D2.1: Initial report on ETHER network architecture, interfaces, and architecture evaluation

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Abstract	This deliverable presents the initial design of ETHER architectural framework integrating terrestrial and non-terrestrial networks. This design is based upon current state-of-the-art, as well as requirements from other technical innovations and the use cases within the scope of the ETHER project. The architectural framework in this document covers in detail both management and orchestration along with end-to-end service layers. This architectural framework is subject to change during the project, therefore a document containing the final design (D2.4) will be released.
Keywords	Architecture, network, interfaces, TN, NTN, integration, SDN, NFV, 5GS

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DISCLAIMER

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* R: Document, report (excluding the periodic and final reports)

DEM: Demonstrator, pilot, prototype, plan designs

DEC: Websites, patents filing, press & media actions, videos, etc.

DATA: Data sets, microdata, etc.

DMP: Data management plan

ETHICS: Deliverables related to ethics issues.

SECURITY: Deliverables related to security issues

OTHER: Software, technical diagram, algorithms, models, etc.

EXECUTIVE SUMMARY

This document presents an initial design of the ETHER architectural framework, aimed at the Terrestrial Networks (TN) – Non-Terrestrial Networks (NTN) integration to support the provisioning of envisioned 6G services across the terrestrial, aerial and space layers. While the proposed concept serves as a theoretical backbone for the 6G networks integration, it also draws clear guidelines for various use cases implementation and demonstration activities in the project. The design steps, which are presented in this document, follow the bottom-up procedure, explained as:

- Analysis of the current state of the art related to the integration of TN-NTN, envisioned 6G features, as well as architectural approaches and trends from the perspective of Standards Developing Organisations, 5G Public Private Partnership (5G PPP), and most notable R&D projects tackling relevant topics.

- Description of specific architectural requirements that support universe design principles, namely: generic, multi-domain, multi-provider, distributed, hierarchical, intent-based, zero-touch, scalable, service-based, modular, and open to extensions.

- Description of novel mechanisms assisting/enabling the TN-NTN integration, such as multi-link aircraft user equipment communications, direct handheld device access to Low Earth Orbit satellites, unified waveform design, flexible payload, Artificial Intelligence (AI)-based predictive vertical/horizontal handover control mechanisms, data analytics, edge computing, and caching including semantics-aware data analytics and control, zero-touch orchestration and AI-driven End-to-End (E2E) optimisation.

- Definition of a high-level ETHER architecture concept with ETHER architectural layers description.

- Initial proposal for hierarchical, generic, and scalable ETHER Management and Orchestration layer, as well as the description of E2E service layer.

TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

3GPP	Third Generation Partnership Project
5G	5^{th} Generation of mobile networks
5G-EIR	5G Equipment Identity Registry
5GS	5G System
5G PPP	5G Public Private Partnership
6G	6^{th} Generation of mobile networks
A2G	Air to Ground
AI	Artificial Intelligence
AIaaS	AI as a Service
AIOps	AI Operations
AF	Application Function
AMF	Access and Mobility Management Function
AP	Application Plane
API	Application Programming Interface
AUSF	Authentication Server Function
BSS	Business Support System
B5G	Beyond 5G
CAPIF	Common Application Programming Interface Framework
CP	Control Plane
CPU	Central Processing Unit
CU	Centralised Unit
CRUD	Create, Read, Update, Delete
CM	Configuration Management
CN	Core Network
CNN	Convolutional Neural Network
CSMF	Communications Service Management Function
DevOps	Development Operations

DI	Domain Infrastructure
DLT	Distributed Ledger Technology
DN	Data Network
DPI	Deep Packet Inspection
DU	Distributed Unit
DMOC	Domain M&O Component
DVB-S2X	Digital Video Broadcasting – Satellite 2 eXtensions
E2E	End to End
E2ESL	E2E Service Layer
EASDF	Edge Application Server Discovery Function
eCPRI	evolved Common Public Radio Interface
EGMF	Exposure Governance Management Function
eMBB	enhanced Massive Broadband
EMS	Element Management System
EMOC	E2E M&O Component
ESA	European Space Agency
ETSI	European Telecommunication Standards Institute
EU	European Union
FCAPS	Fault, Configuration, Accounting, Performance, Security
FFT	Fast Fourier Transform
FiWi	Fibre-Wireless
FM	Fault Management
FPGA	Field Programmable Gate Array
FWA	Fixed Wireless Access
GBR	Guaranteed Bit Rate
GEO	Geostationary Orbit
GNSS	Global Navigation Satellite Systems
GPU	Graphical Processing Unit

GS	Ground Station
GSM	Global System for Mobile communication
GSMA	GSM Association
GSO	GeoStationary Orbit
GSOA	Global Satellite Operators' Association
HAPS	High Altitude Platform System
HARQ	Hybrid Automatic Repeat reQuest
HMTC	High performance Machine Type Communications
HTA	Heavier than Air
HTTP	Hypertext Transfer Protocol
HW	Hardware
ICT	Information and Communications Technology
IETF	Internet Engineering Task Force
IoT	Internet of Things
ISL	Inter-Satellite Link
ISM	In-Slice Management
IP	Internet Protocol
ISG	Industry Specification Group
ITU	International Telecommunication Union
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
KVI	Key Value Indicator
LAN	Local Area Network
LCM	Life Cycle Management
LEO	Low Earth Orbit
LTA	Lighter than Air
MaaS	Management as a Service
MANO	MANagement and Orchestration (layer, solution)

MAPE-K	Monitor-Analyse-Plan-Execute based on Knowledge
MAR	Mobile Autonomous Reporting
MDAF	Management Data Analytics Function
MEAO	MEC Application Orchestrator
MEC	Multi-access Edge Computing
MEO	Medium Earth Orbit
MEP	MEC Platform
MIoT	Massive IoT
ML	Machine Learning
MLOps	ML Operations
MMS	Multimedia Messaging Service
mMTC	massive Machine-Type Communications
MNO	Mobile Network Operator
M&O	Management and Orchestration (activity, process)
MoU	Memorandum of Understanding
MP	Management Plane
MSDNO	Master SDNO
NB-IoT	Narrowband IoT
NBI	Northbound Interface
NEF	Network Exposure Function
NF	Network Function
NFMF	Network Function Management Function
NFV	Network Functions Virtualisation
NFVO	NFV Orchestrator
NG	Next Generation
NGMN	Next Generation Mobile Networks
NGSO	Non-GeoStationary Orbit
NI	Network Intelligence

NIP	Network Intelligence Plane
NMS	Network Management System
NR	New Radio
NRF	Network Repository Function
NSI	Network Slice Instance
NSMF	Network Slice Management Function
NSO	Network Service Orchestrator
NSSaaS	Network Slice Subnet as a Service
NSSAAF	Network Slice-Specific Authentication and Authorisation Function
NSSF	Network Slice Selection Function
NTN	Non-Terrestrial Network
NWDAF	Network Data Analytics Function
OAI	OpenAirInterface
OFDM	Orthogonal Frequency Division Multiplexing
ONAP	Open Network Automation Platform
O-RAN	Open RAN
OSM	Open Source MANO
OSS	Operations Support System
OTFS	Orthogonal Time-Frequency Space
PAT	Pointing, Acquisition, and Tracking
PCF	Policy Control Function
PLMN	Public Land Mobile Network
PM	Performance Management
QIT	Quantum Information Technology
QKD	Quantum Key Distribution
QoS	Quality of Service
R&D	Research and Development
RCP	Required Communication Performance

RCS	Rich Communication Services
REST	REpresentational State Transfer
RIC	Radio Intelligent Controller
RT	Real-Time
RO	Resource Orchestrator
SA	Stand-Alone
SAT	SATellite
SBA	Service-Based Architecture
SBI	Southbound Interface
SCP	Service Communication Proxy
SDG	Sustainable Development Goals
SDN	Software-Defined Network
SDNO	SDN Orchestrator
SDO	Standards Developing Organisation
SEAL	Service Enabler Architecture Layer
SES	Satellite Earth Stations and Systems
SCN	Satellite Communications and Navigation
SMF	Session Management Function
SMO	Service Management and Orchestration
SMS	Short Message Service
SNS JU	Smart Networks and Services Joint Undertaking
S-NSSAI	Single-Network Slice Selection Assistance Information
SotA	State of the Art
SW	Software
TA	Tracking Area
TC	Technical Committee
TN	Terrestrial Network
TR	Technical Report

TRL	Technology Readiness Level
TS	Technical Specification
TTaC	Tracking, Telemetry, and Command
UART	Universal Asynchronous Receiver/Transmitter
UAS	Unmanned Aircraft Systems
UDM	User Data Management
UDR	User Data Repository
UE	User Equipment
UN	United Nations
UP	User Plane
UPF	User Plane Function
URLLC	Ultra-Reliable Low Latency Communications
V2X	Vehicle to everything
VIM	Virtualised Infrastructure Manager
VM	Virtual Machine
VNF	Virtual Network Function
VNFM	VNF Manager
WAN	Wide Area Network
WP	Work Package
WIM	WAN Infrastructure Manager
XR	Extended Reality
ZSM	Zero-touch network and Service Management

1 INTRODUCTION

1.1 OBJECTIVES

The main objective of this deliverable is to outline the initial ETHER architectures supporting the selected use cases within a federated, multi-domain and integrated Terrestrial Networks (TN) – Non-Terrestrial Networks (NTN) ecosystem comprised of terrestrial, aerial and space segments. The document provides a condensed perspective of the fundamental system architecture features and mechanisms (including innovations proposed by the ETHER project), which target the efficient implementation of 3D network services. The deliverable outlines the integrated 3D ETHER system architecture encompassing both terrestrial and non-terrestrial elements, detailing the End-to-End (E2E) data, control, and management planes along with centralised or distributed computing resources. The initial approach to interfaces definition between technologies within the same layer and across different layers (terrestrial, aerial, and space) is also described. As a result, this document serves as a foundation for the future WP2 activities related to the ETHER architecture definition and paves the way for joint cross-WPs efforts regarding the integration of architectural elements developed in the course of WP3 and WP4.

1.2 MOTIVATION AND SCOPE

The rapid evolution of communication technologies has led to the wide deployment of carrier-grade 5G networks. Currently, the ongoing research efforts are already oriented towards defining the principles of the future mobile networks. The design of 4G and 5G systems has been exclusively optimised for terrestrial networks and only recently with the 3GPP Release 17 the importance of NTNs to cover the large coverage holes across the globe in remote and rural areas has been acknowledged. In particular, features in the 5G architectural design are identified for supporting the integration of the satellite segment into terrestrial networks with minimal impact. However, it is straightforward that the optimum network performance can only be achieved by a unified approach where the network design is optimised for both the terrestrial and NTN components. This will be target in 6G networks for which it is largely agreed that they will entail a 3D multi-layer architecture comprising the terrestrial, aerial, such as Unmanned Aerial Vehicles (UAVs) and High Altitude Platform Systems (HAPSs), and space nodes, especially those in non-geostationary orbits – Medium Earth Orbit (MEO)/Low Earth Orbit (LEO) – that can act as base stations and provide communication, edge processing, and caching capabilities in a unified manner. This integration offers the potential for providing ubiquitous coverage, reduced transmission delays, and enhanced quality. While existing research has tackled technical challenges individually, a comprehensive solution is lacking to efficiently manage the complex integrated network, along with addressing key technical issues. Thus, there is a clear motivation to develop a complete, E2E, efficient, and programmable architecture for integrated non-terrestrial and terrestrial networks, enabling the establishment of sustainable business frameworks.

The deliverable addresses the emerging challenges and opportunities presented by the seamless integration of NTNs with terrestrial infrastructure, focusing on the potential of integrated 6G-capable TN-NTN architecture and interfaces. The proposal will leverage the well-established paradigms to accommodate standardised frameworks and achieve low latency, and zero-touch architecture that ensures efficient resource utilisation and seamless communications across diverse network elements.

1.3 RELATIONSHIPS WITH OTHER TASKS IN WP2 AND OTHER ETHER WORK PACKAGES

Deliverable D2.1 is the outcome of task T2.2, focusing on the architecture definition, which considers use cases requirements identified by task T2.1 “ETHER use case, Key Performance Indicator (KPI)/Key Value Indicator (KVI) requirements and definition”. T2.1 defines a comprehensive approach to identifying and specifying technical parameters and specifications for T2.2. Both tasks contribute to the overall project goals by providing a structured framework for defining and assessing the technical aspects and performance of the developed solutions within the broader context of network architecture and specific use cases.

The initial ETHER system architecture described in this deliverable provides the input to task T2.3 “ETHER technoeconomic analysis and business plan” where the special attention will be directed towards conducting a technoeconomic evaluation of the ETHER system, which will involve the development of a relevant cost model incorporating practical insights from the industrial collaborators.

The main relationship between the deliverable research activities is introduced in WP4. As the deliverable scope aims to define the integrated architecture of a 3D ETHER framework, with an emphasis on specifying interfaces, both horizontal and vertical, between different technology domains and architectural layers, WP4 demonstrates the relevance of conducted work in the context of management and orchestration planes of the 3D ETHER network architecture. The WP4 tasks involve the development of advanced orchestration frameworks, resource allocation algorithms, and predictive analytics, which can impact specific architectural features (such as interfaces, exposure mechanisms, integration capabilities with external frameworks, etc.). Deliverable D2.1 and the tasks included in WP4 expose their relevance in the development, design, and optimisation of the ETHER network architecture. Both research works emphasise the importance of interfaces and integration within the network architecture and are geared towards optimisation. Management and control are also included in both D2.1 and WP4. The first task addresses the management and control planes within the architecture, ensuring effective communication and orchestration. The tasks in WP4 involve developing control plane mechanisms, Software-Defined Networks (SDN)-based control, and orchestration frameworks for efficient management.

The deliverable D2.1 is also related to WP3 task T3.4 as both lie in the overarching goals of achieving seamless and uninterrupted connectivity, optimising handover performance based on KPIs, considering different architectural layers, and adhering to standards. Handover mechanisms developed under WP3 may need dedicated architectural support (e.g., exposed interfaces/additional network mechanisms). Both research scopes highlight the significance of effective network management to ensure smooth handovers and uninterrupted services.

1.4 DELIVERABLE STRUCTURE

This document is structured as follows:

- Section 2 presents a short description and explanations for the terminologies used throughout the document to mitigate potential ambiguity of terms or concepts caused, e.g., by different Standards Developing Organisations (SDOs) naming conventions.
- Section 3 provides an overview of pertinent initiatives concerning the integration of TN-NTN, standardisation efforts for integrating 5G and non-terrestrial networks, fundamental attributes of 6G, emerging paradigms, and integrated architectural strategies encompassing management and orchestration.

- Section 4 is devoted to the exploration of the ETHER architectural requirements and design considerations which involves the investigation of the methodology, principles, and the essential architectural prerequisites. This entails the analysis of how the system is structured, ensuring its alignment with the established methodologies, adherence to the fundamental principles, and meeting specific criteria set out in the architectural development framework.

- Section 5 presents the initial ETHER system reference architecture, which encompasses five fundamental layers that collectively define its structure and functionality. This section provides a comprehensive framework for understanding how the system's components interact, how services are delivered, and how the entire system is managed and maintained.

- Section 6 concludes the document.

2 TERMINOLOGY

ETHER project considers different systems and architectural approaches related to different frameworks. Therefore, when integrating them, it is important to consider the differences and even the ontological collisions related to the different meanings of the same names used to represent the different concepts. To avoid terminological inconsistencies, in this document, that may confuse the reader, the following notes are provided regarding the concept of the service as well as functional planes.

A **service** is defined and understood differently in different frameworks:

- European Telecommunication Standards Institute (ETSI) Network Functions Virtualisation (NFV) network service is defined as a group of interconnected network functions building a communication network.
- Third Generation Partnership Project (3GPP) communication service is built on top of the 3GPP network.
- Service-based Architecture concept in which software instances, as producers, expose their services to other software instances acting as consumers.
- Application service runs on top of the communications networks.
- ETHER E2E service is defined according to the different contexts discussed in section 5.

In this document, all references to services will be associated with an explicit statement of the context, e.g., “NFV network service”, “communication service”, “ETHER E2E service” to avoid ambiguity. The exception may be a clear context resulting from the meaning of a section or paragraph.

Control plane is used by the SDN and 3GPP frameworks. In this document, all references to control plane will explicitly state the context, e.g., “5GS control plane”, “SDN control plane” to exclude ambiguity. The exception may be a clear context resulting from the meaning of a section or paragraph.

User plane will be used according to the 3GPP concept of the user data forwarding plane. It is not equal to **data plane** according to the SDN framework or according to various applications architectures. In particular, in the case of SDN, the data plane can transport data of 3GPP user plane, 3GPP control plane, management plane, etc.

In terms of the 3D layer approach, the **space** layer is considered as an equivalent of the **satellite** layer.

For Management and Orchestration acronyms, **M&O** will be used in the context of processes, operations, or activities, and **MANO** in the context of solutions or architectural layers.

3 RELATED WORKS

In this section, the overview of the most recent activities related to the integrated TN-NTN network ecosystem is presented including relevant research projects, and relevant standardisation activities. Also, the key envisioned 6G features, paradigms and architectural approaches are provided to serve as the foundation for the ETHER architecture considerations.

3.1 NGMN

While the 6G standardisation activities have not been officially started yet, the Next Generation Mobile Networks (NGMN) has already published several works related to vision and properties of the future mobile networks. It is envisioned that the 6G systems design will be heavily driven by the most pressing societal challenges, arising market expectations and networks' operational necessities [1]. The key pressing societal issues have been gathered within the United Nations (UN) Sustainable Development Goals (SDG) and include, i.a., environmental sustainability, efficient healthcare, inequality and poverty reduction or public safety and privacy improvements. It is expected that SDG will not only drive 6G development but also set its ultimate targets. Hence, the novel differentiated 6G services and capabilities shall benefit market opportunities expansion, ensure value to the society and provide sustainable return on investment for the Mobile Network Operators (MNOs). The 6G design should also facilitate the resolution of the key operational challenges such as efficiency of network operations, E2E system automation and visibility (comprehensive system monitoring and data collection), system efficiency and management challenges (spectrum utilisation, E2E energy efficiency monitoring and management, energy consumption reduction, security integration). Altogether, the 6G technology contextualisation in terms of societal contribution, end-users and MNOs' value creation should shape the future network design.

Based on the above identified trends, NGMN distinguished four classes of Generic Use Cases sharing key common features [1], which include: enhanced human communication (holographic telepresence communication, extended reality (XR), multi-modal communication for teleoperation, intelligent interaction with sensation, skills and thought sharing), enhanced machine communication (robot network fabric, cobots interaction), enabling services (i.a., 3D positioning, localisation and tracking, digital twins, digital healthcare, smart industry, trusted service composition, automatic detection protection and inspection), and network evolution – trusted native Artificial Intelligence (AI) and AI as a Service (AIaaS), coverage expansion, energy efficiency) [2]. The use cases and specific requirements related to 6G targets have led NGMN to the identification of the principle 6G architecture features, which include:

- Multi access convergence, which involves 6G support for both very wide area and ubiquitous coverage, and fully immersive communications in localised areas. It should be built using well-established Service-Based Architecture (SBA) and Cloud Native approaches and introduce new network functions to handle arising challenges related to seamless multi-access across disparate networks, such as mobility management, routing, security, policy control, charging and subscriber data management.

- Cross-domain and cross-layer scheduling and management supporting E2E deterministic services for industrial applications.

- Communication, sensing and computing as a converged network, deeper integration at the architecture level including the operational management of systems to avoid adding significant complexity.

- Zero-trust-based system security, achieved by embedding security mechanisms into the architecture design and leveraging zero-trust mechanisms.
- Simplicity and legacy problems resolution, including network complexity reduction by phasing out legacy technologies, introduction of new features, and network functions composed of self-contained modules managed through self-organising mechanisms.
- Disaggregation and softwarisation via hardware/software (HW/SW) decoupling, flexible function placement capabilities and introduction of standardised interface specification to provide elasticity for multi-vendor deployment.

It has to be emphasised that in comparison to 5G, the 6G is oriented towards the sustainable performance improvements, e.g., improve rural coverage, the 6G system design should use non-conventional solutions such as non-terrestrial high-altitude-platforms or satellite-based services to deliver mobile services [3]. Moreover, new metrics that enable the qualitative and quantitative network assessment in the context of global environmental impact should be created and applied.

3.2 GSMA

GSM Association (GSMA) recognises the techno-business opportunities of the HAPS-based NTN integration with mobile networks and has published a white paper on the topic (initially [4], and a year later its extended version [5]). Both properties of satellites (for global coverage) and HAPSs (for spotted/regional coverage) are described there, including the essential differentiating features (time per orbit, time in site per gateway, latency, band, etc.). In contrast, HAPS is favoured because, in the GSMA's perception, satellite access requires outdoor antennas, dedicated bands, special Radio Access Technologies (RATs) and terminals, while HAPS (stationary relative to the serviced area) enables gNodeB (gNB) hosting with all its implications for the user and the User Equipment (UE). Three options of HAPS-gNB implementation are assumed: gNB aboard HAPS with a feeder link from the ground, and ground-based gNB with either a transponder (frequency conversion for both ingress and egress traffic directions) – bent-pipe or a relay (no frequency conversion) aboard HAPS. Apart from that, the documents do not contain any in-depth considerations of relevance to architecture.

The next part of the white paper [4], [5] presents an analysis of potential and sample HAPS use cases. For the former, greenfield coverage, white spot reduction (due to more even coverage than in the case of terrestrial base stations), emergency communications and disaster recovery, Internet of Things (IoT) support, temporary coverage for events and tourist hotspots, fixed wireless access (FWA), connectivity for urban air mobility and drones, private networks, terrestrial site backhaul, and extended coverage over the sea are indicated. For the latter, short case studies are presented (greenfield – Denmark, Liberia, and Mexico; FWA – Europe; white spots – Japan and German Alps; disaster response – Japan and Germany; private networks; coverage over the sea) with general market and methodology description, use case analysis, and technical KPIs.

3.3 5G AMERICAS

5G Americas [6] acknowledges the increasing deployment of 5G networks worldwide, with a particular focus on extending services beyond smartphones to enterprise, massive IoT, and machine-type communication devices. They highlight the growing demand for service continuity and the expansion of networks into non-traditional areas. NTN is introduced as part of efforts towards 5G-Advanced and eventual 6G systems, emphasising the potential role of satellite-based communication in delivering 5G services and bridging the digital divide. Unlike the GSMA approach, the role of HAPS is basically omitted.

5G Americas discusses the NTN use cases grouped by 5G service classes. For enhanced Massive Broadband (eMBB), the following use cases have been described: multi connectivity, fixed or mobile cell connectivity, network resilience, trunking, edge network delivery, mobile cell hybrid connectivity, direct-to-node or direct-to-mobile broadcast, and wide or local area public safety. For massive Machine-Type Communications (mMTC), wide or local area IoT service is proposed. Apparently, NTN-based connectivity is not suitable for Ultra-Reliable Low Latency Communications (URLLC) applications, according to the 5G Americas vision. The alliance does not propose any concept relevant to the architecture; instead, they closely follow the development of the 3GPP standardisation.

3.4 ITU

The International Telecommunication Union (ITU) has been dealing with the issues of non-terrestrial communication for many years. Its Radiocommunication Sector (ITU-R) is responsible for international radio spectrum coordination and has been issuing the ITU-R Reports and Recommendations regarding the satellite communication and services alone. The Telecommunication Standardisation Sector (ITU-T) has been working in the field of fixed, mobile and satellite convergence within the Study Group 13 (Future networks) Question 23 “Networks beyond IMT-2020: Fixed, mobile and satellite convergence” (initiated during the Study Period 2017-2021, currently continued during the Study Period 2022-2024). So far, two ITU-T Recommendations have been issued.

The Recommendation ITU-T Y.3200 [7] defines the service and network capability requirements as well as use cases of fixed, mobile and satellite convergence for the International Mobile Telecommunications (IMT)-2020 (i.e., 5G) networks and beyond. They include unified identity and unified subscription management including unified authentication and authorisation; unified service provision and charging; service continuity during vertical handovers; support of best-effort and Guaranteed Bit Rate (GBR) Quality of Service (QoS); support of various types of terminals; support of converged voice, video, data, SMS/MMS/RCS, broadcast and unicast, Multi-access Edge Computing (MEC), vertical, and roaming services; support of converged control, service, and management planes; support of cloud-based infrastructure enabled by NFV and SDN technologies; support of AI/Machine Learning (ML), Distributed Ledger Technology (DLT), and Quantum Information Technology (QIT); support of unified mobility management (including registration, location, and handover management); unified session management (session life cycle management, address allocation, traffic routing, and session continuity); unified connection management (dual connectivity, signalling, status, session continuity – especially for rapid movement of satellites, and user plane management); unified policy control (QoS, access, mobility, and traffic control); unified exposure of converged network mechanisms (Control Plane (CP), User Plane (UP), E2E QoS, MEC, network slicing, MANO, network analytics, and convergence); and converged security. It is also required to support both satellite access and backhaul in the converged network.

The Recommendation ITU-T Y.3201 [8] specifies the design considerations, framework, enabling technologies, network function enhancements, procedures, and security considerations of fixed, mobile and satellite convergence for IMT-2020 networks and beyond. The overall framework includes the multi-access UE connected to fixed, mobile or satellite access network. Each access network may be connected to land- or satellite-based core network, and the interworking function between two types of cores is defined. Land- or satellite-based service platforms and data networks are interconnected with the respective cores. In terms of cores, it is required for the land-based core to implement the full functionality, while in the case of the satellite-based core only the user subscription management entity, network access and mobility control, session management and user plane functions' implementation is mandatory. Due to the comparatively scarce resources and capabilities of satellites, lightweight implementation support of functions is required. Ephemeris data of non-geostationary Earth orbit (non-GEO) satellites have to be supported by the mobility management and service continuity procedures.

