specified in 3GPP with adaption to handle UE ID
FIP 1 ← Multi-Connectivity	Data Flow	IP (DVB-S2X)	IP packets	IP packets
FIP 2 ← Multi-Connectivity	Data Flow	3GPP-ATSSS-N3IWF	UE ID: int	As specified in 3GPP with adaption to handle UE ID

7.8 3GPP-Relay

Table 0-11: Interface specification 3GPP-relay

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → Multi-Connectivity	Data Flow	PDU / Uu (5G-NR)	PDU	with the assumption to be intermediated by a UPF (rebuild IP packets from PDUs)
FOP 2 → 5G-NR	Data Flow			
FOP 3 → Multi-Connectivity	Control Flow	IP (3GPP-Relay)	IP packets	IP packets

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FOP 4 → 5G-NR	Control Flow			
FOP 5 → Antenna	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FOP 6 → Antenna	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 1 ← Multi-Connectivity	Data Flow	PDU / Uu (5G-NR)	PDU	with the assumption to be intermediated by a UPF (rebuild IP packets from PDUs)
FIP 2 ← 5G-NR	Data Flow			
FIP 3 ← Multi-Connectivity	Control Flow	IP (3GPP-Relay)	IP packets	IP packets
FIP 4 ← 5G-NR	Control Flow			
FIP 5 ← Antenna	Data Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly
FIP 6 ← Antenna	Control Flow	RF coaxial/ waveguide	RF Signal	Ku/Ka bands primarily for satellite backhaul; satellite gNodeB can terminate the link directly

7.9 Ground Segment

Table 0-12: Interface specification ground segment

Ports	Functional Exchanges	Type	Data Exchanged	Description / Comment
FOP 1 → Optical Transceiver	Data Flow	IP (OSL)	IP packets	Carries N2 and N3; Examples: Train with optical terminal, Plane with optical terminal, Terrestrial gNB station with optical terminal

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FOP 2 → 5G-Core Multi-Connectivity	Data Flow	3GPP-N3	User data packets (e.g., IP packets, voice, video, etc.)	Protocol: GTP-U over UDP/IP
FOP 3 → Optical Transceiver	Data Flow	IP (OSL)	IP packets	Carries N2 and N3; Examples: Train with optical terminal, Plane with optical terminal, Terrestrial gNB station with optical terminal
FOP 4 → Edge Cluster	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP
FIP 1 ← Optical Transceiver	Data Flow	IP (OSL)	IP packets	Carries N2 and N3; Examples: Train with optical terminal, Plane with optical terminal, Terrestrial gNB station with optical terminal
FIP 2 ← 5G-Core Multi-Connectivity	Data Flow	IP (OSL)	IP packets	Carries N2 and N3; Examples: Train with optical terminal, Plane with optical terminal, Terrestrial gNB station with optical terminal
FIP 3 ← Optical Transceiver	Data Flow	IP (OSL)	IP packets	Carries N2 and N3; Examples: Train with optical terminal, Plane with optical terminal, Terrestrial gNB station with optical terminal
FIP 4 ← Edge Cluster	Data Flow	3GPP-N6	User data (IP packets)	Protocols: Ethernet, IPv4/IPv6, TCP/UDP

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