3.5 IETF

The Internet Engineering Task Force (IETF) analyses problems and requirements related to the usage of satellite constellation for Internet access [9]. This Internet draft considers three main deployment scenarios in which satellite networks can be used for broadband internet access. These scenarios include single satellite as a relay, multiple satellite relays, and inter-satellite networking. Additionally, satellite network as a backhaul for 5G is also considered. The following requirements for communication between satellite and TNs are identified for each of the three satellite constellation usage scenarios: i) bi-directional communication capability of both satellites and ground stations, ii) Ethernet and/or IP address configured for the device and each link of satellites and ground stations, iii) Ethernet hub or switching or IP routing capability of satellites and ground station in order to send Internet traffic or IP date to destination correctly, iv) satellite-ground-station communication over a bilaterally agreed protocol to establish a secured channel, v) secure discover protocol to detect the state of communication peer such as peer's identity, its state and other info, vi) secure transmission of user IP packets in the ground-satellite link, and vii) packet processing on satellite should be very minimal and offloaded to ground as much as possible due to the resource satellite constraint.

Based on this document, the following topics need to be considered in a satellite network: i) deployment of 3GPP 5G User Plane Functions (UPFs) on-board satellites, ii) support of tunnels between LEO satellite UPFs (N19 reference point connection between two Protocol Data Unit (PDU) Session Anchor UPFs for 5G Local Area Network (LAN)-type service), iii) support of multi-hop Inter-Satellite Link (ISL) scenario, and iv) more efficient satellite-based routing protocols should be adopted (further discussed in [10]).

3.6 3GPP

The 5G System (5GS), which is the latest generation of mobile networks, is still under development by 3GPP. In the context of the ETHER scope, the generic 5GS architectural framework [11] provides fundamental functionalities and mechanisms as follows:

- Framework design based on network softwarisation and virtualisation principles; the 5GS management framework is complemented by the ETSI NFV MANO stack (includes it in the overall vision) [12].

- CP programmability augmented by its SBA; the functional CP entities expose services as their producers or discover/consume them as consumers within the RESTful framework Application Programming Interface (API) based on JSON – serialisation, HTTP/2 – application layer, and TCP – transport and fundamental request/response and subscribe/notify. Mechanisms of manageable functions discovery and underlying message brokering enable logical partitioning of 5GS CP. The Management Plane (MP) framework also follows the SBA rules and mechanisms with addition of connect/screaming mechanism.

- UP programmability, i.e., flexible composition of UPF as a chain of atomic functions to process the UP traffic according to the specificity of the use case or communication service requirements, e.g., deep packet inspection, selective marking or altering, encapsulation, classification, forwarding or redirection of some user traffic fractions, firewall, antivirus protection, parental control, etc. The definition and inclusion of other UP traffic treatment entities are possible.

- Network Slicing supported by slice-specific tailoring of UPF, network slice selection and authentication/admission mechanisms, flexible integration slice-specific CP functions using separation mechanisms of the SBA CP communication bus, and ability of UE to be attached to multiple slices on-demand.

- Generic network and management data analytics mechanisms and application-specific ones to be implemented thanks to SBA extendibility, which also enables implementation of control loops, also AI/ML-based. ETSI Zero-touch network and Service Management (ZSM) framework inclusion is also supported [12].

- Ability of CP and MP mechanisms exposure to enable the integration with external systems. Special Application Functions (AFs), acting as "embassies" of the AP services or 3rd party systems, can be hosted by CP. These mechanisms also enable the integration of 5GS CP with ETSI MEC. Additionally, Common Application Programming Interface Framework (CAPIF) [13], i.e., a unified north-bound interface API of 5GS CP, and Service Enabler Architecture Layer for Verticals (SEAL), a standardised high-level Core Network (CN) enablers framework [14] have been specified.

3GPP also considers the field of NTN integration with 5GS and support of NTN-specific requirements. The work done in the 3GPP Release 17 covers the "Integration of satellite components in the 5G architecture" work item, which identifies the following applications for NTN 5G Core (5GC) support: coverage extension, IoT, disaster communication, global roaming, broadcasting. The potential use cases targeting the satellite-based NTN have been identified and analysed in terms of service continuity, ubiquity and scalability: roaming between TN and NTN, broadcast and multicast with a satellite overlay, IoT with a satellite network, temporary use of a satellite component, optimal routing or steering over a satellite, satellite transborder service continuity, global satellite overlay, indirect connection through a 5G satellite access network, 5G fixed backhaul between 5G RAT – New Radio (NR) and the 5G CN, 5G moving platform backhaul, 5G to premises (serving white spots), and satellite connection of remote service centre to off-shore wind farm [15]. Based on the described scenarios, the consolidated satellite service requirements have been derived and incorporated into the 5GS service requirements [16], both functional and QoS-related, namely: delay limits for GEO/MEO/LEO options, and for different usage scenarios – the expected data rates and area traffic capacities both for DL and UL, overall user densities, user activity factors, expected UE speeds and types. The most challenging is the airplane connectivity use case, where 360 Mbps (DL)/180 Mbps (UL) per plane is required at the maximum speed of 1000 kmph.

The study on architecture aspects of using satellite access in 5G [17] features 10 key issues along with possible solutions and adjustments in 5GS. These issues are related to mobility management for different coverage areas (large and moving), delay in satellite, QoS for both satellite access and backhaul, RAN mobility, multi-connectivity (satellite backhaul and hybrid satellite/terrestrial backhaul), content distribution close to edge, and regulatory services for satellites overlapping multiple countries. Following the study, the 5GS specifications of architecture [11], system procedures [18], and policy & charging framework [19] have been updated, primarily focusing on Access and Mobility Management Function (AMF), Session Management Function (SMF), and Policy Control Function (PCF) behaviour to recognise new access method. Additionally, a study on Public Land Mobile Network (PLMN) selection [20] has been performed, which led to updating of the relevant procedure [21] to include access via satellite Next Generation RAN (NG-RAN).

In the field of RAN, the support of non-terrestrial networks into the NR protocol and NG-RAN architecture has been introduced. According to the 3GPP RAN group, the term NTN refers to networks or their segments that are used for transmission:

- Spaceborne vehicles, i.e., GEO (stationary) or non-GEO satellites (non-stationary, LEO or MEO).
- Airborne vehicles: HAPS (quasi-stationary), i.e., Unmanned Aircraft Systems (UAS) – Lighter than Air (LTA) and Heavier than Air (HTA) ones.

3GPP RAN group notes that the specificity of NTN versus TN requires addressing the following issues:

- Operation altitude causing longer latency (especially in case of satellites).
- Motion of space/airborne vehicles movement relative to the Earth causing delay variation and Doppler shift.
- Much larger satellite/HAPS cell footprint than the usual cell coverage area causing differential delay and possible multi-country coverage.
- Different propagation channel models than included in the link power budget considerations.
- Radio unit performance associated with satellite/HAPS payload performance.

According to the 3GPP RAN group vision [22], the NTN gNB is composed of CN-side terrestrial NTN gateway communicating through a feeder link with a space-/airborne vehicle hosting an NTN payload, further communicating with UE through NR service link. Hence, this approach supports only the bent-pipe or relay scenarios (see section 3.2), as it is NTN-payload is allowed to change the carrier frequency. Three cases are distinguished:

- Earth-fixed, e.g., in the case of GEO satellites, continuous coverage of the same geographical areas all the time with fixed beam(s).
- Quasi-Earth-fixed, covering one geographic area for a limited period and then a different geographic area during another limited period (e.g., non-GEO satellites using steerable beams).
- Earth-moving, where coverage area continuously slides over the Earth's surface (e.g., non-GEO satellites using fixed or non-steerable beams).

The specificity of NTN needs a special treatment of the following mechanisms:

- Mobility management in NTN needs that the network provides serving cell's and neighbouring cell's satellite ephemeris needed to access the target serving NTN cell in the handover command. NTN to TN (hand-in) and TN to NTN (hand-out) is supported, while

UE does not need to be connected to both NTN and TN at the same time. Also, the mobility between different orbit NTNs is also supported.

- Feeder link switch over may be referred to the change (soft or hard) of terrestrial feeder link anchor change from one NTN gateway to another a specific NTN payload. It is assumed as a Transport Network Layer procedure and applies to non-GEO satellites.

- AMF (re-)selection by gNB to ensure that UE connects to AMF serving the country in which UE is located.

- Providing gNB with the regular or on-demand ephemeris information (orbital trajectory information or coordinates information) and location of NTN gateways.

Within the current Release 18 going on, the guidelines for extraterritorial 5GSs have been prepared [23], which include the aspects of some services in territorial waters and exclusive economic zones, and exclusion areas of a country, maritime, aeronautical, and extraterritorial (no sovereignty) land areas: public warning system, charging and billing, emergency calls, lawful intercept, data retention policy in cross-border scenarios and international regions, and network access, referring both to UE and network side. The 5GS architecture [11] has been updated with 5G support of satellite backhaul in deployment scenarios, where UPF is deployed on-board satellite. Additionally, AMF and SMF are extended with capability of reporting satellite backhaul category, which can be used to trigger QoS monitoring by PCF if dynamic satellite backhaul category is used. Currently, the 5GS architecture supports the following features relevant to the NTN support: support for identification and restriction of using NR satellite access, support for integrating NR satellite access into 5GS, support of discontinuous network coverage for satellite access, high latency communication (handling mobile-terminated communication with UEs being unreachable due to the active power saving functions or discontinuous coverage), support for integrated access and backhaul (configuration of group of gNBs as a chain of donor-acceptor relations behind one N2/N3 interface), support for 5G satellite backhaul including edge computing via UPF deployed on satellite and local switch for UE-to-UE communications via UPF deployed on GEO satellite.

The 3GPP Release 19 has not been started yet, but the studies on its content are in progress. The report of study on the 3rd phase of satellite access [24] has been released; it proposes new use cases: store and forward for a delay-tolerant/non Real-Time (RT) IoT in distant sites or emergency reporting using ephemeral satellite access, drones connectivity or LAN over satellite access, information exchange between ships at sea, direct UE-satellite-UE (or through an additional intersatellite link) phone calls, video streaming, etc. for feeder link off-loading (including also service continuity during NTN-TN handover), usage of satellite connectivity for collection of information to aid terrestrial network planning, fleet management in the desert, and service differentiation for UEs via satellite access. The gaps analysis is included, and new potential requirements have been identified. The document lists proposals, which will be evaluated and decided to include in the future version of the normative document [16] in December 2023.

3.7 ETSI

The European Telecommunications Standards Institute is one of three European Standards Organisations, ETSI has many technical committees and working groups. Some relevant are considered below. In toto, ETSI has published more than 40,000 studies and specifications, a number it reached in 2018. ETSI also works closely with 3GPP (cf. Section 3.6 above).

3.7.1 ETSI NFV

The NFV work by ETSI separates the software-based implementation of Network Functions (NFs) from the underlying hardware (compute, storage, and connectivity) through addition of the virtualisation layer. This approach adds flexibility to the network architecture, decouples the infrastructure and software life cycles, and increases agility of network management. In the context of NTN, such as satellite networks, Virtual Network Functions (VNFs) deployed on-board satellites would allow to significantly increase the list of available NFs offered by satellite network operators in the form of VNF-as-a-Service. Combined with already high deployment cost of a satellite, and no real possibility of hardware replacement once the satellite is active, NFV focused approach is preferred.

ETSI NFV Industry Specification Group (ISG) published several documents referring to the architecture as well as the use cases of NFV. General NFV MANO architectural framework is defined [25] and the use cases are described [26]. The general idea of the MANO stack is to distinguish the function of orchestrating and managing the life cycle of "NFV Network Service" (i.e., a constellation of VNFs forming a complete communication network) supported by NFV Orchestrator (NFVO) from the function of managing the life cycle of individual VNFs supported by VNF Manager (VNFM), and the function of compute, storage and network infrastructure management supported by Virtualised Infrastructure Manager (VIM). It should be noted that NFV MANO is VNF- and NFV Network Service-agnostic, i.e., does not deal with the business purpose of the software, focusing only on life cycle management and ensuring the required conditions for the software to function, both for the entire constellation and its individual elements. The management of the business purpose aspect of the "NFV Network Service" is delegated to the separate management entity, Operations Support System (OSS)/Business Support System (BSS).

The basic ETSI NFV MANO framework is a simple single-domain and single-data centre one. ETSI NFV also considers the following architectural options related to ETHER project scope:

- Management of Wide Area Network (WAN) infrastructure with WAN Infrastructure Manager (WIM) to support distributed, multi-data centre deployment [27]; both WIM internal to MANO and external (located in the OSS/BSS functionality) can be used.

- In addition to virtualisation technology, initially limited to virtual machines, the support of containerisation technology is included [27].

- Multiple VNFMs in MANO stack to support VNFMs both generic and specific to VNF provider [28].

- Support of multiple infrastructure domains, through interaction of NFVO/VNFM with both multiple VIMs and a Resource Orchestrator (RO), i.e., an "umbrella VIM and Orchestrator". The RO role may be further extended to a role of an "infrastructure broker" if the aspect of business negotiations is also included to interactions. When RO is used, taking this way the infrastructure orchestration tasks from the original NFVO role, the role of the latter is reduced to the role of Network Service Orchestrator (NSO) [28].

- Support of multiple orchestration domains (multiple MANO stacks interconnection) through an NFVO-NFVO reference point (a subset of OSS/BSS-NFVO reference point); ETSI does not extend the hierarchy, but the role of coordinator (dubbed "umbrella NFVO" confusingly) is held by the NFVO of one of the domains [28].

3.7.2 ETSI MEC

The MEC initiative is an ISG within ETSI. The purpose of this group is to create a standardised, open environment that will allow the efficient and seamless integration of applications from vendors, service providers, and third parties across multi-vendor MEC platforms.

The work of the MEC initiative aims to unite the telco and IT-cloud worlds, providing IT and cloud-computing capabilities within the RAN (Radio Access Network). This work is published in the form of normative specifications, informative reports, and white papers [29].

Especially relevant for ETHER is the role of the MEC orchestrator and the MEC platform manager as defined by the standard [30], as the core components that have the complete overview of the system and manage the specific functionality and the applications running on each particular MEC host. Moreover, the ETSI MEC 5G integration [31] describes the key issues, solution proposals and recommendations for the integration of a MEC System into a 5G System.

3.7.3 ETSI ZSM

The ZSM initiative is an ISG within ETSI. The purpose of this group is to accelerate the definition of the required architecture and solutions for a full E2E automation of network and service management.

The ETSI ZSM reference architecture [32] is relevant for the definition of the ETHER zero-touch network and service management layer, as well as the report that tackles the E2E cross-domain service orchestration and automation [33]. Moreover, the use of AI for the automation of network and service management operations is considered in the ETSI Group Specification ZSM 012 reference document [34].

3.7.4 ETSI ENI

The Experiential Networked Intelligence (ENI) ISG of ETSI is defining a Cognitive Network Management architecture, using AI techniques and context-aware policies to adjust offered services based on changes in user needs, environmental conditions, and business goals [35]. As a result, it fully benefits all networks, including 5G networks, by providing automated service provision, operation, and assurance, as well as optimised slice management and resource orchestration. ENI has also launched proofs of concept aiming to demonstrate how AI techniques can be used to assist network operation including 5G.

The use of AI techniques in the network is expected to solve problems of future network deployment and operation. In the context of ETHER, highly relevant is the ENI reference system architecture [36]. It specifies Functional Blocks and Reference Points for providing a model-based, policy-driven, context-aware system that provides recommendations and/or commands to Assisted Systems. This communication is to be done directly or indirectly via a Designated Entity acting on behalf of the Assisted System. A Designated Entity is a Network Management System (NMS), Element Management System (EMS), controller, or current or future management and orchestration systems. The ENI System is expected to enable the Assisted System to perform more accurate and efficient decision making. The ENI system is based on an experiential architecture. This means that it learns through experience (i.e., through the operation of the systems that it assists in governing). This self-learning principle is key to improving operator experience and enables the system to evolve over time from proposing to implementing decisions.

3.7.5 ETSI SES/SCN

The ETSI working Group on Satellite Communications and Navigation (SCN) is part of ETSI's Technical Committee (TC) on Satellite Earth Stations and Systems (SES). Their terms of reference can be read at [37] and [38]. SCN has produced a wide-ranging set of technical reports (TRs) and specifications (TSs) relating to satellite communications.

There are reports and specifications relating to many aspects of satellite communications and navigation, for example in the following areas of potential relevance to ETHER:

- Global Navigation Satellite Systems (GNSS)-related aspects.
- Satellite communications interfaces.
- Life-cycle assessments of satellite broadband greenhouse gas emissions.

In addition, there are two current work items; the first looking at comparing the performance of Digital Video Broadcasting – Satellite 2 eXtensions (DVB-S2X) with 5G-NR over bent-pipe satellites[1]; and the second paving the way for the specifications for quantum key distribution via satellite.

3.8 IEEE

The Institute of Electrical and Electronics Engineers (IEEE) P1981.1 working group defines a framework for the Tactile Internet, including descriptions of various application scenarios, definitions and terminology, functions, and technical assumptions. This framework prominently also includes a reference model and architecture, which defines common architectural entities, interfaces between those entities, and the mapping of functions to those entities. The Tactile Internet encompasses mission critical applications (e.g., manufacturing, transportation, healthcare and mobility), as well as non-critical applications (e.g., edutainment and events). There are mainly two items, the haptic codecs, and the network architecture. Currently, the standard document is under the process to be published.

The Future Networks working group [39] within the IEEE looks to provide direction for both 5G and beyond. Periodically it produces the International Network Generations Roadmap [40] (INGR) that is "*created by experts across industry, government, and academia, helps guide operators, regulators, manufacturers, researchers, and others involved in developing new communication technology ecosystems by laying out a technology roadmap with 3-year, 5-year, and 10-year horizons*". There is a chapter on non-terrestrial networks that includes a taxonomy of different architectures.

3.9 O-RAN

While operators around the world believe that a modern 5G infrastructure will enable new vertical market revenue opportunities, there is unanimous agreement that traditional supply chain and procurement models must change. Status quo, proprietary product architectures and complicated, vendor specific Operations and Management (O&M) systems will not serve these operators' collective goals and must evolve to overcome the real capital, operational,

[1] A bent-pipe satellite is one that simply amplifies the signals from the terrestrial transmitters, shifts the frequency and retransmits the same signal back to the ground. The signal is not demodulated and the data not processed in anyway on board the satellite.

and technical challenges the industry is facing today. The Open RAN (O-RAN) Alliance [41] was founded by operators to clearly define requirements and help the supply chain eco-system build and deploy innovative products and services that will strengthen the industry well into the 21st century.

The most important functional components introduced by the O-RAN architecture are the Non-RT Radio Intelligent Controller (RIC) and the Near-RT RIC. While the former is hosted by the Service Management and Orchestration (SMO) framework of the system (e.g., integrated within Open Network Automation Platform (ONAP) [42]), the latter may be co-located with 3GPP gNB functions, namely, O-RAN-compliant Centralised Unit (O-CU) and/or Distributed Unit (O-DU), or fully decoupled from them as long as latency constraints are respected. The O-RAN architecture also includes the so-called O-Cloud, an O-RAN compliant cloud platform that uses hardware accelerator add-ons when needed (e.g., to speed up Fast Fourier Transform (FFT) or decoding workflows) and a software stack that is decoupled from the hardware to deploy eNBs/gNBs as VNFs in vRAN scenarios.

Both the Non-RT RIC and the Near-RT RIC are potentially relevant to the ETHER activities. Therefore, in the following, we detail the jurisdiction and roles of each functional component defined above.

The SMO framework consolidates several orchestration and management services, which may go beyond pure RAN management such as 3GPP (NG-)core management or E2E network slice management. In the context of O-RAN, the main responsibilities of SMO are (i) fault, configuration, accounting, performance, and security (FCAPS) interface to O-RAN network functions; (ii) large timescale RAN optimisation; and (iii) O-Cloud management and orchestration via O2 interface, including resource discovery, scaling, FCAPS, software management, create, read, update, and delete (CRUD) O-Cloud resources.

Non-RT RIC is a logical function residing within SMO and provides the A1 interface to the Near-RT RIC. Its main goal is to support large timescale RAN optimisation (seconds or minutes), including policy computation, ML model management (e.g., training), and other radio resource management functions within this timescale. Data management tasks requested by the Non-RT RIC should be converted into the O1/O2 interface; and contextual/enrichment information can be provided to the near-RT RIC via A1 interface.

Near-RT RIC is a logical function that enables near-real- time optimisation & control and data monitoring of O-CU and O-DU nodes in near-RT timescales (between 10 ms and 1 s). To this end, Near-RT RIC control is steered by the policies and assisted by models computed/trained by the Non-RT RIC. One of the main operations assigned to the near-RT RIC is radio resource management (RRM) but near-RT RIC also supports 3rd party applications (so-called xApps).

This architecture inherently enables three independent control loops – yet with sporadic interactions:

- **Non-RT RIC control loop:** Long-timescale operation of the orders of seconds or minutes. The goal is to perform O-RAN specific orchestration decisions such as policy configuration or ML model training.

- **Near-RT RIC control loop:** Sub-second time scale operation with the goal of performing tasks such as policy enforcement or radio resource management operations.

- **O-DU Scheduler control loop:** RT operation performing legacy radio operations such as Hybrid Automatic Repeat reQuest (HARQ), beamforming or scheduling – out of O-RAN's scope.

O-RAN's disposition towards software-defined AI-assisted RAN control fosters different degrees of openness, namely, systems comprised of (i) O-RAN-compliant PNFs exposing and using O-RAN interfaces so different vendors can interplay (lowest degree of openness); (ii) chassis of servers and racks in a cloud shared among multiple vendors (higher degree of openness); and (iii) one or multiple O-Clouds, a fabric of commercial off-the-shelf servers (including Field Programmable Gate Arrays (FPGAs) or Graphical Processing Unit (GPU) accelerators) and networking infrastructure hosting O-RAN software that is decoupled from the hardware at different layers: hardware (e.g., ETSI NFV Infrastructure, NFVI, HW sub-layer), middle (e.g., ETSI NFVI virtualisation sub-layer + VIM) and a top layer hosting virtual RAN functions (highest degree of openness).

3.10 5G PPP AND R&D PROJECTS

The ETHER project will seek to foster synergies with several research and innovation activities that exhibit useful complementarities, in the fields of zero-touch orchestration and management, edge computing, AI/ML, use cases, KPIs and verticals as well as non-terrestrial networks. The participation of ETHER partners in these initiatives ensures good alignment as well as smooth collaboration and exchange of know-how. ETHER will attempt to setup communication channels with these initiatives and will pursue the creation of a well-defined collaboration framework by means of a Memorandum of Understanding and Non-Disclosure Agreement. In the following, the main R&D projects targeted by ETHER are detailed as well as their relevance to the project.

3.10.1 MonB5G

The European Union (EU) Horizon 2020 MonB5G project introduced a novel zero-touch multi-domain hierarchical slice management and orchestration platform leveraging AI-driven operations and addressing the problem of scalability of network slice management and orchestration [43]. The proposed concept is based on ITU-T management system decomposition [44] and exploits MAPE (Monitor-Analyse-Plan-Execute) [45] paradigms by introducing generic Monitoring System, Analytic Engine, Decision Engine and Actuator entities to handle AI-driven operations at each hierarchy level and at different time scales. Some of the key features of the MonB5G framework include [43]:

- Separation of concerns achieved by introduction of OSSes/BSSes per orchestration domain, which handle slices' Life Cycle Management (LCM) and resource management in a slice agnostic manner, as well as embedding management into the slices, i.e., implementing In-Slice Management (ISM). Such an approach allows for slice management plane isolation and its separation from domains' OSSes/BSSes (not provided by ETSI NFV MANO and 3GPP).

- AI-driven management operations distribution (node, slice, orchestration domain and E2E slice level operations).

- Orchestration scalability by using hierarchical E2E slice orchestration (master and multiple domain-level orchestrators).

- Slice-driven orchestration issued by slice components via relevant orchestrator interfaces.

- Slice management scalability and programmability, achieved by using ISM (separate management platform for each slice) implemented as a set of VNFs connected to the slice VNFs, and easily extendable during slice run-time.

- Enhanced security of slices by slice management spaces isolation and limiting information exchange between OSS/BSS instances of each domain.
- Support for external slice management provisioning, i.e., Management as a Service (MaaS).
- Infrastructure management programmability and introduction infrastructure of optimisation functions taking part in negotiations between MonB5G framework operator and infrastructure owner (energy and costs optimisation).

The MonB5G framework also satisfies some of the most significant ETSI ZSM requirements [46] in the categories of Monitoring and Data Analytics Functionalities, Management Actions, Management Operations, Control Loops Support and Other Functionalities (e.g., related to slice instances scaling, slice run-time configuration, etc.).

3.10.2 Hexa-X

Hexa-X [47] is a flagship 6G project funded by European Union. It aims to pave the way for the next generation of wireless networks. Hexa-X vision is to connect human, physical, and digital world via 6G enablers. As described in [48], Hexa-X defined 6 main challenges that need to be addressed to enter Beyond 5G (B5G)/6G era, which are:

- Connecting Intelligence, which focuses on coupling the human, physical and digital worlds.
- Network of Networks, which is expected to consist of many specialised sub-networks able for mass-scale and wide-area deployment.
- Sustainability, which focuses on the reduction of global Information and Communications Technology (ICT)-related environmental and CO_2 footprint.
- Global Service Coverage, connecting rural areas, transport over oceans or vast land masses, which will promote economic growth, reduce digital divide, and improve safety and operation efficiency in currently underserved areas.
- Extreme Experience, which focuses on providing extreme bitrates, extremely low latencies, and seemingly infinite capacity.
- Trustworthiness, which focuses on ensuring cyber-resilience, privacy, and trust via security technology enablers tailored to ever emerging new types of threats related to technological advancements and increased scale of interconnected endpoints and subnetworks.

Hexa-X project also defines five main 6G use case families:

- Sustainable development, focusing on UN SDGs of reducing inequalities by providing global access to digital services such as remote healthcare, as well as reduction of environmental impact of infrastructure and services.
- Massive twinning, which expands on the use of digital twins to intertwine physical and digital world, to improve efficiency in areas like manufacturing or agriculture.
- Immersive telepresence, which blurs the boundary between physical and digital world, creating more immersive communication tools in everyday life.

- From robots to cobots (collaborative robots), which includes use cases related to the interaction of robots and autonomous systems with humans. An example of use case is “consumer robots”, which can assist in everyday domestic chores. This use case family is especially connected to Trustworthiness challenge.

- Local trust zones, which encompass different use cases with specialised sub-networks and networks of networks, and require extreme reliability, availability, and resilience, i.e., sensor infrastructure web.

Through these defined challenges and use cases, Hexa-X presents its vision of 6G, as well as creates a list of topics and directions, which can be undertaken by future projects. Hexa-X strongly focuses on the creation of enablers, showcasing some of these defined use cases. 6G architecture vision will be created as a part of the follow-up EU project “Hexa-X II” [49], which at the time of this publication already started. Although general 6G architecture is not yet ready, Hexa-X proposed 6G MANO architecture in D6.2. Key features of this architecture include microservices-based approach, intent-based services, AIOps/DevOps friendly, possibility of private networks and zero-touch management.

ETHER project, aiming to integrate TN and NTN networks, follows described in Hexa-X project vision of 6G, by helping to address both “Network of Network and “Global Service Coverage” challenges.

3.10.3 5G-COMPLETE

5G-COMPLETE aims to revolutionise the beyond 5G architecture, by efficiently combining compute and storage resource functionality over a unified ultra-high capacity converged digital/analogue Fibre-Wireless (FiWi) RAN. By employing the recent advances in Ethernet fronthauling introduced by the evolved Common Public Radio Interface (eCPRI) standard as a launching point, 5G-COMPLETE introduces and combines a series of key technologies under a unique architectural proposition that brings together:

- High capacity of fibre and high-frequency radio.
- Audacity of converged FiWi fronthauling.
- Spectral efficiency of analogue modulation and coding schemes.
- Flexibility of mesh self-organised networks.
- Efficiency of high-speed and time-sensitive packet-switched transport.
- Rapid and cost-efficient service deployment through unikernel technology.
- Enhanced security framework based on post-Quantum cryptosystems.

5G-COMPLETE’s proposed converged Computing/Storage/RAN infrastructure effectively merges the 5G New Radio fronthaul/midhaul/backhaul faculties into one common Ethernet-based platform and transforms the RAN into a low-power distributed computer that shapes new network concepts. 5G-COMPLETE’s results will be validated in a range of scalable lab- and field-trial demonstrators in Athens (Greece), Lannion (France) and Bristol (UK). Upon completion, 5G-COMPLETE will have introduced new business models and novel research opportunities that will be streamlined into tangible results by its 13 consortium partners that expand along the complete 5G research and market chain.

ETHER will be based on and will advance the E2E performance optimisation framework of 5G-COMPLETE by taking into account both the communication, computational and storage resources (terrestrial domain), SDN-NFV Mano, edge computing, and AI/ML algorithms developed within the project.

3.10.4 DAEMON

The DAEMON H2020 European project develops and implements innovative and pragmatic approaches to Network Intelligence (NI) design that enables high performance, sustainable and extremely reliable zero-touch network system. DAEMON designs an E2E NI-native architecture for B5G that fully coordinates NI-assisted functionalities.

In particular, DAEMON will carry out a systematic analysis of which NI tasks are appropriately solved with AI models, providing a solid set of guidelines for the use of machine learning in network functions. Building on the insights of this analysis, DAEMON will design NI algorithms to drive a core set of B5G network functionalities. The NI-assisted functionalities will be finally deployed into an original E2E NI-native architecture for B5G that enables their full coordination.

ETHER will seize opportunities to build upon the DAEMON network intelligence algorithms (AI/ML) and zero-touch orchestration so as to account for the integrated Terrestrial Non-Terrestrial Domain. Specifically, DAEMON defines a Network Intelligence Plane (NIP) that manages the lifecycle of AI/ML models deployed in the mobile network and coordinates their operation in terms of monitoring needs, resource usage and decision-making conflicts [50]. ETHER will explore if such a NIP can be considered in the E2E architecture studied by the project, or if any of its components are relevant to the new solutions devised in ETHER.

3.10.5 QUANGO

The main objective of QUANGO is the design of a network of 12-Unit CubeSat LEO satellites offering combined capabilities for communication secured by Quantum Key Distribution (QKD) and for 5G IoT NTN connection. QUANGO aims at overcoming the current classical cryptographic systems, preventing the vulnerabilities led by the advent of quantum computers by designing and prototyping the key elements of a satellite mission (payloads, sub-systems and ground stations) targeting the delivery of both IoT and QKD services. In particular, in QUANGO, a Technology Readiness Level (TRL) 4 weak coherent source and Pointing, Acquisition, and Tracking (PAT) system are under development, along with the hardware of a 5G radio payload expected to achieve (TRL 5-6).

ETHER will build upon QUANGO by leveraging the payload hardware developed by SIOT as a starting basis for the flexible payload activity within ETHER. The QUANGO payload hardware will be used as part of the testbed for use case 1, where delay-tolerant IoT application using Narrowband IoT (NB-IoT) are a major mMTC that can be deployed over a LEO satellite constellation and that will benefit from regenerative payloads. The QUANGO payload provides functionalities such as 5G IoT NTN and Store and Forward. These functionalities are of special interest in ETHER, as they enable services for delay-tolerant applications, which can be provided with a small LEO constellation. With a constellation of satellites of small size, service and feeder link discontinuities are present, therefore Store and Forward functionalities are required for the user and control plane, functionality leverage from the QUANGO payload.

3.10.6 SaT5G

The SaT5G project [51] was a consortium of sixteen organisations including universities and companies involved in satellite construction, satellite operation, an MNO, and a terrestrial core vendor. This was part of the H2020 call ICT-2016-2 and ran from 2017 to 2020. The project coordinator was Avanti.

The project vision was to develop a cost effective “plug and play” satcom solution for 5G to enable telcos and network vendors to accelerate 5G deployment in all geographies and at the same time create new and growing market opportunities for satcom industry stakeholders. The delivered against six principal project objectives that were to:

- Leverage relevant on going 5G and satellite research activities to assess and define solutions integrating satellite into the 5G network architecture.
- Develop the commercial value propositions for satellite-based network solutions for 5G.
- Define and develop key technical enablers for the identified research challenges.
- Validate key technical enablers in a laboratory test environment.
- Demonstrate selected features and use cases.
- Contribute to the standardisation at ETSI and 3GPP of the features enabling the integration of satcom solutions in 5G.

The project provided significant inputs, over 200, to the 3GPP and ETSI standards tracks to facilitate the seamless integration of satellite communications into 5G.

3.10.7 5GENESIS

The main goal of the 5GENESIS project [52] was to validate 5G KPIs for various 5G use cases, in both controlled set-ups and large-scale events. This brought together results from a considerable number of EU projects as well as the partners’ internal R&D activities to realise an integrated E2E 5G Facility and multiple test beds. This was an H2020 project that ran from 2018 to 2022.

One of the testbeds, based out of Limassol, included the use of some of Avanti’s satellite capacity. Support for 5G satellite backhaul with network slices was demonstrated using conventional satellite communications equipment thus paving the way to add 5G services to existing base stations relying on satellite backhaul without dramatically changing the installed satellite communications equipment, thereby reducing the upgrade costs.

3.10.8 6G-SANDBOX

6G-SANDBOX is part of the 6G Smart Networks and Services Joint Undertaking (SNS JU) Phase 1 program and has as its main objective to develop a large-scale EU-wide experimental platform for 6G emerging technologies. 6G-SANDBOX will provide an evolvable experimental infrastructure for the duration of the SNS programme, where companies and research institutions can test and validate their new technologies. Experimenters can use the platform by contacting the consortium [53].

6G-SANDBOX combines digital and physical nodes to deliver fully configurable, manageable and controllable E2E networks for validating new technologies and research advancements for 6G. It will enable entities across the EU to test promising technical 6G enablers, including network automation, cybersecurity, digital twins, and AI, as well as technologies that streamline energy consumption.

Part of the project’s output includes a satellite emulator to study hybrid-access and dual-connectivity between TN and NTN. In June 2023, 6G-SANDBOX announced the signing of a Memorandum of Understanding (MoU) with the European Space Agency (ESA) to advance innovation towards integrating satellites with terrestrial networks built on 5G and future 6G technologies by connecting 6G-SANDBOX testbeds with ESA 5G/6G Hubs.

ETHER will establish a liaison with 6G-SANDBOX to identify similar and complementary activities and approaches. Common dissemination activities between the two projects may be considered.

3.10.9 5G!Drones

5G!Drones [54] aimed to trial several UAV use cases covering eMBB, URLLC, and mMTC 5G services, and to validate 5G KPIs for supporting such challenging use cases. The project targeted to drive the UAV verticals and 5G networks to a win-win position, on one hand by showing that 5G can guarantee UAV vertical KPIs, and on the other hand by demonstrating that 5G can support challenging use cases that put pressure on network resources, such as low-latency and reliable communication, massive number of connections and high bandwidth requirements, simultaneously. 5G!Drones built on top of the 5G facilities provided by the ICT-17 projects and a few support sites, while identifying and developing the missing components to trial UAV use cases.

The project features network slicing as the key component to simultaneously run the three types of UAV services on the same 5G infrastructure (including the RAN, back/fronthaul, Core), demonstrating that each UAV application runs independently and does not affect the performance of other UAV applications, while covering different 5G services. While considering verticals will be the main users of 5G!Drones, the project built a software layer to automate the run of trials that exposes a high level API to request the execution of a trial according to the scenario defined by the vertical, while enforcing the trial's scenario using the API exposed by the 5G facility, as well as the 5G!Drones enablers API deployed at the facility. Thus, 5G !Drones worked on abstracting all the low-level details to run the trials for a vertical and aimed at validating 5G KPIs to support several UAV use cases via trials using a 5G shared infrastructure, showing that 5G supports the performance requirements of UAVs with several simultaneous UAV applications with different characteristics (eMBB, URLLC and mMTC). Using the obtained results, 5G!Drones will allow the UAV association to make recommendations for further improvements on 5G.

ETHER will build upon 5G!Drones leveraging expertise on light NT platforms. In particular, it will build upon "UC4: Connectivity during crowded events", where an on-demand swarm of UAVs equipped with 5G small cells is employed to provide better coverage and enhance capacity. Main aspects include the deployment of aerial gNBs and the transmission of command and control channel over 5G.

3.10.10 EAGER

EAGER [55] is an ESA-funded project that aims to pave the way for the use cases, technologies, and techniques that will constitute the core of Europe's 6G satellite communications. EAGER will build and advance the existing innovations to prepare for next generation satellite networks, targeting highly efficient and deeply integrated satellite networks in beyond 5G and 6G cellular systems. Its key objectives are to:

- Assess and adopt solutions/use cases including multiple-input multiple-output (MIMO) techniques, mMTC, and more.
- Identify and evaluate novel concepts both in the waveform and in the network domain, as well as in the space and ground segment technologies.

- Develop relevant software and tools to properly assess the performance of the most promising techniques and technologies.

EAGER project is split into the following 5 distinct phases:

- Phase 1: Identify the most promising scenarios and services beyond 5G satellite systems.
- Phase 2: Carry out a review and gap analysis of the techniques and technologies for the identified services.
- Phase 3: Select the techniques and technologies for beyond 5G satellite systems based on the preliminary evaluation.
- Phase 4: Develop an integrated software simulator covering all use cases and techniques in order to assess their performance.
- Phase 5: Define the technology roadmap to increase TRL for the techniques, technologies, and architectures previously assessed.

As in ETHER, EAGER also considers a 3D multi-layered network that comprises terrestrial, aerial, and space layers. Several of the enabling technologies for the hybrid network that are considered in EAGER are also considered in ETHER, such as flexible payloads, inter-NTN links, waveform design, and artificial intelligence and machine learning. Hence, ETHER will be closely following the developments in EAGER and work in liaison with it to jointly promote the advancements of both projects. Such collaboration has already started with a workshop co-organisation, including additional projects, at the EuCNC 2023 conference in Gothenburg, Sweden.

3.10.11 SANSA and DYNASAT

SANSA [56] and DYNASAT [57] were H2020 projects related to the integration of terrestrial with satellite networks. In particular:

- The solution envisaged in SANSA was a spectrum efficient self-reconfigurable hybrid terrestrial-satellite backhaul network based on three key principles: (i) a seamless integration of the satellite segment into terrestrial backhaul networks; (ii) a terrestrial wireless network capable of reconfiguring its topology according to traffic demands; (iii) a shared spectrum between satellite and terrestrial segments.
- The aim of DYNASAT was to research, develop, and demonstrate the use of innovative techniques for bandwidth-efficient transmission and efficient spectrum usages, such as dynamic spectrum allocation and sharing, multi-satellite cooperative multi-user multi-input multi-output (MIMO), beam hopping, multi-beam precoding with user clustering, and advanced interference management.

Relevant to ETHER is the fact that both projects investigate dynamic spectrum sharing approaches between the 2 networks, which is also the aim of ETHER, based on T3.2.

3.10.12 5G-LEO

5G-LEO [58] aims to accelerate the development of OpenAirInterface (OAI) [59] as an open-source tool allowing the exchange and comparison of 5G NTN results by the SatCom community and facilitating the collaboration in R&D activities. The extended OAI software library is seen as an important instrument to develop early prototypes for validating key 5G

NTN design aspects and providing prompt feedback to the 3GPP standardization process. The main objectives of the 5G-LEO project are the following:

- Review the reference scenarios and use cases identified for NR-NTN system deployments by 3GPP and selection of a 5G LEO baseline scenario to be implemented and verified with the extended OAI library.
- Identification of the fundamental gaps and changes needed in the code base for properly extending OAI for the 5G LEO baseline scenario.
- Implementation of the required OAI code adaptations for the different layers of the 3GPP protocol stack to support 5G LEO and closely following the developments in 3GPP standardization for 5G-NTN within the 3GPP Release 17 and potentially in Release 18.
- Set-up an end-to-end 5G LEO demonstrator in the laboratory for experimental validation of the OAI extension for the 5G-LEO baseline scenario.

Relevant to ETHER is the vertical handover mechanism investigation in 5G-LEO.

3.11 GLOBAL SATELLITE OPERATORS' ASSOCIATION

The Global Satellite Operators' Association (GSOA) claims to be "*the global CEO-driven association representing satellite operators*" who provide "*thought-leadership and is recognised as the representative body for satellite operators by international, regional and national bodies*". It has several working groups that consolidate industry views and produce white papers and other positioning statements.

GSOA is the market representation partner (MRP) for the satcom sector in 3GPP.

As of 1st June 2023, GSOA merged with the Global VSAT Forum (GVF) that "*will result in GSOA becoming a trade association comprised of 70 member companies spanning the entire satellite ecosystem from across the globe with unparalleled resources, experience and relationships developed over their combined 48 years of existence, providing a strong single voice for the satellite industry*". GVF brings some additional working groups and provides training.

3.12 SUMMARY OF THE STATE OF THE ART

The integration of TN and NTN increasingly becomes a popular topic, creating many research activities. It is essential for the ETHER project to leverage its work based on the output of these activities. The presented State of the Art (SotA) helps to identify the current technological trends, use cases, societal issues and gaps between the existing solutions. The most notable emerging technological trends surrounding TN-NTN integration, which is the focus of ETHER project, are related to network softwarisation, cloud-native solutions, and AI-driven distributed MANO. Most of the associated issues are related to dynamic nature of satellite constellations, which require new routing algorithms, smart SDN placement, and regenerative payloads. New access networks also create the necessity of RAN unification as well as new waveform design. Envisioned 6G features provide a focal point for the ETHER approach.

ETHER project will provide demonstrations for use cases related to mission-critical avionics scenarios, semantics-aware and delay-tolerant IoT applications and direct handheld access to

LEO satellites further expanding SotA and bringing the technology closer to the envisioned 6G network.

4 ARCHITECTURAL REQUIREMENTS, INNOVATIONS, AND DESIGN PRINCIPLES

This section provides the outline of the rationale behind the ETHER architecture design. The focus is laid on the use case specific requirements and embedded innovations, which, together with the recent research outcomes (described in section 3) contribute to the ETHER architecture design principles.

4.1 ETHER USE CASE-SPECIFIC REQUIREMENTS

The following use case specific requirements that have been identified in task T2.1, and in the current D2.2 draft are shown in Table 4-1 below. The requirement identifiers are in the form *ETH-REQ-UCXn-tt-xxx*. Where *Xn* is 1, 2 or 3 for the use case, and *x* is a sequential integer for each category and use case. In use case 2 and 3 *tt* is FN for functional requirements whereas it is NF for non-functional requirements. In use case 1 *tt* refers to the specific aspects; so, FP = Flexible Payload & service orchestration, DT = Delay Tolerant IoT, and SE = SEmantics-aware information handling.

Table 4-1: Initially identified requirements

Identifier	Requirement	Description
ETH-REQ-UC1-FP-01	Payload FPGA resources management	Manage and deploy in a dynamic and autonomous way FPGA resources considering specific context.
ETH-REQ-UC1-FP-02	Payload FPGA resources availability	Control available resources and its percentage of use.
ETH-REQ-UC1-FP-03	Payload FPGA services deployment	Ensure that services are deployed correctly using virtualisation techniques plus containers.
ETH-REQ-UC1-FP-04	Payload FPGA resources sharing	Ensure proper multiplexing for resource sharing, considering interfaces (UART, Ethernet, ...) and other hardware resources (memory, buffers, analogue-to-digital converters).
ETH-REQ-UC1-FP-05	Payload system performance metrics	Extract metrics of the system when enabled to monitor different parameters of the system: power consumption, CPU, disk and memory usage.
ETH-REQ-UC1-DT-01	Intermittent – scheduled contacts	Agreement to establish a contact at a particular time.
ETH-REQ-UC1-DT-02	Intermittent – opportunistic contacts	Contacts are not scheduled but present themselves unexpectedly.
ETH-REQ-UC1-DT-03	Intermittent – predicted contacts	Predicted contacts have no fixed schedule, but instead are predictions of likely contact times and durations based on a history of previous observed contacts or some other information (satellite ephemerides) and ML ETHER.
ETH-REQ-UC1-DT-04	Congestion and flow control	Device messages arrive at destination, vertical and horizontal Handover, support of congestion and flow control, message retransmissions.
ETH-REQ-UC1-DT-05	High latency, low data rate	Support for high latency at low data rates for Delay-Tolerant IoT Applications.

Identifier	Requirement	Description
ETH-REQ-UC1-DT-06	Connection discontinuity	Support of a Low-Density LEO Constellation with service link and feeder link discontinuity.
ETH-REQ-UC1-DT-07	Store and forward	Support for store and forward on low density LEO CONSTELLATION, to solve connection discontinuity, and support of store and forward over vertical and horizontal handovers according to ML ETHER.
ETH-REQ-UC1-DT-08	Traffic model Mobile Autonomous Reporting (MAR)	MAR exception reports (notify sporadic events), MAR periodic reporting (regular transmission), firmware updates.
ETH-REQ-UC1-DT-09	Mobility management	Dynamic organisation of moving tracking areas, or broadcasting of ephemerides to end devices to assist them in using network and power resources efficiently.
ETH-REQ-UC1-DT-10	Support for different services	Support of multi-radio applications based in NB-IoT using ML ETHER and orchestrated by the MANO.
ETH-REQ-UC1-SE-01	Sample processing	Need to influence the whole information chain from the point we generate the information, encoding, transmitting, and receiving. Furthermore, the utilisation of information to achieve a certain goal, for example datasets (or partial datasets) to train an ML algorithm.
ETH-REQ-UC1-SE-02	Joint sample and transmit	Need to influence the whole information chain from the point we generate the information, encoding, transmitting, and receiving. Furthermore, the utilisation of information to achieve a certain goal, for example datasets (or partial datasets) to train an ML algorithm.
ETH-REQ-UC1-SE-03	Support for E2E information handling beyond the sample and transmit	Need to influence the whole information chain from the point we generate the information, encoding, transmitting, and receiving. Furthermore, the utilisation of information to achieve a certain goal, for example datasets (or partial datasets) to train an ML algorithm.
ETH-REQ-UC1-SE-04	Content caching	Need to find the criteria for reusable traffic to effectively cache the freshest and also valuable information proactively.
ETH-REQ-UC2-FN-01	Migrate TN to NTN	Migration of the communication of a user from a terrestrial RAT to a non-terrestrial one and vice versa when it is needed.
ETH-REQ-UC2-FN-02	Vertical handover	The vertical handover process can involve either the AMF of the open air-interface core that will be used or (NG handover) or the Xn interface between the base stations that belong to the different RATs.
ETH-REQ-UC2-FN-03	Waveform	Choice of a suitable waveform in the cases of communication with either stationary or fast-moving platforms.
ETH-REQ-UC2-FN-04	LEO swarm	LEO satellites work in swarm formations and transmit the same signal in the distributed way towards a user on the ground.
ETH-REQ-UC2-FN-05	UE beam steering	Designed handheld device antenna enables electronic beam-steering, based on which the trajectory of a moving platform acting as a base station, such as a LEO satellite, can be followed.
ETH-REQ-UC2-NF-01	Vertical handover	Seamless vertical handover process to the users.

Identifier	Requirement	Description
ETH-REQ-UC2-NF-02	Broadband	Broadband communication to the users by either terrestrial or non-terrestrial means.
ETH-REQ-UC2-NF-03	Coverage	Complete user coverage in urban and remote/rural areas.
ETH-REQ-UC3-FN-01	RAN in TN, HAPSs, and SAT	Enables the 3D network layers to communicate with the aircraft user equipment, with a possibility to link them through a unified radio access network (RAN) framework.
ETH-REQ-UC3-FN-02	Open 5G core network	Required to communicate with the core network resource allocation and user mobility and management gateway functions through specific APIs.
ETH-REQ-UC3-FN-03	Channel emulation	Required for satellite channel, aircraft UE channel, and all the channels of deployed base stations in the 3 layers including terrestrial, HAPSs, and satellite.
ETH-REQ-UC3-FN-04	Network resource monitoring	contributes towards E2E service communications and management with guaranteed QoS, adaptive scheduling for computation offloading and contents caching.
ETH-REQ-UC3-FN-05	Multilink functionality	In-flight operations are justified by the required communication performance (RCP) and connectivity resilience related to the impact of safety and the efficiency of ATM operations.
ETH-REQ-UC3-FN-06	Network orchestrator	Self-evolving 3D network links and edge resources orchestration, employing predictive data analytics associated with traffic monitoring, traffic prioritisation, resource allocation per flight phase and meeting the expected E2E network performance.
ETH-REQ-UC3-FN-07	3D unified SDN management	Manages the relationship between the different controllers running in the 3D network layers. The emphasis vision for the centralised controllers is focused on improving the control plane efficiency by minimising the signalling required prior to aircraft communication transmission and improving the data plane in the different integrated layers.
ETH-REQ-UC3-FN-08	Service performance degradation	Ensures E2E performance guarantee perspective, from end-device to the last application function, which require evolving time-sensitive network (TSN) capabilities and integrating model predictive control (MPC) solutions for dynamic ATM applications.
ETH-REQ-UC3-NF-01	RCP requirements	Where the capacity provided by the ETHER network architecture should be efficiently allocated to support scenarios requesting reliable, resilient, low latency and high data rates connectivity with integrity, considering high aircraft traffic density. The scenarios are intended to meet the RCPs requirements of the different ATM communication services delivered in the different flight phases.
ETH-REQ-UC3-NF-02	Reliability (availability)	Implies the support of low latency and high ATM communications service availability, where a very high degree of connectivity reliability, resilience and integrity should be met.

Identifier	Requirement	Description
ETH-REQ-UC3-NF-03	3D RAN low latency	Where the overall service latency depends on the delay at the different 5G RAN radio interfaces deployed in the different 3D network layers, the transmission within the 5G RANs deployed in terrestrial, HAPSs and satellites, the transmission to a server which may be external to the whole 5G network, and the data processing. Some of these elements depend directly on the 5G RAN itself, whereas for others the impact can be reduced by suitable interconnections between the 5G RAN and external services by allowing, for example, local services hosting on network edges.
ETH-REQ-UC3-NF-04	Handover reliability and delay	Considers delay resulting in the horizontal handover (HH) process during the process of transferring data from one cell to another, inside the same access core network (i.e., intra-system handover). Or, vertical handover (VH), which involves handover between different access technologies when they are available, but the objective remains the same: transparently guarantee the session continuity from a final aircraft users' point of view.
ETH-REQ-UC3-NF-05	3D network programmability	Turns the 3D network layers from connectivity platform to service enablement platforms by applying service-based architecture patterns (RESTful-based HTTP APIs) across all layers.
ETH-REQ-UC3-NF-06	3D network connected intelligence	Contributes to building up a data and connectivity infrastructure supporting cooperation of trusted AI functions from different network layers.
ETH-REQ-UC3-NF-07	3D network resources optimisation	Contributes to optimised network resource provisioning that leverages AI-enabled data analytics and ensures E2E QoS requirements of each service in a transparent way.
ETH-REQ-UC3-NF-08	Joint network resources optimisation	Configure communication, computation, and storage resources that support highly critical avionics services in an optimal and flexible manner.

4.2 TECHNICAL INNOVATIONS

ETHER introduces eight main technical innovations extending SotA. These innovations will impact the architecture design and should be supported by the ETHER architecture.

4.2.1 (T-1) Integrated architecture

According to the definition of work provided in the ETHER project Grant Agreement, the vision of the project assumes bringing together key technologies for the integration of NTNs to cope with 6G services, exploiting the air and space assets in the best possible way and providing seamless solutions for different scenarios, which cannot be supported exclusively by TNs due to economical and/or physical infeasibility, or excessive energy consumption. The evolution of mobile networks towards multi-domain SDN control and automation aims to cover radio access, transport and core network. E2E hierarchical orchestrators are also conceived as parts of transformed 5G network architectures, leveraging on standard models and interfaces, and covering innovative aspects like slicing management. In the satellite domain, especially in complex multi-orbit, multi-system networks, NTN resources and services orchestrators will also be required, following a similar conceptual approach, to manage the complexity of the domain exposing APIs to relevant systems for the management of the domain functionality with regard to such factors like high RAN nodes mobility.

In this line, ETHER proposes the management of such heterogeneous space-air assets by means of an integrated terrestrial/aerial/space orchestrator, i.e., ETHER Management and Orchestration (MANO), capable of interfacing the 5G Core Network and the TN/NTN virtualisation infrastructure. Thus, a single telecom network can make use of NTN assets in an optimal and seamless manner, which eventually hides the complexity of the dynamic topology that the aerial and space segment brings. The vision of the overall ETHER architecture satisfying the above principles is depicted in Figure 4-1. The main innovations (cf. T-2 to T-8 further in the text) that define specific mechanisms that ETHER aims to bring are also indicated there, namely:

- Seamless vertical and horizontal handovers to address node mobility impact.
- Unified waveform.
- Direct handheld access.
- Flexible payload in the aerial and space layers.
- MEC and caching.
- Semantics-aware data analytics.
- AI-enabled E2E network performance optimisation.
- Integrated ETHER MANO for autonomous ETHER network orchestration.

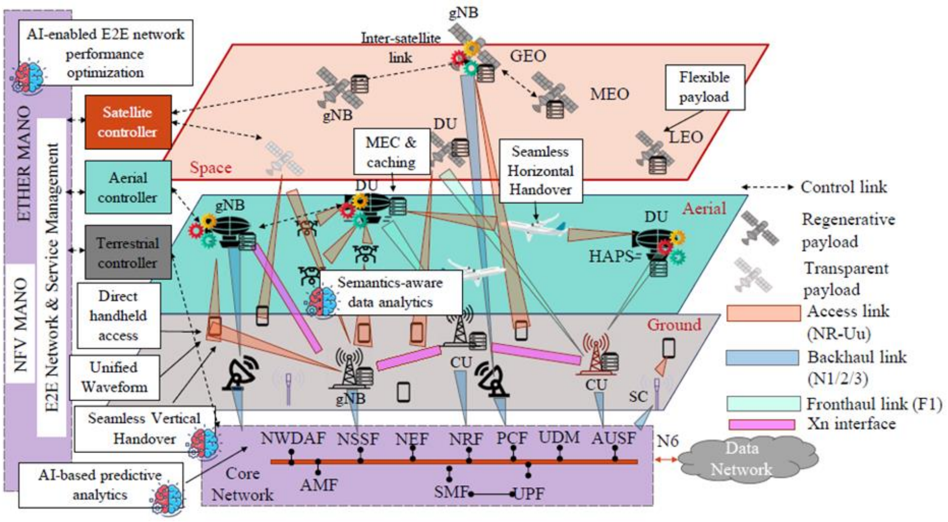

Figure 4-1: ETHER Envisioned 3D Multi-layered Architecture

The ETHER architecture aims to decouple user/data and control planes and to minimise hardware constraints. The overall management of the networks independently of the elements will be enabled by abstraction of lower layer functions (e.g., data forwarding replaced by functions at the control plane). A cross-domain SDN architecture is envisioned, as shown in Figure 4-2, with distributed SDN controllers across the terrestrial, aerial and space layers. In particular, due to the challenging conditions and limited capabilities in fast moving platforms such as LEOs and UAVs, the placement of distributed controllers for the coordination of the rest of the components of each layer through them will be considered in WP4.

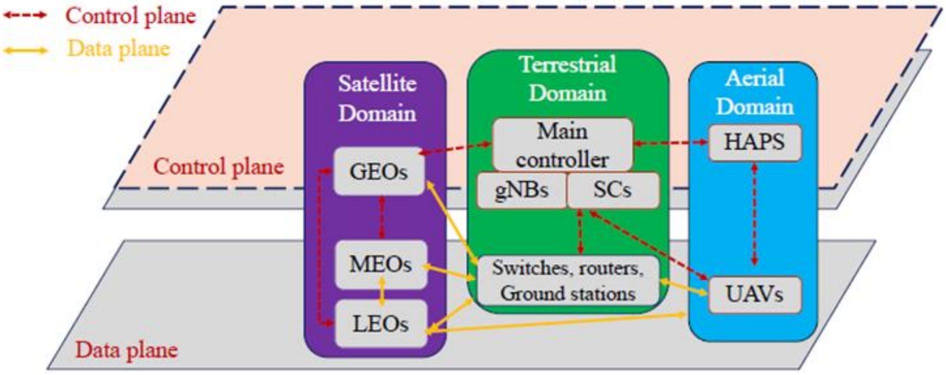

Figure 4-2: Cross-domain ETHER SDN architecture

According to the fundamental 5GS principle, the NFV will be adopted to replace the physical network functions on dedicated hardware with virtualised instances running as software on generic hardware platforms with placement flexibility. It will enable efficient delivery of service and network on demand support network slicing. As current satellite networks are based on different dedicated hardware at different levels (such as router, gateway and modem with limited genericity and flexibility), adoption of NFV with its inherent abstraction will allow to better support beyond 5G and 6G requirements (e.g., support of network slicing in the satellite domain) and will enable their seamless integration with TN via the use of standard 3GPP network interfaces in the satellite network. Additionally, the reduction of satellite system components costs can be achieved by leveraging on the existing large terrestrial system solutions. In particular, the usage of standardised and homogeneous software frameworks in satellite systems will enable the deployment of VNF. Note that satellite systems are currently being developed in a custom manner. Specifically, the hardware and software design are conceived by each satellite manufacturer and mission requirements. This poses some limitations in terms of service/application compatibility among different satellites that with the usage of current virtualisation frameworks could be addressed. The initial overall ETHER architecture is described in the entirety of section 5 of this document.

4.2.2 (T-2) Direct handheld device access at the Ka band from LEO satellites – distributed LEO swarms

6G networks promise massive connectivity of people and devices. However, a very large proportion of the people living in remote/rural areas do not have access to broadband communication due to the lack of the necessary terrestrial infrastructure. Hence, the integration of TN with NTNs primarily aims to bridge such a digital division gap. In terms of direct handheld device access from NTN platforms, this is feasible and has already been demonstrated in the S band. However, due to its congested spectrum there is a notable gap between the user rates that can be offered by terrestrial networks operating in bandwidth-rich millimetre-wave (mmWave) bands and what can be offered by satellites for direct handheld device access in the S band. As a result, in order to provide the potential for broadband direct handheld device access anywhere in the world, the first feasibility study on the topic considers the communication between a very LEO satellite of altitude around 350 km and direct handheld device access at the Ka band [60]. According to its findings, broadband handheld device from LEO satellites is feasible under certain conditions, such as the satellites being almost vertical above the handheld device (smallest distance) and there are not detrimental weather conditions, such as rain and fog. The latter are known to affect mmWave bands more than their sub-6 GHz counterparts.

The above mentioned strict and limiting satellite position and weather requirements for enabling broadband handheld device access at mmWave bands can be alleviated by considering the possibility of HAPSs achieving this due to their much lower altitude. However, since they are not as mature a technology as the one of satellites, it is important to provide solutions that broadband direct handheld devise access from LEO satellites at mmWave bands and, in particular, Ka band (28-40 GHz). Towards this end, ETHER radically considers the deployment of swarm formations of LEO satellites that can cooperatively and coherently transmit signals to ground terminal or receive from them. An indicative scenario is depicted in Figure 4-3. In the corresponding scenario, a ground user in possession of a handheld device is initially connected to a ground gNB from which it received broadband communication at the Ka band. As it moves, the connection starts deteriorating due to an obstacle, such as a building in the radio path. To enable uninterrupted connectivity, the communication with the ground user can be handed over to LEO satellites. If a LEO satellite is almost vertical to the user, possibly one LEO satellite would be enough, under ideal weather conditions to achieve broadband downlink communication with the ground UE, as initial studies have shown [60]. However, in case of adverse weather conditions or low elevation angles of the LEO satellites with respect to the users, we consider that small LEO satellites that fly in swarm formations will collaboratively act as virtual arrays by transmitting the same signal to the ground user so that coherent combining is performed at the latter. Hence, the ETHER architecture considers that small LEO satellites, such as cubesats that fly in a formation, will be orchestrated when needed so that they form virtual arrays and collaboratively either they transmit the same signal to a ground handheld device, or they receive the same signal from it [61]. In the latter case, an assigned master satellite among them is responsible to gather the sample data from all the satellites and perform the needed combining so that the quality of the reception is increased. This architecture requires fast inter-satellite links for dealing with common impairments that such distributive collaboration entails, such as time, carrier frequency, and phase desynchronisation. The latter can arise due to the small perturbation of the satellites that can put the beamforming/combining operations out of coherence if they are not adequately tracked.

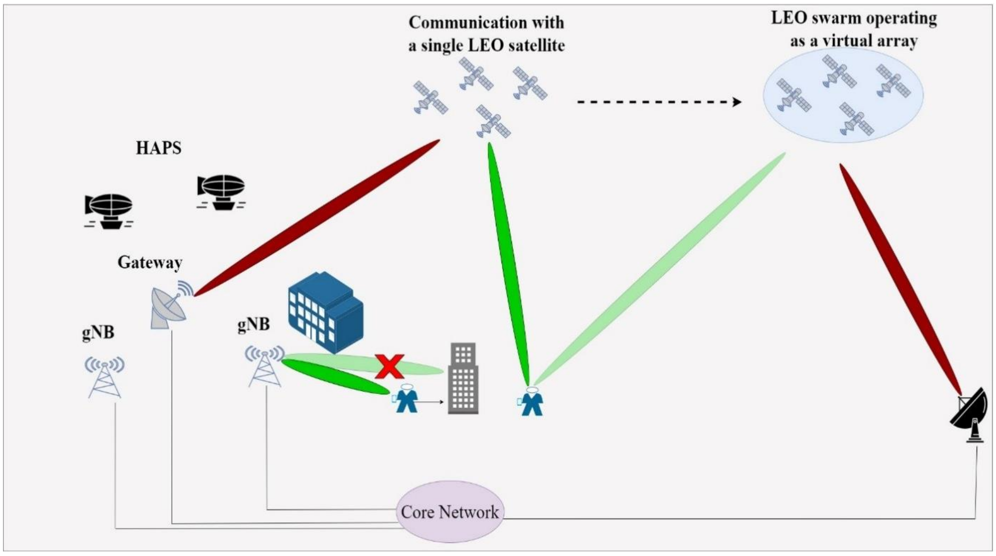

Figure 4-3: Distributed transmission from a swarm of LEO satellites

4.2.3 (T-3) Unified waveform design

The commonly used standardised 5G Orthogonal Frequency Division Multiplexing (OFDM) waveform can induce high performance degradation since it is very sensitive to Doppler frequency shifts that can arise from the communication of ground terminals with the fast-moving LEO and MEO satellites. This is why the newly introduced Orthogonal Time-Frequency Space (OTFS) modulation has been brought forward as a waveform that is insensitive to such shifts and suitable for communication with both stationary and fast-moving platforms, such as

LEO satellites [62]. Hence, the first step in ETHER would be to identify potential scenarios incorporating communication with fast-moving flying nodes, such as LEO satellites where OTFS is much more beneficial than OFDM. In addition, the ETHER project will go one step beyond by designing the most suitable waveform, based on the application, through AI means. A potential reference architecture is illustrated in Figure 4-4.

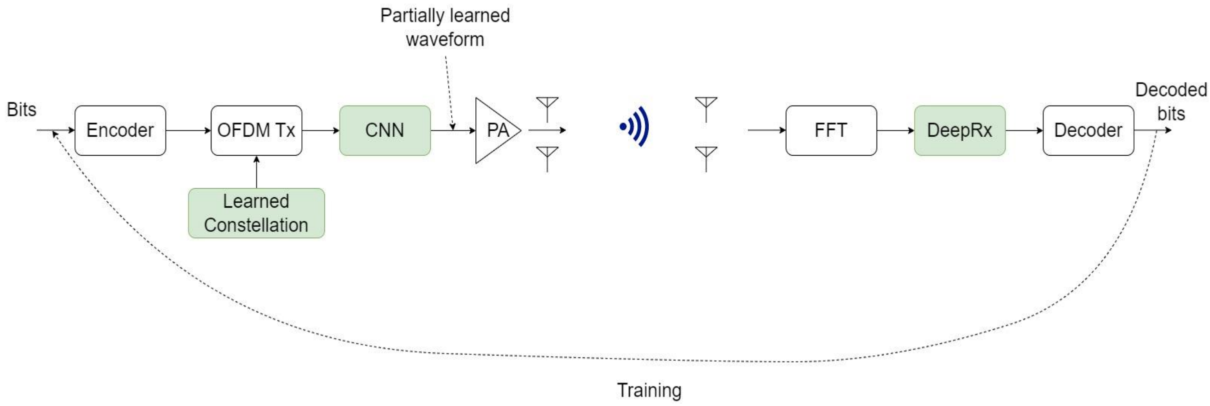

Figure 4-4: AI-based waveform adaptation

According to the illustration of Figure 4-4, having as a starting point an OFDM block at the transmitter two neural network blocks, Convolutional Neural Network (CNN) and Deep Learning Receiver (DeepRx), are included in the transmitter and receiver for waveform adaptation in real time. Such RT waveform adaptation can be well supported through current commercial fast FPGAs. In ETHER we are going to investigate different architectures regarding the position of the neural network blocks at the transmitter and receiver and assess which on average gives the best performance for relevant applications.

4.2.4 (T-4) Flexible payloads

The use of Software-Defined Radio platforms to define satellite payloads gives flexibility to adapt satellite to operator/s services. The introduced flexible payload concept is based on three main mechanisms which are presented as three different flexibility levels studied in the project:

- Flexibility level 1: hardware reconfiguration (full or partial) to add extra resources to the system for services use and adapt for future services.
- Flexibility level 2: software reprogramming and operating system abstraction by applying virtualisation techniques, which give flexibility and the possibility to manage resources using a software perspective.
- Flexibility level 3: service-based deployment from outside the satellite using an orchestrator and the possibilities offered by the levels 1 and 2.

A general diagram of the envisioned flexible payload concept is shown below:

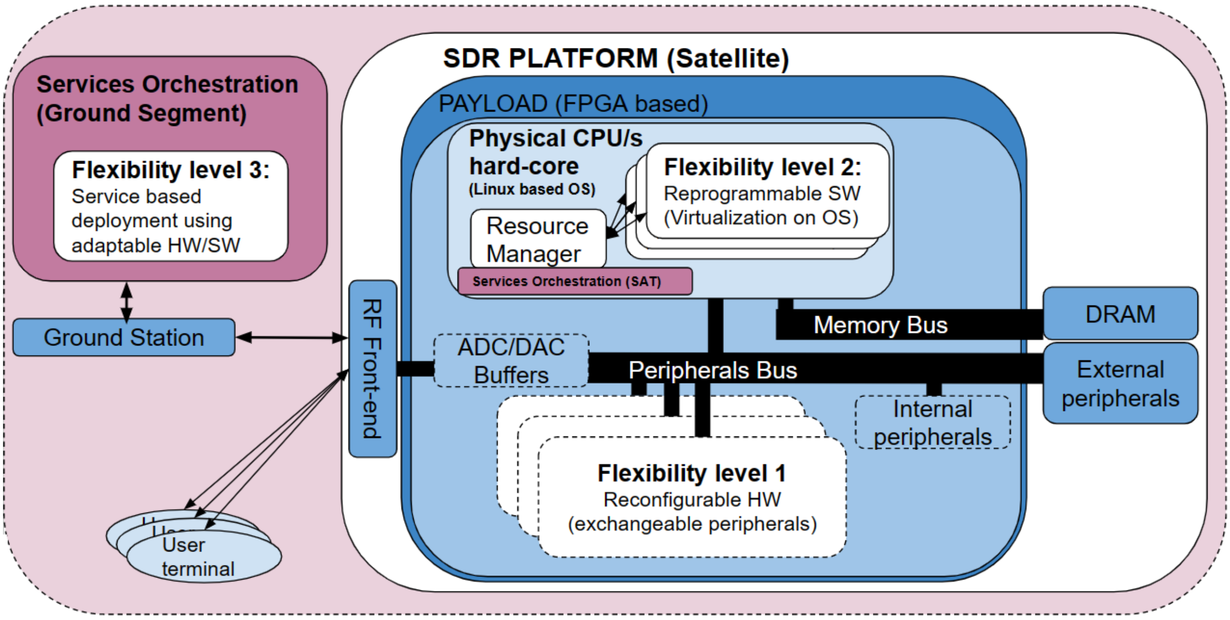

Figure 4-5: Representation of the virtualisation levels achieved in the Flexible Payload design

4.2.5 (T-5) Data analytics, edge computing, and caching incl. semantics-aware data analytics and control

ETHER will utilise the semantics of information in NTNs combined with edge computing and caching to increase the efficiency further and reduce the E2E latency without affecting the amount of conveyed information. In particular, semantics refer to the importance and relevance rather than the meaning of information. More specifically, by leveraging semantics in NTNs, ETHER will allow to generate and transmit only a small fraction of data without affecting the conveyed information.

This can be achieved by defining metrics that capture the innate and contextual attributes of information and could include the cost of actuation error when we target remote control and actuation of devices as well as the Age, Version, and Value of Information that can capture the timeliness and the importance of information in status updating systems. Furthermore, adapting those metrics to capture the unique characteristics of NTNs is crucial. Thereby, the development of caching schemes and cooperative computing techniques will be enabled that will outperform the current schemes by achieving lower latency and higher energy efficiency. For example, incorporating the Version Age of Information in caching schemes can allow for less frequent updating leading to less power required for the operation and transmissions, thus, higher energy efficiency. By reducing the transmissions, we reduce the delays inside the network, thus further reducing the E2E latency.

These metrics will be further utilised in data analytics schemes where the current approaches neglect importance and relevance of information thus making them cumbersome to be applied directly in NTNs.

4.2.6 (T-6) Horizontal/vertical handovers incl. AI-based handover control mechanisms

In such a heterogeneous 3D architecture, efficient horizontal/vertical handovers mechanisms should be developed to achieve a good trade-off between complexity and performance. ETHER advances common handover implementations, which leverage mainly signal quality metrics obtained by the UE, considering additional parameters, such as time availability and network sustainability. For example, handover requests within satellites may need to go through store and forward mechanisms and be processed only when connection with the ground segment is available.

ETHER will consider more elaborate criteria for performing horizontal and vertical handovers in hybrid terrestrial/non-terrestrial networks by leveraging AI-based algorithms to make the process autonomous. This allows to deal with several parameters that need to be considered when migrating to another gNB. For example, even if Xn interfaces among the terrestrial, aerial, and space gNBs are always available, the Xn-type handover (direct handover leveraging the Xn logical interfaces among the gNBs without the need to go through the AMF of the core network) might not be always the best solution. This is due to the serving gNBs might have limited context information about how the network will evolve over time in contrast to gathered information in the core network, which will affect the decision for handovers. If, for example, a LEO satellite can provide better quality over a serving terrestrial one for a particular service, but the link is available for a short amount of time due to its fast movement, such a handover should be avoided.

Another important parameter is the future traffic that target gNBs need to facilitate, together with their energy consumption demands arising from the user migrations. The latter is especially important for grid-less platforms that can act as target gNBs, such as LEO satellites and HAPS. Owing to the aforementioned considerations, ETHER will design novel ML-based algorithms for horizontal/vertical handovers in the integrated network that will balance a variety of criteria related to the evolvement of the network, such as latency, rate, traffic, while targeting 70% higher energy efficiency than the SotA work [22]. Towards this, the federated learning will be also leveraged for proactive handovers due to avoiding the need for exchanging a large amount of data among the nodes, which is beneficial in terms of latency and energy consumption.

4.2.7 (T-7) Automated MANO for the integrated network

Satellite communications involve the utilisation of artificial satellites positioned in space to facilitate the transmission and reception of information across extensive distances. This technology plays a pivotal role in modern telecommunications systems, providing worldwide connectivity and supporting diverse applications such as broadcasting television, enabling internet access, facilitating telephone services, enhancing avionics communication and navigation systems. The current structure of satellite communication networks consists of a Ground Station (GS), a Satellite (SAT) serving a specific geographical region, and a client situated within the coverage area of the satellite, receiving the respective service. It is assumed that the satellites possess the capability to deploy Virtual Machines (VMs) or containers, enabling them to instantiate an application image for service provision or configuration modification. Additionally, the satellites can establish communication links with other satellites via ISL. However, the effectiveness of these relies on hardware ability to establish communication links and the density of the satellite constellation, which directly influences coverage.

In this environment, the satellites must establish a connection with the GS in order to communicate the requested application image on-demand or possess sufficient available storage space to store it. Given the constrained CPU resources, it is not desirable to compile the application dynamically. Consequently, the CPU remains available to fulfil the primary mission requirements before change configuration or deploy a different service.

In terms of architecture, the satellite network is made up of at least one SAT, one GS, and UE. Each SAT is an individual node acting independently of other SATs; however, interconnected satellite constellations can be integrated. These can provide both direct and indirect connectivity to the UE.

Connectivity in satellite networks is limited to a) GS-SAT link: point-to-point communication system between the GS and each satellite, mainly used for Tracking, Telemetry, and Command (TTaC), loading application images, and schedule the deployment of applications; and b) between satellite and UE to provide a service to an end user. Nonetheless, due to the constant movement of the satellite, dictated by the dynamics of its orbit, connectivity is intermittent.

Coordination is a critical aspect of satellite communication, managed remotely by an operator alongside the GS-SAT link. By accessing this link, the operator can change satellite configurations and deploy different applications to offer a new service. If the satellite experiences any failure, it cannot be reported until the next contact with GS, and there is no possibility of self-healing for VNF. Therefore, it is crucial to ensure the reliability of the satellite and prevent any potential failures.

Resource management is a crucial factor in satellite communication. All resources have been static and defined since the mission's inception. The operator is responsible for managing the available resources at the satellite by selecting which applications can run simultaneously with other applications, or which applications require the entire system to run. Services can be configured remotely through the GS.

In summary, satellite communications present several unique challenges, including resource management, coordination, and autonomy. Based on the current environment of the satellite communications networks, we propose integrating the satellite segment as part of the NFVI in the ETSI architectural framework, as shown in Figure 4-6, to improve the efficiency and reliability of satellite communication systems. Based on this integration, we develop three possible scenarios where the satellite is cooperated with its hardware resources to the infrastructure as part of a multi node cluster that can share resources, essentially creating a distributed infrastructure in space. This integration will enable satellites to act as MEC devices that can be reconfigured based on the needs of the network, creating a data-driven architecture. This concept is already integrated in the new 5G architecture.

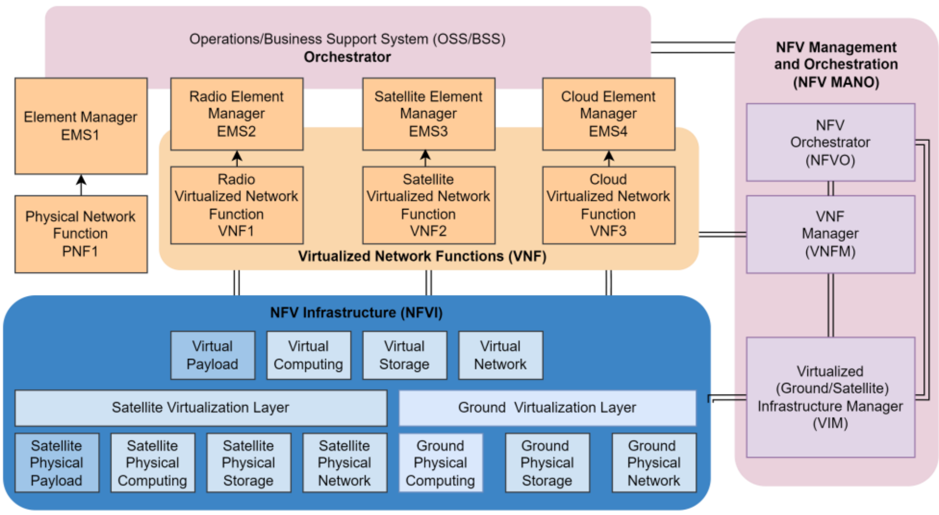

Figure 4-6: Architecture representation based on ETSI architecture with satellite systems integration

Architecture: the constellation architecture is based on a multi-node cluster managed by the GS. The satellites in the constellation act as the cluster nodes, contributing their hardware resources to the cluster. The cluster of satellites is organised in a constellation and features a distributed master system, where the master is not only located at the GS but distributed across multiple nodes to ensure high availability conditions. This distribution of masters enables the cluster to collaborate and implement services even in the event of failure of one or more nodes.

Coordination: the master node is responsible for performing resource allocation duties, tasks scheduling, and ensuring the overall health and availability of the cluster. The database of available resources is disseminated across various nodes within the cluster and can be accessed by the nearest master to execute any changes. This assures efficient and effective use of all available resources by the cluster.

Resource Management: as the master is distributed across multiple nodes, it requires connections to other masters to update the available resources. This distribution of masters significantly increases the resiliency of the cluster and each satellite in the constellation contributes its hardware resources to the cluster.

Connectivity: the architecture utilises ISLs for more comprehensive information replication, thereby improving the overall connectivity of the cluster.

Federation: each master exclusively belongs to a single cluster and cannot independently form new clusters. Federation between satellites is enabled at network level, as each satellite will provide routing capabilities to the cluster network. The GS is responsible for managing resource allocation and coordinating tasks, while the satellites act as nodes in the cluster, routing the network's traffic.

Autonomy: if the cluster loses a node, it is capable of self-healing and reallocating new resources to provide service in the affected area. It can also self-heal the service and allocate new resources to provide service over the affected area. Furthermore, if the cluster loses contact with the GS, it can deploy new services and maintain the status of existing ones until the lost connection is re-established. Overall, these enhancements significantly improve the system's reliability and resiliency, assuring continuous service provision even under challenging circumstances.

This scenario offers the possibility for a highly efficient and flexible infrastructure in space. By considering the resources of multiple satellites in a constellation as a pool of resources, it is possible to create a powerful distributed computing platform that can support a wide range of services and applications.

Satellites mobility management

In the context of ETSI NFV architecture in satellite communications, VIM holds a crucial role. It does not only manage the infrastructure of the satellite constellation, but also handles satellite mobility within the cluster and ensures network connectivity. For virtualisation, containers emerge as a promising choice due to their small footprint and ease of deploying existing applications in various languages. A container orchestrator is necessary to manage multiple containers across multiple hosts efficiently. This layer automates the deployment, scaling, and management of containers.

A container orchestrator abstracts the underlying infrastructure, providing a high-level interface for managing a cluster of containers hosted by satellites. It handles container scheduling, maintaining the desired system state, and facilitates scaling, self-healing, and application migration between satellites to ensure an uninterrupted service. Most key concepts in container orchestration include:

Nodes: referring to the physical machines running containerised applications on each satellite.

Pods: groups of one or more containers sharing a single network and storage.

Services: logical groupings of pods providing a single endpoint for client access to the application.

ReplicaSets: mechanisms for scaling and self-healing, ensuring a specified number of replicas of a pod are running.

ConfigMaps: decoupling configuration data from container images for easier management and deployment.

Kubernetes [63], originally developed by Google and now part of the Cloud Native Computing Foundation, serves as a container orchestrator, commonly referred to as “k8s”. The architecture offers self-healing capabilities, high redundancy, high availability, and resilience, which are crucial for space networks. Kubernetes’ architecture utilises a database to store ConfigMaps, a central manager for applying changes, a scheduler for Pod deployment, and an API server for component communication.

Kubernetes’ self-healing is achieved through ConfigMaps that specify the desired number of replicas and scaling based on CPU usage or connection metrics. High availability and redundancy are ensured through replication across multiple instances. The control plane can be distributed across different instances, ensuring governance with a consensus algorithm. Resilience is supported by Node affinity, which tags components in the cluster based mainly on hardware capabilities or specialised components, allowing the scheduler to deploy services on nodes with specific tags to provide the desired service on the most capable node.

Kubernetes’ behaviour, along with a personalised metrics collector and satellite orbit propagation, can be effectively utilised in space networks to ensure continuous services as satellites move in space. By strategically deploying ReplicaSets based on the distance of satellites to the target service area and assigning tags to the closest satellites, the scheduler is directed to deploy pods on these nearby satellites. Additionally, through autoscaling automation, satellites that are moving away from the target area can be released. This approach guarantees that the service appears steady from the user’s perspective, even though the underlying hardware infrastructure is in constant motion. In essence, Kubernetes in combination with these techniques enables seamless and uninterrupted connectivity in dynamic space environments.

ETHER WIM: SDN has significantly transformed network management, introducing a paradigm shift in the design, management, and operation of networks. By separating the network control plane from the forwarding plane, SDN facilitates centralised, programmable control of network traffic, which enables more dynamic network management and configurations (cf. Figure 4-7). This degree of control allows the network infrastructure to adapt to changing business needs on-the-fly, avoiding the need for physical access to network devices. Moreover, SDN promotes automation and integration with other systems via APIs, thus augmenting operational efficiency and mitigating human errors. By fostering a programmable network infrastructure, SDN, as a complementary technology, underpins the definition of innovative NFV-based use cases such as network function virtualisation, enabling the service function chaining. Thereby, establishing itself as a vital catalyst for network agility and innovation.

Building upon the central role that SDN plays in network management, the importance of the Northbound Interface (NBI) and SouthBound Interface (SBI) must be emphasised. NBI, acting as a channel between the SDN controller and the application layer, enables SDN applications to program the network and request services. In contrast, the SBI facilitates the connection between the SDN controller and network devices, thereby allowing the controller to implement rules and configurations. Through these vital interfaces, SDN applications can provide a range of innovative solutions, including but not limited to automated network provisioning, dynamic bandwidth allocation, and traffic management.

With the understanding of the core concepts and components of SDN, it becomes important to explore the foundational infrastructure upon which these elements operate – the transport network. In telecommunications, a transport network refers to the underlying physical network infrastructure responsible for transmitting data across different nodes/layers within a network. It includes all hardware elements such as routers, switches, and all types of links, wireless or wired. In the context of integrated TN-NTN, the transport network serves as the backbone that interconnects both ground and space segments. It forms a comprehensive infrastructure, intertwining wired connections (TNs) and wireless links such as aerial-based components or satellites. The transport network in this integrated system, therefore, is essential for seamless data transmission across different layers and nodes within the network, facilitating reliable and efficient communication. In the following, the WIM concept as well as its application in integrating TN and NTN are introduced.

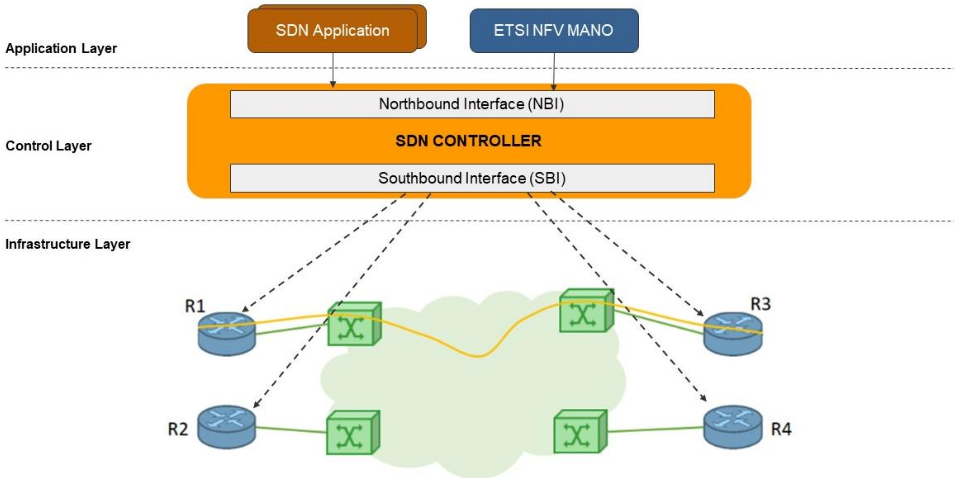

Figure 4-7: SDN architectural framework

Software-defined transport networks refers to the principle of using SDN paradigm to manage and control the transport layer of a communication network. As mentioned in the previous section, currently traditional networks rely on manual configuration and static provisioning of traffic flows. Unlike this approach, SDN provides network programmability by implementing a centralised controller which enables dynamic, flexible, and efficient management of transport network resources.

Following the SDN principle, the transport network SDN controller abstracts the underlying physical infrastructure, such as routers, switches, and optical transport equipment, and provides to the network operators or vertical clients a general view of the network topology by having a single software-based control layer. It not only enables network operators to customise and automate network operations, but also allows them to optimise the resource utilisation.

Transport networks usually are referenced as WANs whose objective is to interconnect several administrative domains distributed geographically. WANs could interconnect enterprise domains and public domains. Applying SDN to WAN is a well-studied technology called SD-WAN. Several commercial vendors have proposed programable solutions to handle the connectivity between domains [64]. However, those solutions do not allow the management of the network elements that compose the transport layers.

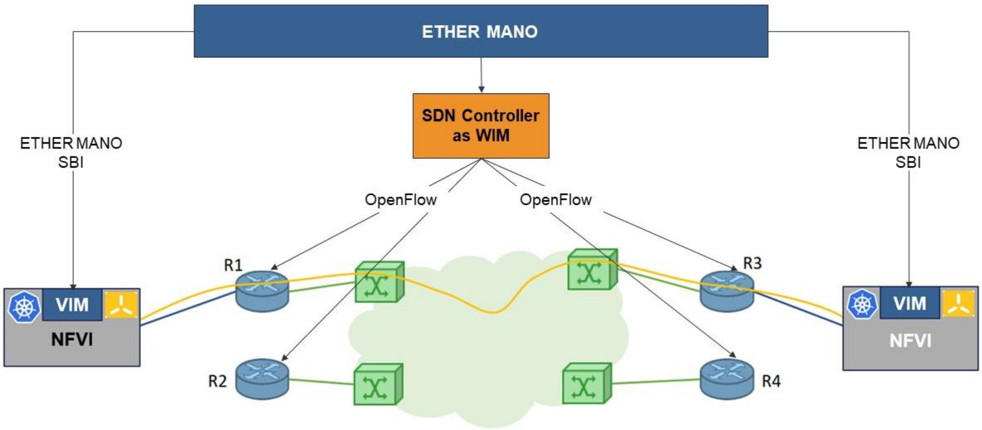

Figure 4-8: SDN as WIM controller in transport networks

In that sense, the integration of SDN with NFV in multi-domain environments has led to the introduction of the concept of WIM, which has been defined by ETSI in the document GS NFV-MAN 001 [25] (cf. Figure 4-8). WIM has been specified by ETSI as a key component that serves as a central entity responsible for the E2E management and orchestration of resources and services (VNFs) spread across multiple domains and technologies in WANs. Following the SDN approach, WIM provides a unified interface and control plane for network operators to configure, monitor, and manage the transport network elements.

WIM can leverage the VNFs orchestrated by ETSI NFV framework to allocate the appropriate transport resources efficiently. This integration enables operators to dynamically link VNFs through well-provisioned transport network resources, resulting in enhanced service agility, improved resource utilisation, and optimised network performance.

The main functionalities of WIM include:

- **Resource Abstraction:** WIM abstracts the underlying infrastructure of the transport network, which includes components such as optical fibres, network switches, routers, and other devices. This abstraction offers a high-level and simplified representation of the network resources, facilitating easier management and efficient allocation for operators. Also, the abstraction could be customised per tenant, according to the service level agreements and network service requirements.

- **Flexible Resource Allocation:** according to the RT traffic conditions and service demands, WIM supports dynamic configurations in the network resources. It means, WIM allows adjusting bandwidth, reconfiguration of traffic routes, and scale network capacity on the fly, ensuring optimal resource utilisation and network performance.

- **Network Orchestration:** WIM facilitates the coordination of network components across various domains and technologies, ensuring E2E connectivity. It empowers network operators or communication providers to specify service requirements, customise connectivity paths, and allocate resources to fulfil the demands of diverse services and applications.

Multi-layer optimal SDN controller placement

The traditional approach in integrated satellite-terrestrial networks has been to deploy a number of SDN controllers in the ground segment for controlling the unified network. However, in the 3D architecture introduced by ETHER that comprises the terrestrial, aerial, and satellite layers, such an approach is no longer viable. This is due to very high network complexity and the fact that the number of aerial and space elements increases at a higher pace than the number of ground stations. Hence, controlling such a highly complex network through only ground segment SDN controllers would become largely infeasible.

To counteract the above, literature has started to consider placing controllers also in non-terrestrial platforms [65]. The optimal placement of the controllers is subject to a multitude of metrics of importance, such as the communications latency between the SDN controllers and switches, the coverage view of the controllers, potential link and node failures, and the cost of deployment. The optimal SDN controller placement is more challenging in the hybrid 3D networks than solely terrestrial networks since the potential SDN controller hosting nodes are more diverse in terms of capabilities, and several nodes are non-stationary. As an example of multilayer SDN controller placement works have considers there are works that have considered placing the controllers in GEO, MEO LEO satellites, apart from ground stations (see Table 4 of [65]). By such a deployment, different aspects of the satellite position are leveraged, such as the wide coverage of the GEO satellites that reduces the number of controllers needed and the low latency of LEO satellites with respect to communication to the ground.

In general, there are two main approaches for placing the controllers [66]: i) The static approach in which the deployment is based on offline studies about meeting average metrics ii) The dynamic approach in which a number of backup controllers can be deployed in the different layers (terrestrial, aerial, and the satellites in different altitudes) and in real time the ones that will be active are chosen, based on the data demands. As expected, and based on [66], the static deployment is more cost effective, but the dynamic one achieves a better performance that an increased cost and complexity.

In the context of ETHER, a multi-layer SDN controller possibility is assumed, as depicted in Figure 4-7. In particular, we consider that the controllers can be placed in terrestrial, aerial, and space layers. In addition, in a hierarchical approach, there is a chief controller in each of the layers that controls slave controllers in the particular layer and there is also a master controller in the ground segment to which information is gathered from and to the chief controllers at each layer. Our aim in ETHER is to investigate the optimal SDN controller placement under both static and dynamic approaches, based on a multitude of metrics of interest that originate from the service requirements. By incorporating the aerial layer as an additional target for the SDN controller placement the placement problems become more challenging, which raises the need for low complexity algorithmic solutions, particularly for the dynamic approach. In addition, it would be of importance the joint optimisation of the SDN controller placement and the aerial and satellite infrastructure design instead of just optimising the position of the SDN controllers for an already existing aerial and satellite infrastructure. The latter would be suboptimal compared to the former.

MEC and application orchestration

Edge computing provides computing capabilities outside of the data centre, closer to where the data is being created and to the devices using it. By combining edge computing with satellite communications, users are able to experience faster and more reliable connections to applications and services, while also reducing latency and improving data security.

Co-funded by the European Union

In the context of the ETHER proposal, where the satellites are collocated with edge computing resources to function as MEC devices, there is a need not only for network orchestration, as previously described, but also for end-users' application orchestration.

This requires a smart orchestrator to automatically deal with the placement and migration of tasks on the edge servers. ETHER proposes a zero-touch orchestration framework for lifecycle management of application and edge resources. This includes the use of AI/optimisation algorithms with the objective of providing closed-loop autonomy and zero-touch reconfiguration at all layers of the edge infrastructure.

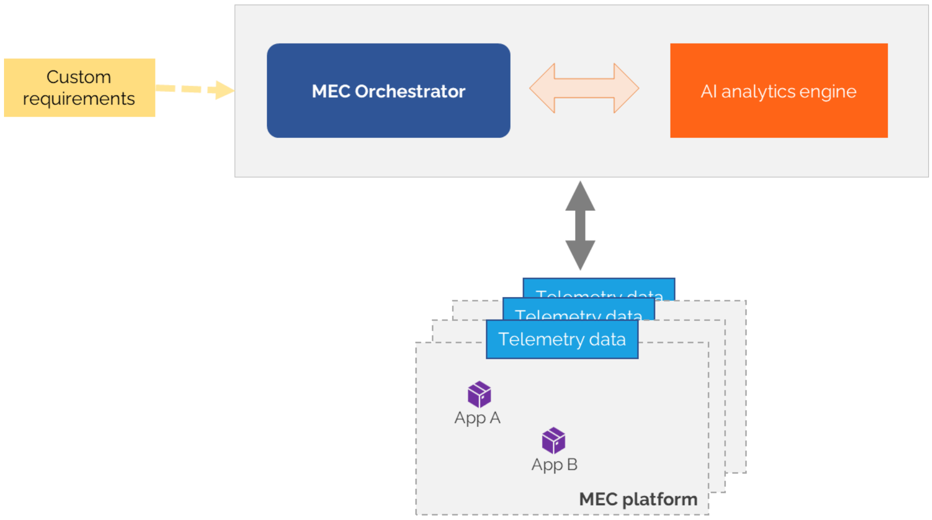

Figure 4-9: MEC and application orchestration

The main elements to be considered for the MEC and application orchestration are shown in Figure 4-9 and detailed below:

- The **MEC orchestrator**, guided by the AI/optimisation analytics, executes decisions pertaining to application placement or migration within the edge infrastructure.
- The **AI analytics engine module** analyses the collected telemetry data (and/or any other source of relevant data) and provides decisions or suggestions to the orchestrator.
- The **MEC platform**(s) (or terrestrial/non-terrestrial edge nodes), are the geographically distributed computing resources, attached to the satellites where the applications are deployed. As an example, each edge node can consist of a Kubernetes cluster.
- The **custom requirements** are the target QoS/Quality of Experience (QoE) objectives of the AI analytics engine and the MEC orchestrator.
- The **telemetry data**, including various live metrics of interest from the platform and applications, which may encompass factors such as energy availability, latency, or end-user location, among others.
- The **applications** are the end-user orchestrated MEC applications.

4.2.8 (T-8) AI-driven E2E network performance optimisation

From an E2E viewpoint, the mechanisms for management of the RAN and the solutions for zero-touch orchestration of the resources (across the virtualised network and cloud continuum) must be integrated. Such an integration is paramount to enable a comprehensive and effective coordination of network slices, from the RAN to the core segments, for different kinds of 6G services and accounting for heterogeneous terrestrial, aerial and satellite radio access domains.

The E2E management and orchestration framework builds on the architectural specifications already presented above, for RAN and core, and does not introduce further requirements from an architectural viewpoint. Yet, it introduces a need for original mechanisms capable of meeting the following targets:

- RT network monitoring and KPI prediction.
- Online (for run-time self-configuration) and offline (for long-timescale self-configuration) E2E cross-layer optimisation procedures that build on the monitoring and prediction tools above. These mechanisms shall ensure that:
  - The QoS/QoE requirements of each service are met in a transparent way with respect to the radio access domain the user equipment is in (e.g., by prioritising core network traffic to compensate for different radio access latency and meet E2E delay targets).
  - High energy and cost efficiency are achieved (e.g., by solving a joint network, computational and storage resource allocation problem based on the deployment scenario).

Given the complexity of the tasks above, it is expected that data-driven models based on SotA AI paradigms, tailored to the ETHER context, need to be developed to effectively meet the requirements.

4.3 ARCHITECTURE DESIGN PRINCIPLES

The ETHER architecture is expected to provide the integrated TN-NTN ecosystem capable to accommodate cross-layer 5G and beyond services. To this end, to provide a compatible solution in the long-time perspective, it is essential to consider main 6G visions, trends and paradigms in the overall architecture design (as described in section 3.1). The ETHER architecture will also need to support and efficiently integrate the technical innovations (see section X), some of which are built on the foundation of SotA solutions. Moreover, the planned use cases can also impose specific requirements on the architecture shape, e.g., in terms of openness, genericity or exposure capabilities to integrate with frameworks external to ETHER. Finally, the business ecosystem characteristics need to be reflected as well to enable the creation of new business opportunities in the integrated TN-NTN ecosystem. The typical nowadays business environment is a multi-stakeholder ecosystem, resulting in the following general requirements to be considered in the ETHER architecture design: multiple administration domains (both in terms of distributed ownership of underlying resources or potential unbundling of resources ownership and the role of resource management, including, for example, the role of a consolidated resource manager or infrastructure broker), heterogenous domain-specific technologies (commodity or specific hardware), etc. The undertaken approach to architecture shape will focus on opening new business opportunities and creating new business roles to maximise potential benefits from the TN-NTN integration (which will be further analysed in WP6).

The following principal features will be taken into account when designing the ETHER architecture:

- Generic – ability to accommodate different frameworks, e.g., ETSI NFV/MEC, SDN, 3GPP 5GS, O-RAN.
- Multi-domain – both in terms of 3D access domains (terrestrial, aerial, space) and in terms of functional split (RAN, edge, core, transport).
- Multi-provider – ability to accommodate different providers' solutions, provided they follow standardised mechanisms or can be adapted to them.
- Hierarchical – following a hierarchical approach to the scope of responsibility or concern, in particular the communication service-network-subnetwork-function-resource hierarchy, to functional split, management and orchestration.
- Distributed – ensuring the placement of processing functions as close as possible to the points of data generation, avoiding unnecessary data transfer back and forth, etc.
- Intent-based – using the high-level approach to interactions, instead of micro-management by detailed parameters impact.
- Zero-touch – automated, AI-based network/service M&O – minimising the necessity of manual interactions in operations and management.
- Scalable – able to expand with a service/traffic demand growth.
- Service-based – focused on discrete functionality units instead of a monolithic design, where the service producer/consumer relation is followed, applying the publish-subscribe, request-response mechanisms, and REST API-based.
- Modular (associated with the preceding two) – based on the functional split into modules to support their independent creation, testing, parametrisation, modification, replacement, exchange, interconnection, logical separation, etc.
- Openness to future extensions and trends (e.g., micro-service mesh).

5 INITIAL ETHER REFERENCE ARCHITECTURE

5.1 OVERALL ARCHITECTURE AND ARCHITECTURAL LAYERS

The high-level ETHER architecture conceptualisation is presented in Figure 5-1. The ETHER system is immersed in a shared infrastructure that includes both physical and virtual infrastructure resources. The 3D ETHER system aspect is represented by Terrestrial, Aerial, and Satellite strata through which softwarised Application, Communication, and Steering strata are laid out. While the Application and Communication strata directly and visibly serve the user, the Steering stratum one ensures seamless operation of these former. The continuity of the mutually cooperating planes through all the strata is ensured by resources (especially transport ones) and mechanisms of interconnection and mediation. Two additional parallel strata encompass orthogonally three abovementioned strata as well as the infrastructure expanse: Management and Orchestration Stratum, and AI Stratum. The role of the former is to provide management of the ETHER system and orchestration of resources and other planes. The latter supports not only the former for automation and autonomy, but exposes its services also to applications, communication, and steering mechanisms. This is how the idea of embedding AI as a native element of the ETHER system is expressed. The Application Stratum is an integral part – not external – of the ETHER system using common resources and mechanisms of steering, management and orchestration powered by common AI. In this manner, the maximum flattening of the system is achieved to augment its performance efficiency.

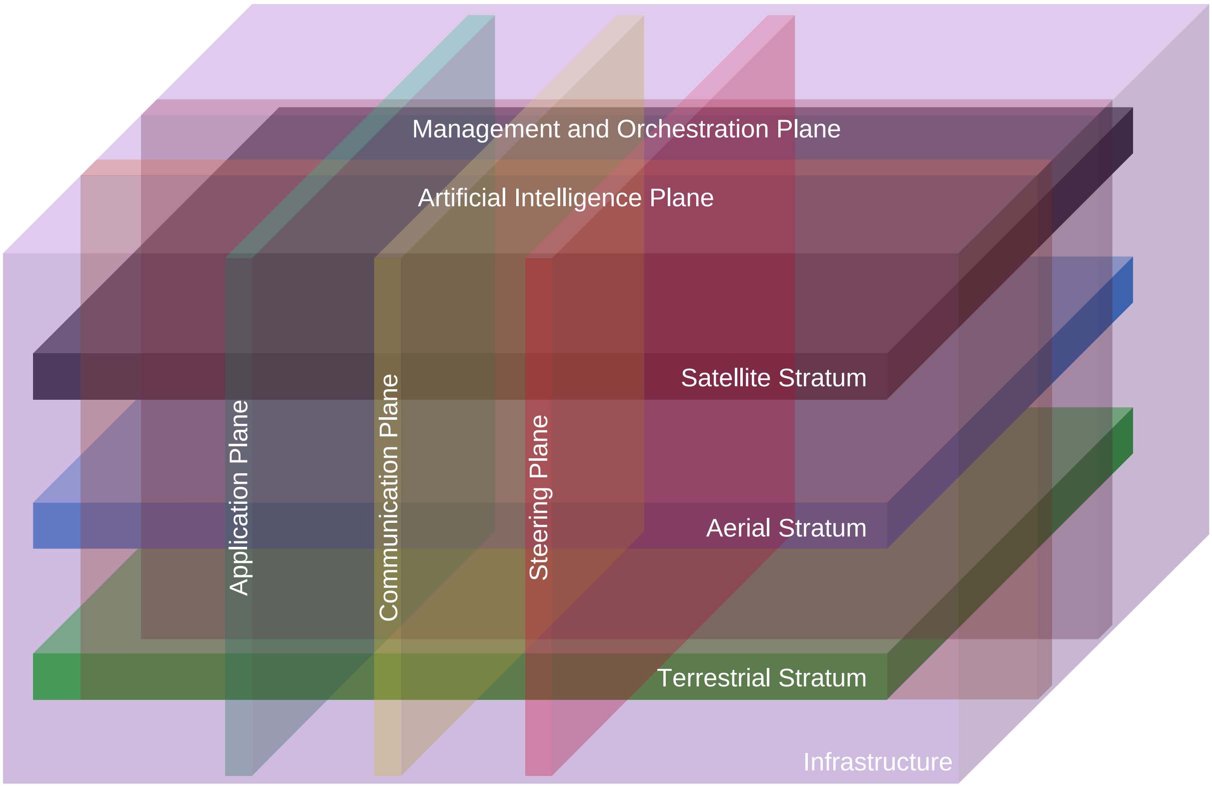

Figure 5-1: High-level ETHER architecture conceptualisation

The overall ETHER system architecture, based on the presented conceptualisation is shown in Figure 5-2.

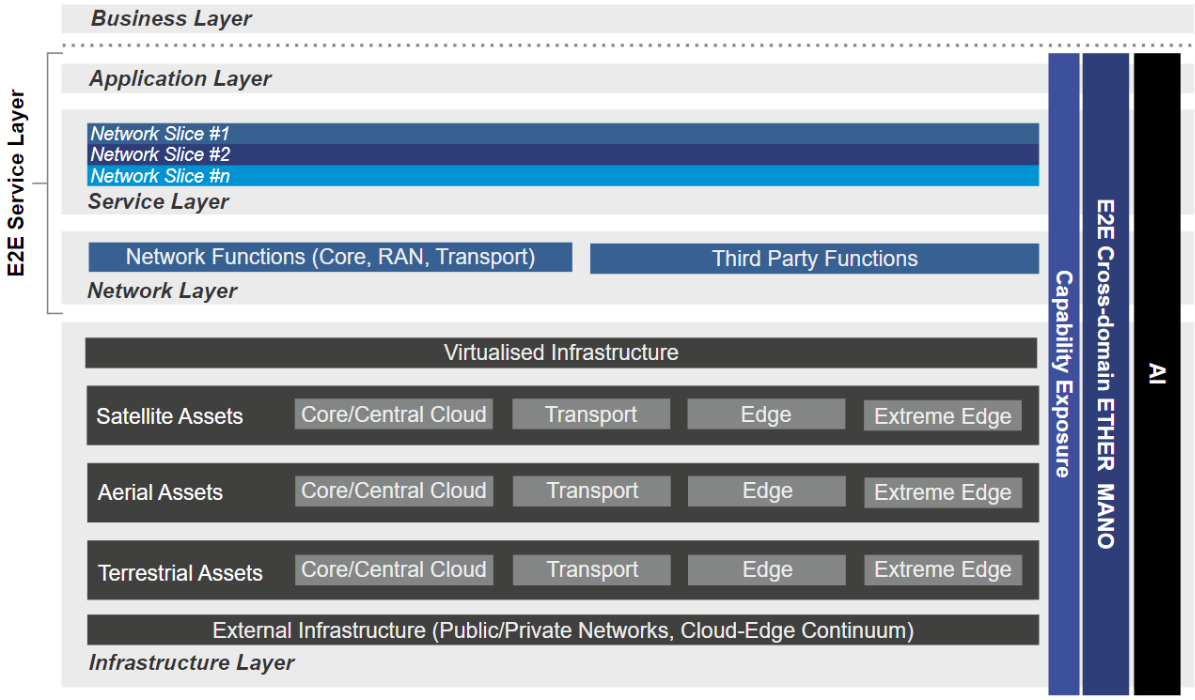

Figure 5-2: Overall ETHER system architecture

The overall ETHER system architecture is composed of:

- **Infrastructure Layer** that includes the TN and NTN assets (both satellite and aerial components) serving as Core/Central Cloud, Transport, Edge and Extreme Edge infrastructure, external infrastructure such as Public/Private Networks, or Cloud-Edge Continuum resources offered by the providers external to the ETHER system, and Virtualised Infrastructure (obtained by virtualisation of the above physical assets or provided by external entities). This layer can be seen as an NFVI layer of ETSI MANO extended by non-virtualised resources.

- **Network Layer** composed of NFs (i.a., 3GPP CN, RAN, Transport-related functions) and Third-Party Functions understood as any functions external to the ETHER scope but supporting the network operation. This layer can be seen as a VNF layer of ETSI with dedicated PNF support functions.

- **Service Layer** constituted by the Network Slice Instances (NSIs) composed of NFs residing in the Network Layer with the relevant slice management and mechanisms for exposure to the upper layers.

- **Application Layer** containing applications that exploit the capabilities provided by NSI (or several NSIs).

- **Business Layer** constituted by the relevant business actors (MNOs, verticals) interacting with the MANO framework. The business model aspects are out of the scope of this document and will be investigated by WP6.

The above-mentioned layers are coordinated on multiple levels by the E2E cross-domain ETHER MANO solution (constituting also the MANO layer of the ETHER system), leveraged by the capabilities provided by the internal AI applications (e.g., AI-based MANO enablers) or external to the ETHER system, e.g., exposed to the framework via AIaaS mechanisms. The following sections will provide a high-level functional view of each of the ETHER system layers.

5.2 INFRASTRUCTURE LAYER

ETHER envisions building a 6G integrated 3D multi-layered network infrastructure comprised of NTN assets represented by space, HAPSs, aerial, and TN. As a result, a 3D multi-layered horizontally and vertically integrated TN-NTN network has emerged de facto as a global network to provide communication services to users active in the different integrated 3D network layers. The users include both flying objects like aircraft, electric vehicles, UAVs and space IoT devices attached to low or high-altitude platforms (L(H)APs) and terrestrial objects like ground users and IoT devices. The designed 3D network provides a global broadband coverage to remote and rural areas that cannot be covered by the existing terrestrial communication network infrastructure. This is referred to the deployment cost and high energy consumption of the different terrestrial infrastructure components.

ETHER 3D network infrastructure deployed in the three layers (cf. Figure 5-1) is described as follows:

- **Satellite layer** is the upper layer in the 6G ETHER 3D network architecture. It comprises satellites operating at different altitudes in orbits, namely geostationary orbit (GSO) and non-geostationary orbit (NGSO) satellites. The latter include satellites in the MEO (10,000 to 20,000 km) and satellites in the LEO (300 to 1,500 km). Due to their fast movement with respect to the ground, they require a constellation to maintain their connectivity. Regarding the services provided by the different orbit satellites, GSO satellites are mostly suitable for satellite TV and weather monitoring. The MEO SAT has been used for positioning and navigation, such as GPS. Whereas the LEO satellites have been deployed for remote sensing, high-resolution Earth observation, military reconnaissance, fast broadband direct communication to end users, and Internet of Things/Internet of Remote Things. They can also provide a faster way for inter-continental communications than the terrestrial- high-speed optical fibre networks.

- **Aerial layer** comprises platforms such as commercial airplanes (aircraft), UAVs, and HAPS that fly at altitudes of 8-11 km, up to 1 km, and 17-20 km, respectively. In 6G networks, the aerial platforms are envisioned to be boarded with 5G gNBs. These turn them into flying base stations that can serve users within the same network layer, as well as other users within the layers above and below their layer. The advantage of operating gNBs on-board HAPS stems from their much lower altitude relative to the ground than the satellites installed in the different orbits. Also, the quasi-stationary nature of HAPSs eliminates the need for frequent handovers, like the case with NGSOs when they are about to lose visibility with ground terminals. Furthermore, their altitude and size allow to equip them with sizeable antenna that can offer high gains. This enables direct handheld device access even at mmWaves (e.g., Ka band). Moreover, as their service coverage gets wider, relying on their much larger footprint compared to the terrestrial gNBs, it would better prevent the frequent handovers of high-mobility users such as aircraft or UAVs, in contrast with fast-moving ground network mobility, such as trains, where terrestrial cells may fail in providing ubiquitous services. However, what differentiates this layer more is that, the gNBs on-board the platforms deployed within this layer can act as a relay node enabling the expansion for the visibility of NGSOs to better serve ground users and those in the other network layers. The UAVs have been used for different purposes including military, cargo, and rescue operations. They can also act as aerial gNBs in the case of natural disasters and high-traffic demand events like sport events. Airplanes (aircraft) require resilient and reliable networks not only to support critical operations or safety, but also to provide continuous broadband connections for passengers on board. This has been challenging and costly with TN networks and can only be expected during the take-off and landing times. However, when airplanes spend the majority of their flight time at high altitudes, the ETHER integrated 3D network can be deployed to support the required broadband coverage, which can be provided by means of satellites, like LEO, NGSO, and HAPS.

- **Terrestrial layer** involves a multitude of heterogenous radio, wireless, cellular, ground satellite, HAPSs base stations and small cells operating at different frequency bands, primarily sub-6 GHz and mmWave. Until 5G, the antennas of these base station nodes have been downwards tilted to serve the ground users. However, the ETHER project follows the changes considered in the 6G network concept by either equipping them with a large number of antennas to enable 3D beamforming or with up-tilted antennas. This would allow, in turn, to better interconnect (integrate) terrestrial base stations or users with other aerial and space users, including flying base stations installed on-board satellite spaceship, aircraft, HAPS or UAVs. The availability of such access networks in the different layers provides a resilient communication network to aircraft, which supports their critical-time operations and safety. It also enables the flying objects (e.g., aircraft, UAVs) to select the air-to-ground (A2G) links according to their communication performance requirements. Obviously, network scenarios such as traffic or user load balancing, traffic re-routing can be realised to better serve aerial and space users. The terrestrial network infrastructure includes also different gateways that connect the aerial and space platforms to the terrestrial core network through feeder links.

- **ETHER 3D edge computing and storage continuum** is another capability that would majorly distinguish the designed 3D network in the sense it would become more responsive to service demands type, volume and matching it with the requested infrastructure availability in an efficient manner relying on RT predictive data analytics. Noting that a key difference of the 3GPP Release 19 with earlier releases regarding the integration of TNs with NTNs is that the Release 19 will include the regenerative payload feature for NTN platforms. This means that the nodes will be able to encode and decode the received information and act as aerial and space gNBs. This, in turn, will enable them to act as edge computing and storage units, which can heavily alleviate the large amount of data that the cloud terrestrial networks need to process and store. Hence, the ETHER 3D network is a TN-NTN distributed edge computing and storage network that allows such tasks to be performed in terrestrial, aerial, and space nodes. This can be possible by the existence of inter-space-air-terrestrial links for fast data routing among nodes. The federation of the multi-edge computing deployed in the different 3D network layers will be of paramount importance to support the full single pilot operations. It will also allow to run machine learning and artificial intelligence algorithms, training, and testing on the fly to better ensure aircraft operations and navigation.

The above infrastructure contains diverse resources, including radio channels, wireless, cellular and satellite air interface and spectrum, 5G core network functions; as well as, added memory, storage, processing, and communication payload to HAPSs and satellites, in addition to the content cache and edge computing distributed in the different network layers. These diverse resources provide opportunities for creating and deploying massive virtualisation assets to support 3D network slices that can meet the emerging requirements of E2E space, aerial and ground applications. It helps space, aerial and ground network operators to immediately open their physical network infrastructure platforms to the concurrent deployment of multiple logical self-contained networks, virtualised and orchestrated according to their specific E2E service requirements. The created network slices are temporarily owned by tenants who have control over multiple layers, i.e., the physical layer, the virtualisation layer, and the service layer in 3D, of a unified 5G infrastructure, while they are also verticals. That is, they integrate the 5G infrastructure vertically on ground, aerial and space networks. The availability of this vertical market multiplies the monetisation opportunities of the network infrastructure as (i) new players, such as space industry and military, may come into play, and (ii) a higher infrastructure capacity utilisation can be achieved by admitting network slice requests and exploiting multiplexing gains. With network slicing, different services, such as, space IoT, safety-critical aircraft operations connectivity, UAVs connectivity, mobile broadband, can be provided by different network slice instances. Each of these instances consists of a set of virtual network functions that run on the same infrastructure with a tailored orchestration. In this way, heterogeneous requirements can be provided on the same infrastructure, as different network slice instances can be orchestrated and configured separately according to their specific requirements, e.g., in terms of network QoS. Additionally, this is performed in a cost-efficient manner as the different network slice tenants share the same physical infrastructure.

Additionally, to these connectivity services, the capability to deploy virtual assets in NTN infrastructure enables to explore new commercial opportunities from other domains. For instance, the possibility to deploy software-based payloads allows to execute algorithms or applications associated to Earth Observation use cases [67], or Radio Frequency Interference (RFI) monitoring [68]. This capability opens thus the opportunity to explore the re-usage of operative non-terrestrial infrastructure. This approach also contributes to the recycling of spacecraft and aircraft. Specifically, satellites may become decommissioned if the original mission has been achieved. The possibility to deploy new applications in this hardware, without considering any hardware dependency, enable to recycle these satellites for new purposes. The usage thus of this novel architecture that enables to automatically deploy applications on top of non-terrestrial infrastructure would promote the apparition of new commercial opportunities.

To harness the power of such virtualised infrastructure an intelligent architecture of upcoming 5G networks calls for an efficient management framework that provides a uniform and coherent orchestration of various resources across the multiple layers of the 5G ecosystems deployed in the different 3D network layers. NFV and their MANO systems offer themselves as effective approaches, aiming at decreasing cost and complexity of implementing and deploying novel services, maintaining running services, and managing available resources in the ETHER 3D network infrastructure.

5.3 ETHER MANO LAYER

As future networks strive towards softwarisation, network functions virtualisation becomes the leading trend, with 5GC using a service based architecture (SBA), and the envisioned 6G MANO [69] also being service-based (service-based management architecture), it is evident that the orchestration of network services requires special attention.

In future 6G networks, orchestration processes can be split into four basic categories [69]:

- E2E seamless integration processes, which refers to orchestration of services using available infrastructure as a common pool of resources. These processes' main challenge is the increasing heterogeneity of infrastructure resources.

- Programmable processes, which refer to network programmability, focusing on deployment of enablers for management and troubleshooting of network devices.

- Automation processes, which are a direct consequence of network programmability. With the rapidly increasing sophistication of networks, manual processes are no longer a viable option.

- Data-driven processes, which mainly refer to the optimisation of networks using data originating from multiple network levels (slice, service, infrastructure, etc.). Main example of data-driven process is AI/ML driven orchestration, which is a necessity for zero-touch automation.

The main focus of ETHER MANO will revolve around E2E seamless integration processes, such as orchestration of E2E slices/services and MEC Applications, which can be done in at least two main ways [69]:

- Using centralised orchestration, which can directly orchestrate resources of different subnetworks.

- Use multiple orchestration domains with a dedicated orchestrator each.

This chapter will present both approaches to orchestration and propose the initial architecture of ETHER MANO. The key features of Hexa-X's (which is the flagship EU-funded 6G project) 6G MANO include: microservices-based approach, intent-based services, AIOps/DevOps friendly, possibility of private networks and zero-touch management. While Hexa-X proposes MANO architecture specifically tailored to future 6G networks, and features decoupling of management from orchestration, ETHER relies on standardised MANO solutions tailored to existing 5G network, and aims to extend them by considering gaps, possible solutions and novel features of MANO recognised by Hexa-X. These extensions will be possible through the creation of generic MANO framework, able to host diverse solutions. The most notable standardised MANO framework compatible with the 3GPP management system is ETSI NFV MANO.

5.3.1 ETSI NFV MANO capabilities and open issues

The NFV MANO framework, proposed by ETSI, is a perspective solution for the MNOs' M&O operations due to both maturity of standardisation and extensive support regarding the exposed interfaces and dedicated support. The open-source community has also made a significant progress regarding the development of the concept, e.g., in the form of successful and ETSI-compliant software implementation, i.e., Open Source MANO (OSM) [70]. It must be emphasised that the NFV MANO framework is solely focused on the virtualisation aspects. However, as outlined in the previous sections, due to significant paradigm shift in the B5G and 6G networks, the base NFV-MANO concept will need to undergo significant changes and accommodate extensions to satisfy the requirements of the highly heterogeneous networks of the future. Due to the significant advancements, it has been decided that the ETHER MANO concept will be strongly based on ETSI NFV MANO and propose solutions that facilitate the effective exploitation of the framework in the M&O operations over the unified TN-NTN

To enable integration between TN and NTN, both aerial and satellite infrastructure needs to be as configurable and flexible as their terrestrial counterparts. This flexibility is brought by NFV architecture, where services are software-based and independent of dedicated hardware. Key component responsible for orchestration in NFV is an NFV Orchestrator (NFVO, cf. Figure 5-3). NFVO performs orchestration in two layers – service layer and resource layer – and coordinates the entire MANO stack. A service is a set of different interworking VNFs, which together provide specific functionality (i.e., complete security solution). Service orchestration performed by NFVO is based upon coordination of different VNFMs to deploy and connect all VNFs of which the service is comprised. Resource orchestration includes interaction with NFVI either directly or through VIM, to make sure that the orchestrated service (consisting of VNFs) has adequate compute, network and storage infrastructural resources.

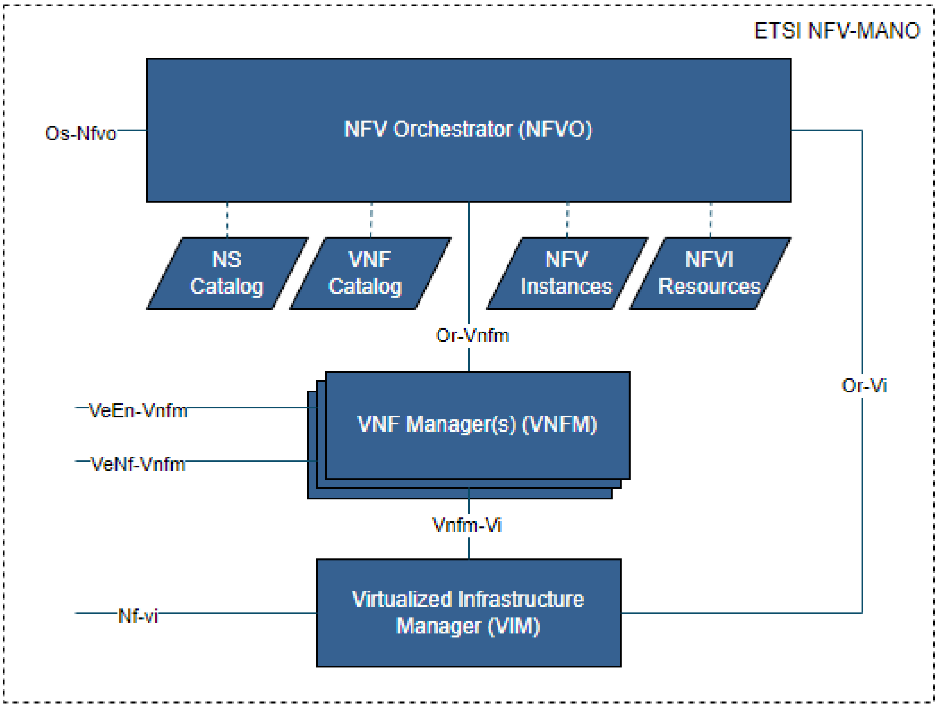

Figure 5-3: ETSI NFV-MANO stack

Following the SD-WAN concept, integration of TN and NTN networks could be facilitated by WIM, as described in section 4.2. Orchestration of applications on the network edge can be achieved by using the ETSI MEC framework. The usage of MEC within NFV MANO framework is described as an architectural option in ETSI MEC-in-NFV [30]. As previously mentioned, one way of performing E2E service orchestration is with a centralised approach. An example of E2E MANO, featuring ETSI NFV and ETSI MEC with SD-WAN concept with one central NFVO is presented in Figure 5-4.

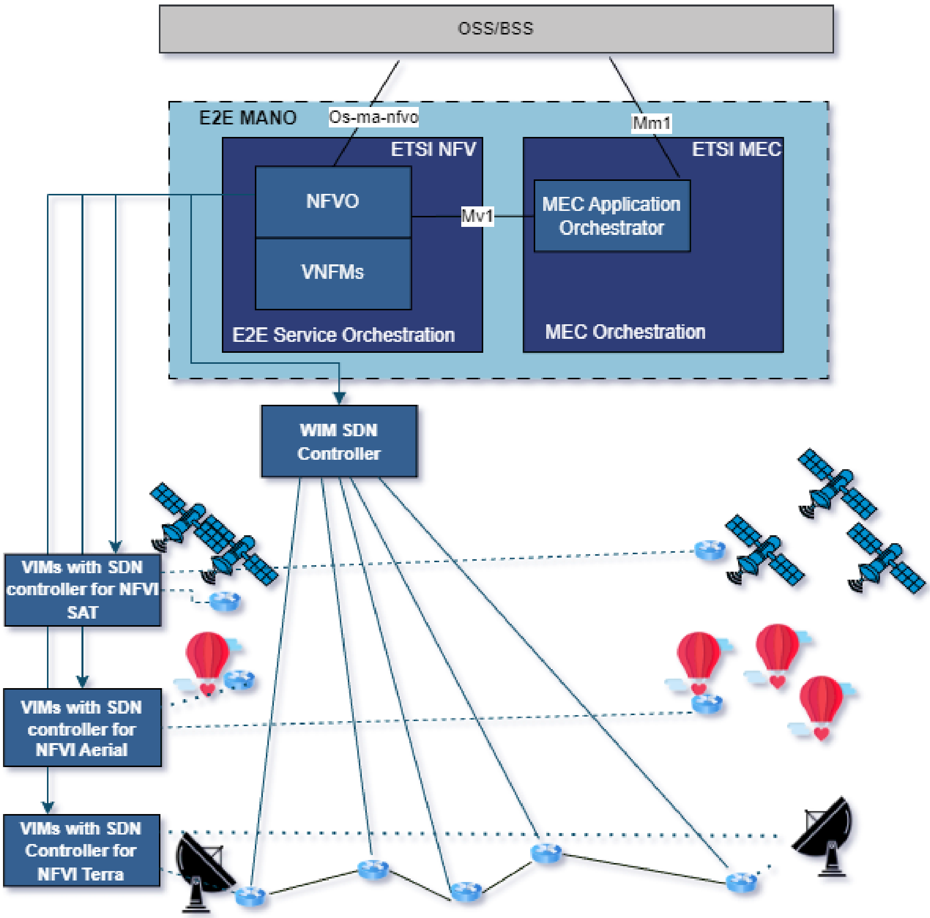

Figure 5-4: E2E MANO example using a single NFV MANO and MEC stacks over 3D infrastructure domains and common SD-WAN

Figure 5-4 features a single E2E MANO block consisting of ETSI NFV MANO stack and ETSI MEC Application Orchestrator (MEAO). In this example, 3D domain separation is handled on VIM level. In theory, this solution bridges the gap between different vertical domains and allows for E2E application/slice/service orchestration with a single orchestration domain. This approach, however, also raises a question regarding scalability and genericity of the solution. Its multi-domain and multi-vendor capabilities are limited and suffer from bottleneck with the growth of the network. It is also worth noting, that ETSI MEC in NFV is a relatively immature approach, that can be troublesome to implement [71]. A generic MANO framework not tied to specific standardised approaches is therefore needed. These are the main issues, which among others listed below, need to be addressed by ETHER MANO architecture:

- Scalability – a single, centralised component handling orchestration of all services across all domains is at a great risk of monitoring overload. As the network grows, monitoring capacity slowly shrinks until it is exhausted, at which point such component becomes overloaded. As a result, delay of network operations increases. This is especially important in context of reconfigurations needed for handovers, which will be further discussed in section 5.4 regarding E2E service layer.

- Genericity – the ETSI MANO approach requires the strict compliance of interfaces between the orchestrators in both flat and hierarchical deployments, i.e., each orchestrator has to implement the predefined set of interfaces (such as *Or-Or* or *Os-Ma-Nfvo*). Considering the already high distribution and heterogeneity of the underlying network environment (i.e., different providers exposing non- or partly compliant MANO solutions), the integration with third-party systems will be problematic. To this end, the potential solution is the use of intent-based communication, i.e., exposing high-level human-interpretable interfaces, which encapsulate the underlying logic and set of operations making them invisible to the interface consumer. Such an approach would allow for interfaces unification and flexible integration with dynamically changing conditions.

- Semi-static NFVI – in the ETSI MANO approach the infrastructural resources are generally considered static with no business interfaces allowing for the dynamic addition of new NFVI points of presence or exploitation of resource-flexibility provided by the cloud continuum concept (seamless to the user integration of Far Edge, Edge and Central Clouds) [72]. To fully benefit from the network softwarisation, the framework extensions are needed to allow, i.a., resource-related contracts negotiation, communication with continuum brokers, NFVI resources selection based on the MNOs criteria (considering energy, cost, spatial location, security policies, etc.).

- Capabilities exposure – in certain cases the VNF-driven reconfiguration can be needed, e.g., to request upscaling of resources assigned to the VNF, perform connectivity reconfigurations, or support the VNF with M&O-specific data (e.g., to optimise handovers). To facilitate such cases the interfaces or additional functions should be defined which allow for exposure of the internal MANO mechanisms and issuing M&O requests to the authorised entities.

5.3.2 ETHER MANO generic architecture

One of potential solutions to tackle scalability issue can be introduced by inclusion of hierarchical ETHER MANO, with administrative domain split. This is the second of the previously mentioned E2E orchestration approaches. In this approach, each ETHER MANO Domain is self-managed and responsible for LCM of its VNFs and services. E2E ETHER MANO facilitates creation of E2E services across multiple domains. On the Administrative Domain Level, there can be multiple domain types with different administrative and technological properties (e.g., TN/NTN cloud, RAN, edge, transport, domain combinations, etc.).

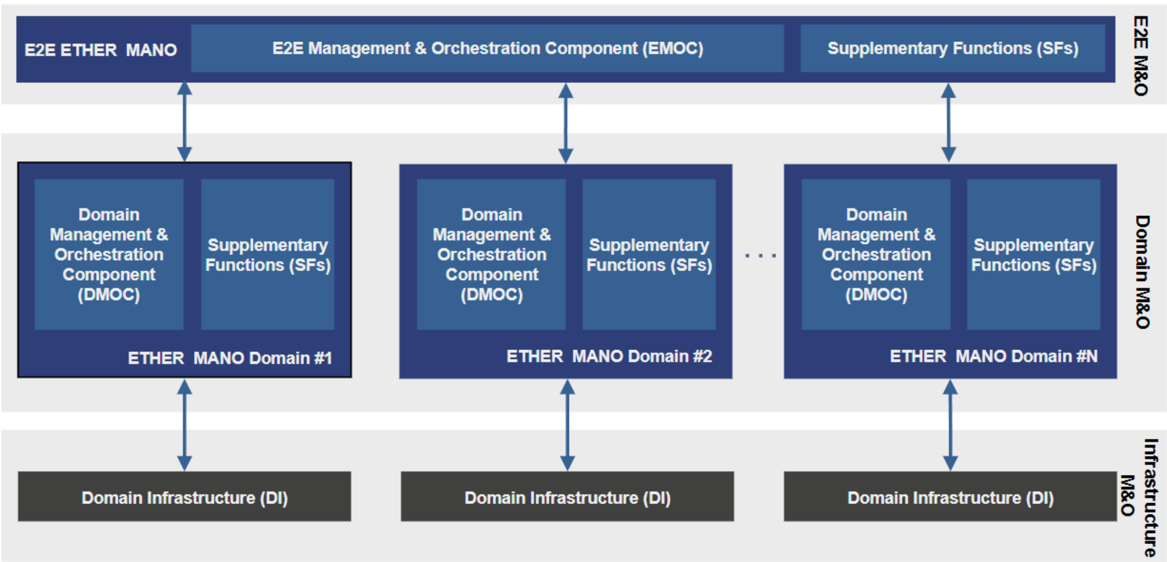

Figure 5-5: Generic ETHER MANO architecture

M&O support in ETHER MANO is split into three levels of hierarchy (cf. Figure 5-5):

- **E2E level** – composed of E2E Management & Orchestration Component (EMOC) having the global visibility of the available technological and administrative domains together with interconnections between them (i.e., the spatial distribution and topology of domains under the umbrella of ETHER MANO), and responsible for E2E M&O as well as required Supplementary Functions (SFs) supporting E2E network operations and capabilities exposure.

- **Domain level** – composed of multiple self-contained and isolated domains composed of Domain Management & Orchestration Component (DMOC) and additional functions supporting domain-specific operations and capabilities exposure.

- **Infrastructure level** – composed of multiple Domain Infrastructure (DI) entities constituting an abstracted view of the underlying infrastructure (physical, virtual, combination thereof).

Considering the key ETHER MANO functionalities and mechanisms, the main capabilities of EMOC and DMOC have been identified. It is assumed that in order to maintain the separation of concerns between M&O and M&O-related processes (e.g., business logic, secure capability exposure) both on the domain and global levels, the EMOC/DMOC are focused on M&O, while the latter are implemented in the form of a service mesh denoted as SFs (e.g., micro-services).

The key functions of EMOC include:

- **E2E M&O processes** including LCM of E2E slices/services, E2E slice/service template partitioning to sub-slices, selection of target domains for the respective sub-slices and sending intent-based requests to the respective DMOCs. It is assumed that the selection of domains and partitioning can be driven by multiple factors including the capabilities offered by the specific domain as well as business aspects (e.g., price for the deployment of slice/sub-slice components).

- **E2E M&O optimisation** by exploiting relevant functions of the orchestrator (e.g., via MAPE-K-based control loops [45]).

- **Handling the dynamic registration** and connectivity establishment to new administrative/technological domains to allow intent-based communication. It is assumed that dedicated SFs can be deployed to assist the connection process.

The key DMOC functionalities are:

- **Domain M&O processes**, which include the LCM of domain slice/sub-slice/service implemented using service templates indicated by the DMOC or requested via domain-level business interfaces, and capabilities exposure mechanisms (e.g., the domain M&O APIs, NS/VNFs catalogue).

- **Domain-level M&O processes optimisation**, e.g., VNF placement decisions, VNF migration, resource scaling, domain M&O FCAPS.

- **Resource orchestration** via direct interaction with NFVI or SFs mediating the communication with external NFVI providers (e.g., handling the negotiation processes, or interconnect with cloud-edge continuum).

To allow the proper separation of concerns, the EMOC/DMOC components are focused on the resource aspects, while the slice/service-specific management is performed via dedicated functions implementing the In-Slice Management [73] concept (VNFs deployed in a form of

SFs attached to the VNFs constituting the slice). To this end the following functionalities of ETHER MANO are implemented by the loosely coupled SFs operating both on the E2E level and domain-levels:

- OSS/BSS system compliant with the 3GPP approach.
- ETHER MANO exposure mechanisms towards business stakeholders allowing for i.a., issuing high-level requests for E2E/domain slices and services (such as GST/NEST [74]) and their translation to E2E templates, LCM of E2E slice/service.
- Support for AIaaS including maintenance of AI models catalogue for AI-driven M&O, exposure of AI-models used within the framework, interconnection with external AI models consumption, and anonymised data sharing to trusted entities.
- Security-related mechanisms leveraging zero-trust approach handling the authorisation and authentication of entities interacting with the ETHER MANO framework.
- Zero-touch management of E2E slices/services exploiting the ISM concept on the domain level with hierarchical component managing the entire sub-service chain.
- Interconnection with NFVI providers including interactions with cloud continuum brokers and NFVI providers.
- Support for adopting autonomic control loops to automate ETHER MANO processes.

It is assumed that the above list of functionalities is non-exhaustive. Hence any function extending the framework can be implemented as a dedicated SF.

5.3.3 Architecture instantiation using existing management and orchestration frameworks (OPL, ALL)

The ETHER MANO approach described in Section 5.3.2 allows the integration of multiple different MANO stacks under the umbrella of technology-agnostic EMOC. ETHER MANO is a generic framework and therefore existing MANO solutions should be able to fit inside its boundaries. Hereby, we outline the proposal of instantiation of the ETHER MANO framework with technological domain separation using other existing MANO frameworks. On the domain level, ETHER architecture considers administrative and technological domains such as Cloud, Edge (e.g., MEC-based edge), RAN and Transport residing in the Terrestrial (T), Aerial (A) and Space (S) Layers. The example of this architecture instantiation is presented in Figure 5-6.

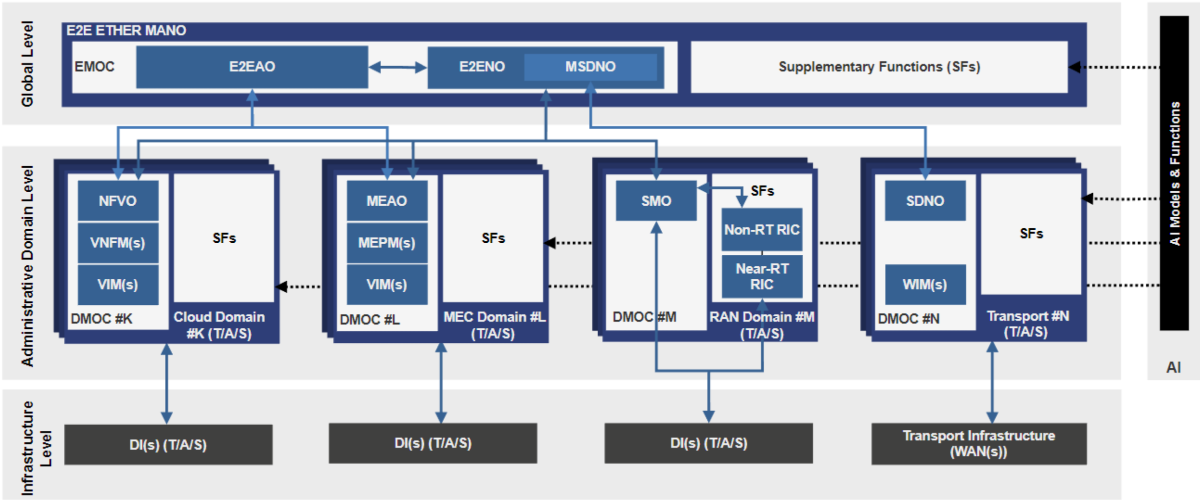

Figure 5-6: High-level view of ETHER MANO with cloud, MEC, RAN and transport domain separation

In this example, the cloud domains are handled by ETSI NFV MANO orchestrators and edge domains by MEC orchestrators, implementing the full technological stacks as standardised by ETSI. To perform RAN management open-source frameworks such as Open RAN [41] or proprietary controllers can be used. Specifically, the different functions would be deployed in the Cloud domain, composing thus the O-Cloud of O-RAN. Additionally, SMO and both RICs would conform a dedicated RAN domain that directly interacts with the disaggregated gNB functions (e.g., RU, CU, DU) previously deployed and using the O-RAN interfaces. O-RAN management system is explained in detail in [75] and summarised in section 3.9. The interconnection of the domains is performed via multiple Transport Domains, each consisting of two main blocks: SDN Orchestrator (SDNO), and WIM (WAN Infrastructure Manager). This approach is an extension to SD-WAN concept previously mentioned in Section 4.2. The SDNO block is responsible for sending domain-level SDN orchestration requests, which are supposed to enable connectivity of services within single transport domain. WIM is responsible for translation of SDNO requests into SDN configuration requirements for SDN Controllers it manages. It has to be noted that one SDNO can contact multiple WIMs (i.e., operate in the multi-vendor and multi-provider WAN environment) to obtain the path at the domain-level (cf. Figure 5-7), however, it is generally expected that stitching of the path (i.e., composing the E2E path from a number of domain paths) will be performed on the E2E level.

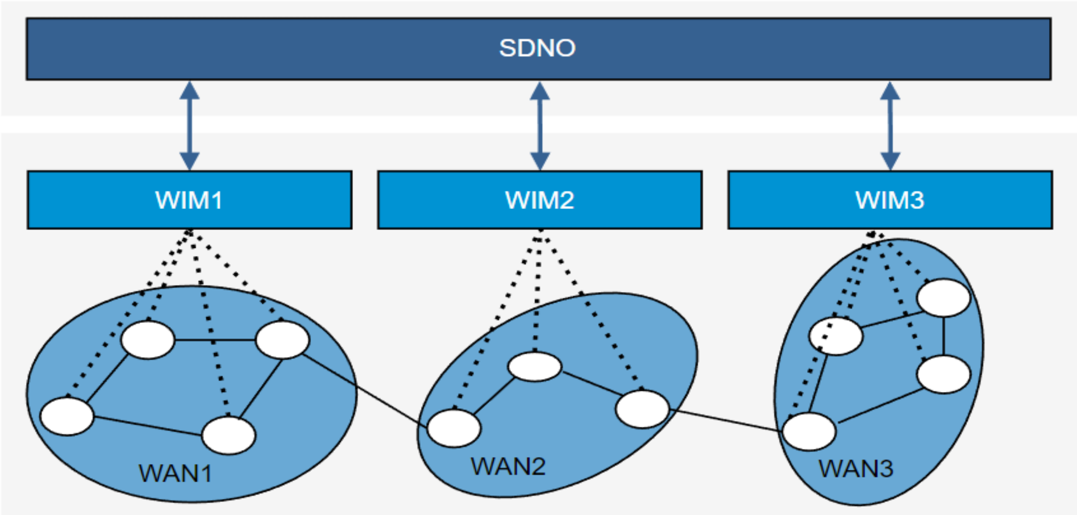

Figure 5-7: SDNO interactions with multiple WIMs (WAN providers) within a single Transport Domain

EMOC in E2E ETHER MANO consists of two functional blocks:

- E2E Application Orchestrator (E2EAO), which overlooks Cloud and MEC domains in order to orchestrate MEC Applications.
- E2E Network Orchestrator (E2ENO), which overlooks all orchestration domains and facilitates creation of E2E network slices/services. E2ENO also hosts Master SDNO (MSDNO), which is responsible for E2E SDN Orchestration, which includes coordination of SDNOs to create cross-domain virtual links for E2E slices/services out of domain-level virtual links provided by relevant Transport Domains.

Proposed ETHER MANO architecture is scalable, generic and provides strong separation of concerns. This genericity allows the adaptation of different frameworks, such as ETSI NFV for Cloud domains, ETSI MEC for MEC domains and O-RAN for RAN domains. It allows for management on different levels of hierarchy. Presence of intra-domain supplementary functions allows for other concepts like In-Slice Management or AI-driven M&O to be used if needed. Specific domains can be tailored to work either with specific vertical infrastructural levels (satellite/aerial/terrestrial) or any combination of them at the same time. Adoption of virtualisation allows for high flexibility of the network, which is especially important in context of satellite and aerial infrastructure. To enable full E2E integration within ETHER MANO framework, it is imperative to specify inter-level, as well as intra-level interfaces, which is within the scope of future work of WP2 and WP4.

5.4 ETHER E2E SERVICE LAYER

The ETHER E2E service layer (E2ESL) implements the Application, Communication, and Steering strata, as designed in the overall ETHER architecture (cf. section 5.1). The following subsections present the key features of the 3GPP 5GS Stand-Alone (SA) architecture that are crucial for the ETHER System architecture, the analysis of the ETHER requirements associated with E2ESL, and the outline of E2ESL with embedded 5GS SA.

5.4.1 3GPP 5GS SA architecture and its key features

Generic 5GS architecture framework

The evolution of the mobile network towards the 5G has followed the opportunities created both by softwarisation of the network and separation of its hardware and software layers. The mobile network is traditionally organised in two planes, which reflect fundamental activities of the network: user data transfer (User Plane, UP) and network control mechanisms (Control Plane, CP). In 5G network, these planes are spatially separated, i.e., may be located optimally, according to the spatial distribution of user data traffic and control traffic. Furthermore, the softwarised CP NFs and their interactions have been reorganised into the Service-Based Architecture (SBA) utilising well-known web mechanisms (REST API, HTTP/2, JSON format). The diagram of the generic vision of the 5GS SA architecture [11] with the indication of the most important functions is shown in Figure 5-8.

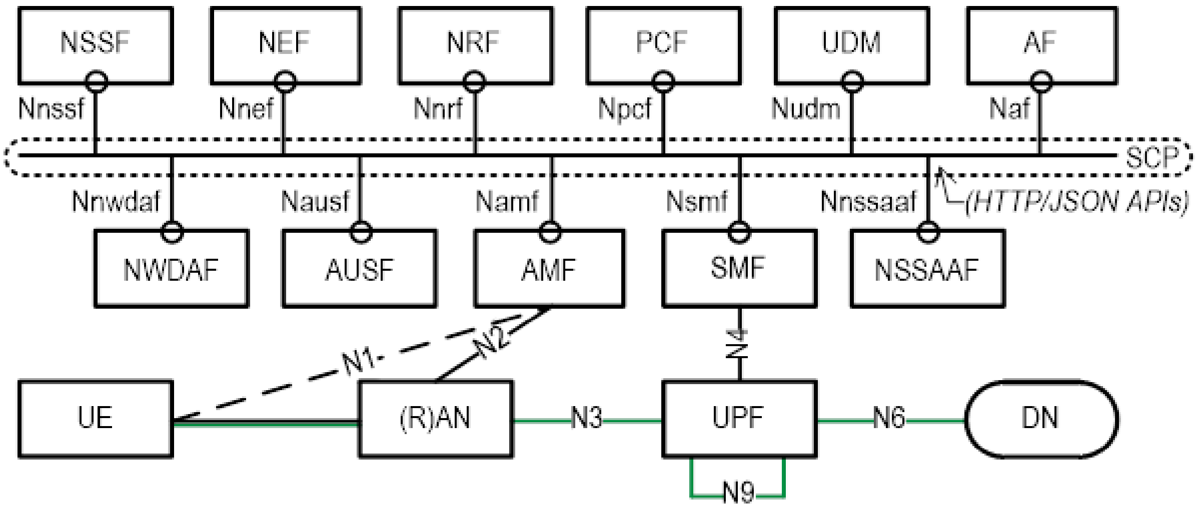

Figure 5-8: Generic 5GS architecture

The user terminal (i.e., UE) communicates with the core part of the mobile network via the access network (usually Radio Access Network, RAN). The user data follow the path of UP (depicted as green), where the external IP-based Data Network (DN, e.g., the public Internet) is reached via the UPF, which represents a chain of various data processing functions, e.g., packets inspection and classification, selective forking/rerouting, firewalling, marking/enrichment, validation, etc. Unlike in the previous mobile network generations, in which UP was just a data tunnel anchored at one point, the UPF can be now flexibly arranged according to the service class specificity and then further tailored and parametrised following the individual use case's needs. The signalling traffic between UE and the Core Network (represented as N1) is forwarded by RAN to the AMF, which acts as a CP-side termination point of UE-CP signalling and coordinates all UE interactions with CN. RAN is controlled by CN via the interface N2.

The CP functions, according to the SBA paradigm, expose CP services as their "producers" and utilise them as "consumers" (both Request-Reply and Subscribe-Notify mechanisms are possible). The mutual interaction and communication of CP NFs is supported by the Service Communication Proxy (SCP) as a CP message broker and Network Repository Function (NRF) for CP services discovery. The User Data Management (UDM) function with User Data Repository (UDR) behind manages user subscription data to be demanded for UE requests validation (network attach, data session establishing, quality of service etc.). The user data session-related requests from UE are forwarded by AMF to dedicated UPF-specific SMF supported by PCF. Also, the UE mobility-related network activities (e.g., UE handovers between base stations, UE tracking) are coordinated by AMF with SMF and RAN for UP flow continuity. The process of UE authentication is supported by the Authentication Server Function (AUSF). The service of analytics of network events and performance data, collected from all NFs, is produced by the Network Data Analytics Function (NWDAF) and served to all subscribing consumer functions.

To provide services to users outside the area of their own home network, the roaming implementation architecture of the 5GS framework has been defined. From the users' point of view, two basic strategies of UP traffic handling are distinguished: home-routed (the user's UP chain is terminated in the DN far away from the current location of the user) and local breakout (UPF is terminated in the nearby DN). Each strategy might be applied according to the user data channel use case specificity. The interested reader may find more details in [11].

5G network exposure

The role of the Network Exposure Function (NEF) is to act as CP gateway for non-native or untrusted CP NFs. They will consume the exposed CP services via NEF. NEF is also designed as for integration of external higher architecture level systems, e.g., business or operation support layer systems as well as vertical's environments, with the mobile network control mechanisms. In particular, NEF supports the following functionality:

- Secure exposure of capabilities, events, charging information and network analytics.
- Secure exposure/supplying the information of/for NWDAF at the 5G network CP border.
- Secure provision of information from external systems to 5G network.
- Format adaptation, translation of information, including masking of network/user sensitive information.

In the case of NEF used for external CP exposure to the northbound systems and environments (i.e., higher level systems), CAPIF defined by 3GPP [13] may be used that standardises common aspects applicable to any northbound service APIs of the 5GS (discovery and publishing of service APIs, authorisation, logging, charging, API management). Additionally, SEAL [14] has been defined, which specifies the functional architecture and the procedures, information flows and APIs for each SEAL service to support vertical applications over the 5GS.

Mechanism of Application Function

The Application Function (AF) architectural entity may be considered as the "embassy" of the application layer within the mobile network CP. It provides means for use case-specific applications to interact with the CP mechanisms; as AFs are aware of the quality situation in UP, usually the interaction with PCF is indicated for reconfiguring the UPF by altering the traffic routing, requesting the bandwidth or usage thresholds according to the application's requirements, as well as subscribing for session events' notifications. However, AF may potentially consume all CP services to the extent granted by the 5G network operator. For trusted AFs (e.g., operator's own) the interaction with CP NFs may be set direct, while for untrusted AFs – via NEF.

Slicing in 5GS

The support of network slicing by the 5GS is illustrated in Figure 5-9. The slicing-aware UE, according to some application's needs, may request establishing the data session through a service type- or use case-specific UPF chain controlled by its dedicated SMF, accompanied by PCF, to a specific DN (e.g., VPN). NSI selection process is supported by a special functional entity Network Slice Selection Function (NSSF) based on user subscription data in UDM. It is assumed that UE may be concurrently attached to up to 8 different NSIs [22]. NSSF determines availability of a requested NSI in a specific area and indicates a substituting NSI in case of unavailability. In some specific situations, the UE admission to the NSI may be associated with a special authentication and authorisation procedure, e.g., with the participation of a third party. To that end, the Network Slice-Specific Authentication and Authorisation Function (NSSAAF) may be involved.

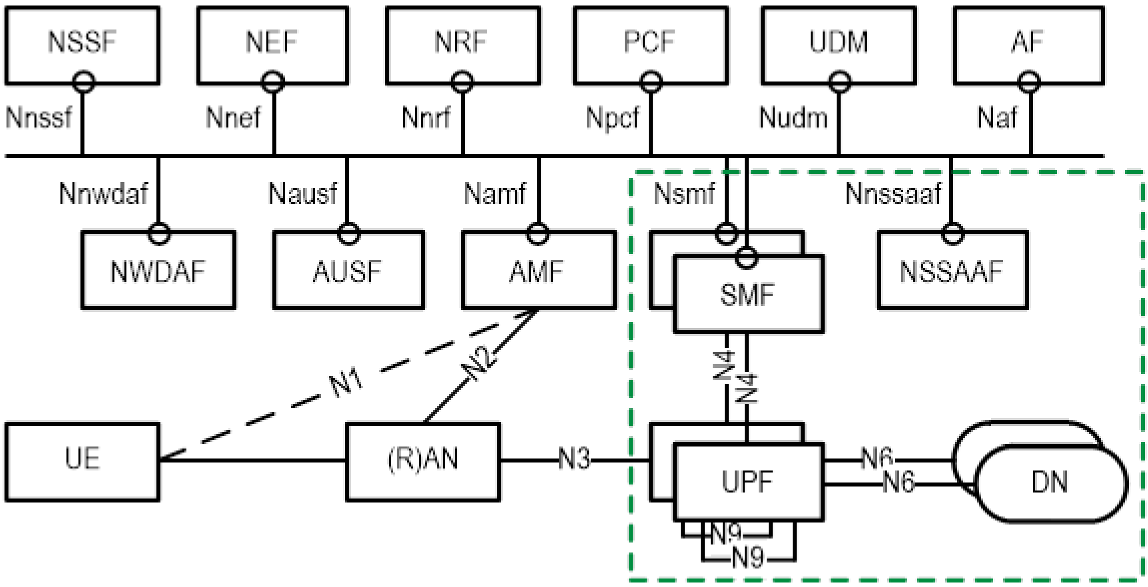

Figure 5-9: Network slicing in 5GS

The entire signalling exchange between UE and AMF, to distinguish the context of specific NSI, is labelled with the unique Single-Network Slice Selection Assistance Information (S-NSSAI) [11], which is composed of Slice Service Type (SST – 8 bits) and optional Slice Differentiator (SD – 24 bits; according to operator's naming convention may encode properties of specific network slice template, purpose, usage, tenant etc.). So far, 3GPP has defined 5 SSTs: eMBB; URLLC; Massive IoT (MIoT), as defined by ITU-R IMT-2020 [76], and further, gradually coming extensions: V2X and High performance Machine Type Communications (HMTC). Generic network slice templates, based on a defined list of attributes, are described by GSMA [74].

The area surrounded by a green dashed line in Figure 5-9 shows the group of NSI-specific functions (primarily UPF-SMF pairs for UP slicing and optional NSSAAF). There are, however, other ways of slicing implementation in CP.

To satisfy the specific needs of a certain use case or application, NWDAF may implement additional analytic algorithms, e.g., a mechanism of detection and early warning of possible communication loss if the UE trajectory is maintained. The NWDAF functionality may be split and distributed within CP and multiple, differently specialised NWDAFs with the scope related to supported NFs classes, collection and analytics mechanisms can be deployed per area or span level (global, shared by several NSIs or slice-specific – per individual NSI). The implementation of AF may be also either NSI-specific or AF can be shared by a group of NSIs if a specific AF has a wider scope of applicability than a single tenant's use case. NEF may implement services specific to a use case/NSI application.

Finally, network slicing in CP is supported by the CP SBA mechanisms presented earlier (NRF, NEF, SCP). While NRF supports NF service discovery, maintains NF profiles with available NF instances, their supported services and health status, these features may refer to NF instance span level. In particular, these are the authorisation of CP NFs services discovery and access at the per-producer/per-consumer level, which enables logical partitioning of CP into "common/dedicated slices".

Network slicing is also envisioned in RAN, aiming to better utilise the available physical resources, which are limited by the spectrum width. 5G slices overcome the QoS issue in 4G that does not have the ability to perform E2E traffic isolation. While 4G QoS mechanisms can discriminate between different types of traffic but cannot discriminate and differentially treat the same type of traffic coming from different sources, 5GS, due to slicing, is able to do both at a deeper granularity (per user session). 5G Network slicing also provides isolation between slices, thanks to radio partitioning in RAN. The allocation of Radio Resources to specific slices (scheduling) is achieved at two levels: radio spectrum allocation per slice (inter-slice) and specific scheduling within each slice (intra-slice). When resources are exhausted in a cell or in a slice, the pre-emption will ensure that each slice from a prioritised pool can have the minimal number of resources that were provisioned to it and that services with the highest priority are supported within a slice. There are the mechanisms of congestion control – if a requested slice is overloaded, a new UE will be connected to a default slice.

RAN also supports the abovementioned mechanism of S-NSSAI. RAN slices are coupled to AMF instance based on S-NSSAI in the initial attach procedure, which may be provided either by UE or 5G CN. UE admission includes protection against unauthorised access to a slice. RAN Slicing supports service continuity over mobility; when a slice indicated in the handover request is not supported in the next cell, the service is handed over to a slice with the most similar QoS.

Role of SMF

The fundamental role of SMF is to provide the CP services that control UPF. The interaction between the SMF and UPF in 5GS involves coordination and communication to ensure proper management and handling of user data during sessions. Here are the key aspects of the SMF and UPF interaction:

- Session establishment – When a PDU (Packet Data Unit) session is established, SMF determines the appropriate UPF for the session. It selects and assigns a specific UPF instance based on policy rules, QoS (Quality of Service) requirements, and other factors.

- Data routing – Once the session is established, SMF communicates with the assigned UPF to provide the necessary information for data routing. This includes sharing information about the PDU Session ID, QoS parameters, and other session-related details.

- Policy enforcement – SMF communicates policy rules and enforcement instructions to the UPF. It instructs UPF on how to handle user data packets, enforce traffic rules, apply QoS policies, and ensure appropriate security measures.

- User data forwarding – UPF performs the actual data forwarding and processing tasks based on the instructions received from SMF. It routes user data packets to the appropriate destination, applies policy-based traffic shaping or filtering, and manages data flows according to the defined QoS parameters.

- Dynamic control – SMF and UPF maintain ongoing communication to dynamically adjust the data handling based on changing conditions or events. This may involve updating policy rules, modifying QoS parameters, or responding to session-related events triggered by SMF.

- Session termination – When a PDU session is terminated, SMF instructs the assigned UPF to release the associated resources and terminate the data forwarding for that session.

The SMF and UPF interaction is crucial for ensuring proper management, control, and processing of user data during sessions in the 5G network, especially the continuity of user data flow (see the description of SMF involvement in handover procedures). Through their coordination, SMF defines policies and rules, while UPF implements them and performs the necessary data forwarding and traffic management tasks.

Mechanisms of handover

In the context of 5GS, there are two fundamental ways for managing handovers. The first way, known as “Xn-based” handover, utilises the Xn interface between the source and target NG-RAN (Next Generation Radio Access Network) Base Stations (BSs) to manage the handover process. In this scenario, the Xn interface serves as the primary means of communication for coordinating the handover. The second case is referred to as “N2-based” handover, where the N2 interface between the NG-RAN BS and AMF is utilised to manage the handover. Here, the N2 interface plays a crucial role in facilitating the communication and coordination between the NG-RAN BS and the AMF during the handover process. Below is a high-level description of NF roles in both approaches, highlighting the differences and similarities:

- Xn-based handover – the procedure is initiated and coordinated by the source BS in direct interaction with the target BS. Source BS is able to determine the target BS itself. 5GS CN (via the gateway, AMF) is informed about the actions taken and the need to switch the UP N2 path. SMF manages the preparation and execution of UPF path reconfiguration to provide its continuity before and after the handover. After the successful handover, the target BS takes the responsibility of the UE serving, and the source BS releases its resources.

- N2-based handover – the procedure is initiated by the source BS, which is unable to determine the target BS within the same AMF area. It requests its source AMF to take the coordination role. The source AMF selects the target AMF and the latter requests SMF to prepare the UP switching. After the successful path preparation, the target BS is requested for handover preparation, and then the source AMF is notified about the preparation completeness. When the execution of handover is triggered by the source AMF, and both source BS (directly) and target BS (via the target AMF) are activated to proceed. After the successful UE synchronisation to the new target BS, SMF is requested to coordinate the path switching execution in UPF. Then, as the target BS and AMF have taken the responsibility of the UE serving, the source AMF and BS are released.

The basic principles of the 5GS architecture are the maximum possible flattening of the communication network and the delegation of decision-making powers of the CP as close to the EU as possible in order to shorten and accelerate the decision-making path. Therefore, an Xn handover is preferred where the coordination takes place at the NG-RAN level, and if this is not possible then an N2 handover coordinated by CN takes place. However, regardless of the coordination point of the handover procedure, the responsibility for controlling the preparation and execution of the UPF path for UE each time lies on SMF.

Scalability

The scalability is often referred to as the property of the network to keep its performance independent of its size. In the hitherto reality, especially related to the existence of a universal general-purpose mobile network (up to 4G), the only way to keep pace with the increase in service and traffic demand was the continuous, gradual expansion of network capacity through the installation of more or bigger network devices to be then gradually filled up until the next expansion cycle driven by their saturation. In view of the paradigm shift in favour of flexible delivery of individualised solutions, as well as the growing importance of energy efficiency, such a development model cannot be sustained, but also does not have to be thanks to new technologies. The need for scalability has also a strong business dimension: it is related to how easily a use case-supporting network solution can be upscaled or downscaled following the dynamically changing demand ("pay as you go" model) without overspending at one extremity or performance threat at the other.

The scalability of the 5G network is brought at different levels:

- Network softwarisation – decoupling of hardware and software enables functions portability to follow the demand in space; software load balancing mechanisms allow for flexible reaction (running more or less application instances) to the load.

- Network virtualisation/containerisation – the underlying hardware can be upscaled/down-scaled without impact on upper layers; its lifecycle does not impact the lifecycle of the virtualised resources or applications consuming them.

- SBA of the 5G CN and high granularity of the functional decomposition – the softwarised functions can be run on demand to serve a specific demand (spatial, type of service- or network slice-related, etc.); mechanisms of NEF, NRF and SCP additionally support logical partitioning of the entire network.

- Network slicing – isolation and individual processing of a traffic fraction, in the way tailored to use case requirements.

The mechanisms of scaling control, acting at different levels, have to be coordinated by the management layer to avoid their mutual competition leading to instability. A very important aspect of scaling is the dynamics – while the timescale of "old fashioned" hardware-based network extension was months, the virtualised infrastructure level scaling timescale is tens of seconds up to minutes. The unanswered challenge is still a dynamic slicing, i.e., delivery on demand or lifecycle operations of the E2E network slice in a second timescale.

Integration of MEC and 5G

The 5GS can be integrated with the MEC technology. The MEC Platform (MEP) communicates with a Data Plane (i.e., the underlying mobile network used for forwarding the MEC application traffic) via *Mp2* interfaces. In particular, through this way, the MEP requests the network to redirect the traffic from the mobile terminal to the MEC application located at the Edge host. This is also the interface through which MEP can acquire the information to be further exposed to applications through MEP APIs related to bandwidth, radio interface, user location and identity.

From the point of view of 5GS, MEP is seen as a special case of AF within the 5GS CP, consuming the CP services. Consequently, the *Mp2* interface is equal to *Naf* according to the 5GS framework convention (cf. Figure 5-8). If MEP is trusted, it can communicate directly with other CP NFs. In a general case, it will be “gatewayed” by NEF. The Edge Application Server, where MEC applications reside, is seen within some local DN, different to the central one, through which the general user’s traffic is forwarded. Additionally, to support the mutual understanding between both frameworks, 5GS and MEC, the new CP NF has been introduced: Edge Application Server Discovery Function (EASDF) [77]. It should be noted that the cooperation of both has to be also assured, e.g., for coordination of terminal handover between base stations and MEC client at mobile terminal handover between MEC application instances located at different hosts. Additionally, integration with MEC provides an additional factor to increase the scalability of 5GS.

Cross-layer management and orchestration according to 3GPP

The approach of 3GPP is complementary to the ETSI NFV vision (cf. [12], Annex A.4), as it is shown in Figure 5-10. The hierarchy of the 3GPP management functions: Communications Service Management Function (CSMF) – Network Slice Management Function (NSMF) – Network Slice Subnet Management Function (NSSMF) – Network Function Management Function (NFMF) is mapped so that NFMF is the equivalent of NE according to ETSI NFV, and NSSMF is the equivalent of OSS/BSS to ETSI NFV. In this way, 3GPP supports the integration of many technological and administrative domains, in particular, the exposition of Network Slice Subnet as a Service (NSSaaS) by an operator to another operator.

The communications service and network management vision applies the SBA approach to the 5GS management plane similarly to 5GS CP with all relevant concepts (Producer-Consumer, Request-Reply, Subscribe-Notify). Additionally, the equivalents of NEF and NWDAF in the 5GS management plane are Exposure Governance Management Function (EGMF) and Management Data Analytics Function (MDAF).

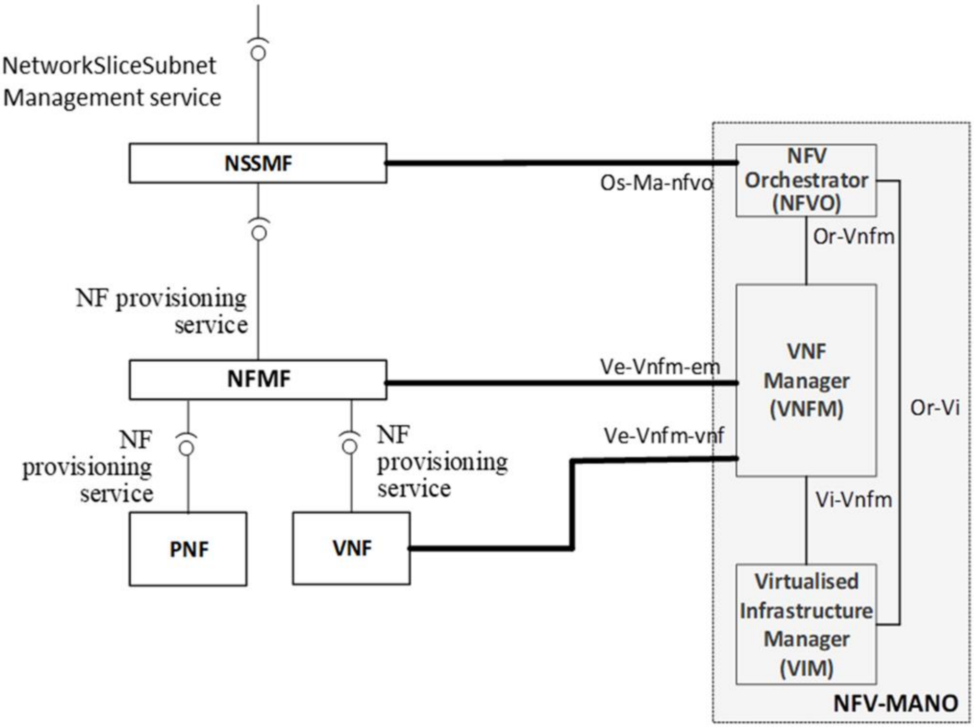

Figure 5-10: Integration of the 3GPP network and service management framework and ETSI NFV MANO framework [12]

According to Figure 5-10, NSSMF and NFMF are consumers of the ETSI NFV MANO reference points *Os-Ma-Nfvo* and *Ve-Vnfm-em* interfaces, respectively.

- The NSSMF can consume the VNF LCM (Lifecycle Management) and network service LCM services provided by NFV MANO. It is also a producer of network slice subnet-related management services. NSSMF is responsible for managing network slice subnets, which are subsets of a network slice. It consumes VNF LCM and network service LCM services to orchestrate the lifecycle of VNFs and network services within the network slice subnet.

- The NFMF is capable of application-level management of VNFs and PNFs (Physical Network Functions). It acts as a producer of the NF Provisioning service, which includes Configuration Management (CM), Fault Management (FM), and Performance Management (PM). NFMF also consumes the NF Provisioning service produced by VNFs and PNFs. NFMF is deployed for managing VNFs and PNFs at the application level. It handles tasks such as provisioning, configuration management, fault detection and resolution, and performance monitoring. It produces the NF Provisioning service, enabling other entities to consume these management services. NSSMF focuses on network slice subnet management, consuming VNF and network service LCM services, while NFMF is involved in the application-level management of VNFs and PNFs, both producing and consuming the NF Provisioning service for CM, FM, and PM.

5.4.2 Key issues for the E2E service layer of the ETHER system and proposed solutions

Below, the 3GPP 5GS features have been validated against the requirements and basic considerations described in Section 4.

Genericity is supported by embracing standardisation, employing a modular architecture, using APIs, virtualisation, supporting multi-domain operation, in the ETHER core network. This flexibility allows the network to accommodate different frameworks and technologies, making it adaptable to evolving industry requirements and advancements.

Multi-domain capability of the ETHER core network facilitates the integration, coordination, and seamless communication between different access (terrestrial, aerial, space) and functional domains (RAN, edge, core, transport). Integration ETHER core network with ETSI MANO supports the multi-domain paradigm, facilitating the coordination, orchestration, and management of resources, services, and functions across diverse administrative or functional domains. Network Slice Subnet (NSS) and NSSaaS are also essential components in the multi-domain paradigm of ETHER network. They enable the creation, coordination, and dynamic composition of network slices that span across multiple domains, allowing for collaboration among different stakeholders in the ETHER ecosystem.

Multi-provider functionality is fulfilled as logical implication of multi-domain paradigm. Resources provided by different service providers, operators, enterprises, or regulatory operators being virtualised are used to implement services within different domains. These domains refer to distinct entities or organisations that have administrative control over specific parts of the network enabling collaboration and interoperability between different stakeholders.

Modularity is achieved by representing the individual network functions in the ETHER core network that are provided as independent services. Each network function service encapsulates a specific functionality, such as mobility management, session management, authentication, or policy control. By decomposing network functions into standalone services, the SBA achieves modularity, allowing functions to be developed, deployed, and updated independently.

Zero Touch Management and **Intent-based** principle in the ETHER core network can be achieved by service providers and network operators which consume provided APIs. NEF, NRF, and NWDAF are the functions to provide data for the exposed APIs. APIs form the foundation for building an automated, flexible, and efficient ETHER core network that operates with minimal human intervention and delivers mechanisms to continuously monitor the network and evaluate its performance against the defined intent.

Hierarchical approach refers to management organisation and is supported by management functions stack (cf. the issue “Cross-layer management and orchestration according to 3GPP” in section 5.4.1). CP and UP are designed as flat as possible to avoid unnecessary processing delays. However, the hierarchical approach to management by 3GPP enables fast-acting local mechanisms, while upwards the hierarchy, slower mechanisms can be used, but at a higher level of abstraction.

Distribution implies the dispersal of network functions, services, or resources across different locations or entities, aiming to optimise performance, resilience, and resource proximity. The 5GS SBA architecture with underlying virtualisation technology allows network functions, services, or resources to be distributed across different geographical locations or data centres to reduce latency, improve performance, ensure fault tolerance and resilience in case of failures, or enhance availability.

Scalability in 5GS is achieved both at the level of its architecture as network function services (NFS) are designed to be modular and horizontally scalable, enabling the addition or removal of instances on demand, and vertical scaling mechanisms supported by the underlying virtualisation technology.

Service-based principle is inherent due to the SBA architecture of 5GS CP including the publish-subscribe, and request-response model, and consuming REST API-based interfaces and service discovery supported by NRF.

Openness to future extensions and trends embraces flexibility, modularity, and SBA principle of 5GS, virtualisation technologies and cloud-native principles enabling the seamless integration of new technologies and services (e.g., micro-service mesh) as they become available.

The validation above refers to the UP and CP, of the ETHER E2ESL. For AP, compatibility will be implementation-specific.

In Table 5-1 below, the evaluation of the ETHER requirements support by 5GS is provided including the potential solutions, also for cases of gaps. The ETHER “definition of work” in the Grant Agreement states that “*Design of the ETHER architecture will be consistent with the management architecture for integrated satellite NR-RAT proposed by 3GPP in Release 17*”. However, the evaluation below versus the 5GS architecture (cf. TS 23.501, relevant versions) includes also the currently existing 3GPP solutions in the Release 18 as well as visions of future scope of the Release 19.

Table 5-1: Evaluation of the ETHER requirements with impact on the E2E Service Layer

Identifier	**Requirement**	**Key Issue for E2ESL Architecture**	**Potential Solution**
ETH-REQ-UC1-DT-01	Intermittent – scheduled contacts	UE should be notified by about a contact schedule.	From LEO/MEO system OSS to UE through AP.
ETH-REQ-UC1-DT-02	Intermittent – opportunistic contacts	UE should detect the presence of LEO/MEO satellite and request a contact.	Standard 5GS mechanism; presence sampling period vs. battery saving to be determined.
ETH-REQ-UC1-DT-04	Congestion and flow control	1. There should be included mechanisms of flow control in UE-satellite and satellite-ground links to avoid congestion and data loss (including reception validation and retransmission). 2. Mobility management mechanisms should include redirection of DL data during the handover procedure. 3. In case of Low-Density LEO constellation, “no interruption” feature may not be possible, but the next approaching satellite to serve the specific UE is known due to the defined orbit, so the DL data for the UE can be forwarded from the source satellite (losing a contact with UE) to the target satellite (about to catch a contact with UE) in advance together with UE context.	1. Flow control through Application Plane (AP) to keep the UE genericity. 2. Standard handover procedures include necessary DL data redirections. 3. No such feature in 3GPP R17, development is needed (update of UPF, SMF, AMF, gNB functions).
ETH-REQ-UC1-DT-06	Connection discontinuity	1. Service link (UE-satellite) should be resistant to temporary interruptions (loss of contact). 2. ETHER E2ESL should be immune to temporary system partitioning due to loss of feeder link (satellite-ground).	1. Flow control/AP mechanisms and gNB presence detection by UE (standard 5GS mechanism). 2. 5GS may be distributed over the terrestrial and non-terrestrial layers.
ETH-REQ-UC1-DT-07	Store and forward	ETHER E2ESL should support store and forward functionality.	No such mechanism supported in 3GPP R17

Identifier	Requirement	Key Issue for E2ESL Architecture	Potential Solution
			(Store and forward mechanism in 3GPP R19 requirements study; update of UPF, SMF, AMF functions). Development is needed in these areas.
ETH-REQ-UC1-DT-09	Mobility management	1. Integration of NTN with TN needs dynamic reallocation of gNBs in motion (LEO/MEO) between Tracking Areas (TAs) to ensure permanent mapping of geographical areas and TAs. Satellites moving over successive countries should be dynamically connected to TNs in these countries and the relevant TAs. 2. Cf. ETH-REQ-UC1-DT-01.	1. Such mechanism is supported in 3GPP R17 (Tracking Area handling for NR satellite access), which ensures that each TA is Earth-stationary even if the radio cells are moving across the Earth's surface. 2. From LEO/MEO system OSS to UE through AP or CP (N1 interface, either access or non-access stratum, FFS).
ETH-REQ-UC1-DT-10	Support for different services	ETHER E2ESL should support integration of different RATs with the same CN (e.g., 4G and 5G).	The integration of different 3GPP RATs with the same CN implies the non-SA 5GS architecture where network slicing is not supported, according to the 3GPP approach. The requirement contradicts with the general network slicing support expectation as well as ETH-REQ-UC3-FN-01.
ETH-REQ-UC1-SE-01	Sample processing	ETHER E2ESL should support both access to data contained in all its planes and ability to influence them back.	CP provides a generic mechanism with NEF to be used with all 5GS CP databases. Other impact on other CP NFs may require their functional upgrade. Sampling and return impact on UP data needs inclusion of additional processing functions to UPF, e.g., deep packet inspection (DPI), buffering, etc. In the case of AP, the means will be use case- and implementation-specific. These mechanisms will be exposed to other ETHER layers.
ETH-REQ-UC1-SE-02	Joint sample and transmit	Cf. ETH-REQ-UC1-SE-01	Cf. ETH-REQ-UC1-SE-01
ETH-REQ-UC1-SE-03	Support for E2E information handling beyond the sample and transmit	Cf. ETH-REQ-UC1-SE-01	Cf. ETH-REQ-UC1-SE-01
ETH-REQ-UC1-SE-04	Content caching	Cf. ETH-REQ-UC1-SE-01	Cf. ETH-REQ-UC1-SE-01
ETH-REQ-UC2-FN-01	Migrate TN to NTN	E2ESL should support handovers between 3D layers.	3GPP R17 supports Xn and N2 handovers; no need of new CP functions identified; however, exposure of AMF and gNB for impact of

Identifier	Requirement	Key Issue for E2ESL Architecture	Potential Solution
			external logic (AI-driven) may need additional development.
ETH-REQ-UC2-FN-02	Vertical handover	Cf. ETH-REQ-UC2-FN-02	Cf. ETH-REQ-UC2-FN-02
ETH-REQ-UC2-NF-01	Vertical handover	ETHER E2ESL should support handovers that are autonomous and imperceptible for the end user.	3GPP R17 supports Xn and N2 handovers without involvement of the end user; no need of new CP functions identified; however, exposure of AMF and gNB for impact of external logic (AI-driven) may need additional development, as AI-driven handover prediction may be crucial for providing near to zero interruption time during vertical handovers.
ETH-REQ-UC2-NF-02	Broadband	ETHER E2ESL should support broadband communication service and TN-NTN handovers.	3GPP R17 supports Xn and N2 handovers (cf. ETH-REQ-UC2-FN-01); in case of NTN sufficient gNB capacity has to be provided.
ETH-REQ-UC2-NF-03	Coverage	ETHER E2ESL should provide 100% coverage.	No direct impact on E2ESL; for feasibility, TN/NTN integration is needed.
ETH-REQ-UC3-FN-01	RAN in TN, HAPSs, and SAT	ETHER E2ESL should provide a unified RAT to be exploited by unified UEs.	Unified RAT in 3D layers needed.
ETH-REQ-UC3-FN-02	Open 5G core network	ETHER E2ESL should provide APIs for trusted external systems.	3GPP R17 supports NEF/AF functionality in 5G CP; in case of RAN, OSS should expose NBI or O-RAN with NBI and x-App/r-App may be exploited.
ETH-REQ-UC3-FN-05	Multilink functionality	ETHER E2ESL should provide connectivity resilience (e.g., redundant connectivity links).	3GPP R17 supports dual connectivity/multi-connectivity; its compatibility with NTN integration should be validated; however, no need of new CP functions identified. A compatible UE and traffic control software has to be used.
ETH-REQ-UC3-NF-04	Handover reliability and delay	ETHER E2ESL should provide seamless vertical/horizontal handover mechanisms that include proactive approach in minimising the interruption time.	If the target gNB can be selected, the session continuity is provided by a principle in 3GPP R17. For the other aspects, cf. ETH-REQ-UC2-FN-01 and ETH-REQ-UC2-NF-01.
ETH-REQ-UC3-NF-05	3D network programmability	ETHER E2ESL should provide RESTful APIs for interconnection with other layers.	In 3GPP R17, both internal CP bus and APIs exposed through NEF RESTful-based. gNB-RAN OSS interface – seems to be left by 3GPP for implementation; O-RAN interfaces are subject to O-RAN Alliance standardisation (if no RESTful API at specific reference point is available, a mediation module

Identifier	Requirement	Key Issue for E2ESL Architecture	Potential Solution
			development may be necessary).
GENERAL-FN-01	Detection of UE NTN gNBs attach capability	ETHER E2ESL should detect the UE capability to be served by NTN to prevent infeasible mobility management.	In 3GPP R17, no such mechanism is defined. 5G Equipment Identity Registry (5G-EIR) could be involved during the Registration/Attach procedure to label a registered UE as NTN-capable. gNB and AMF should be updated for compatibility.
GENERAL-FN-02	Detection of UE non-stationary NTN gNBs attach capability	ETHER E2ESL should detect the UE capability to be served by the non-stationary NTN gNBs (e.g., Doppler shift-proof waveforms) to prevent infeasible mobility management.	In 3GPP R17, no such mechanism is defined. 5G-EIR could be involved during the Registration/Attach procedure to label a registered UE as NTN-capable. gNB and AMF should be updated for compatibility.
GENERAL-FN-03	Detection of TN-preferred UEs	ETHER E2ESL should detect the UEs with preference of being served by TN access, however able to be served by NTN access.	In 3GPP R17, no such mechanism is defined. 5G-EIR could be involved during the Registration/Attach procedure to label a registered UE as NTN-capable. RAT preference mechanism is not supported, gNB and AMF should be updated for compatibility.
GENERAL-FN-04	Detection of NTN subscription	ETHER E2ESL should be aware of UE NTN subscription to prevent mobility management not allowed by subscription.	In 3GPP R17, mechanisms of forbidden area and service area restrictions can be used for NR satellite access. The mobility restrictions can be enforced based on NTN RAT type identifiers defined by 3GPP: NR(LEO), NR(MEO), NR(GEO), and NR(OTHERSAT).
GENERAL-FN-05	SDN-based transport	ETHER E2ESL should be able to control the UPF continuity in an SDN-based transport.	SMF should interact with the SDN CP via the N4 interface [78]. The need of SMF update for compatibility needs further validation.

5.4.3 ETHER E2E service layer architecture

The ETHER E2ESL comprises AP, UP, and CP that implement the Application, Communication, and Steering strata respectively (cf. Figure 5-1). UP and CP are implemented with the 3GPP 5G+ network, according to the ETHER assumptions based on the analysis of the 3GPP 5GS framework architecture and its cross-verification with the ETHER requirements presented in sections 5.4.1 and 5.4.2 respectively. All these planes are orchestrated and managed by the ETHER MANO layer supported by the ETHER AI layer. It should be noted that the 5G+ network CP is not an exclusive implementation of Steering Stratum. SDN CP, outside of the perimeter of 3GPP 5GS, also implements it.

The roles of all planes composing E2ESL are as below:

- AP hosts the application-level services. It is localised at the UE side (the UE application or application implemented in a local system that includes UE) and at the application platform, which is, in general, a distributed solution, hosting a distributed application server. The application platform is embedded in the ETHER system shared resources. Moreover, it is assumed that AP can consume the services exposed by the ETHER AI layer, e.g., exploit AI models for predictive analytics to optimise the applications performance. The detailed AP architecture will, however, depend on the solution specificity.

- UP provides connectivity service for AP with predefined QoS guarantees (latency, bandwidth, reliability, etc.). The UP operations include application-specific data forwarding and processing (e.g., Deep Packet Inspection, traffic filtering, parental control, etc.), also (and especially) in terms of relative mobility of terminals and networks, since both UE mobility and radio access node mobility are supported in the ETHER system.

- CP provides all necessary mechanisms to provide the UP services for the communication services user. These control mechanisms run autonomously or can be exposed through a CP API.

The simplified ETHER E2ESL architecture is presented in Figure 5-11. The AP interactions are served by the 5G+ UP composed of a service-specific UPF, which is a chain of atomic virtualised functions distributed in the virtualised infrastructure (not shown in the picture except for SDN-based transport providing the transport layer for the functions composing the UPF chain, so the 5G+ UPF connections can go down to the SDN-based transport and back several times).

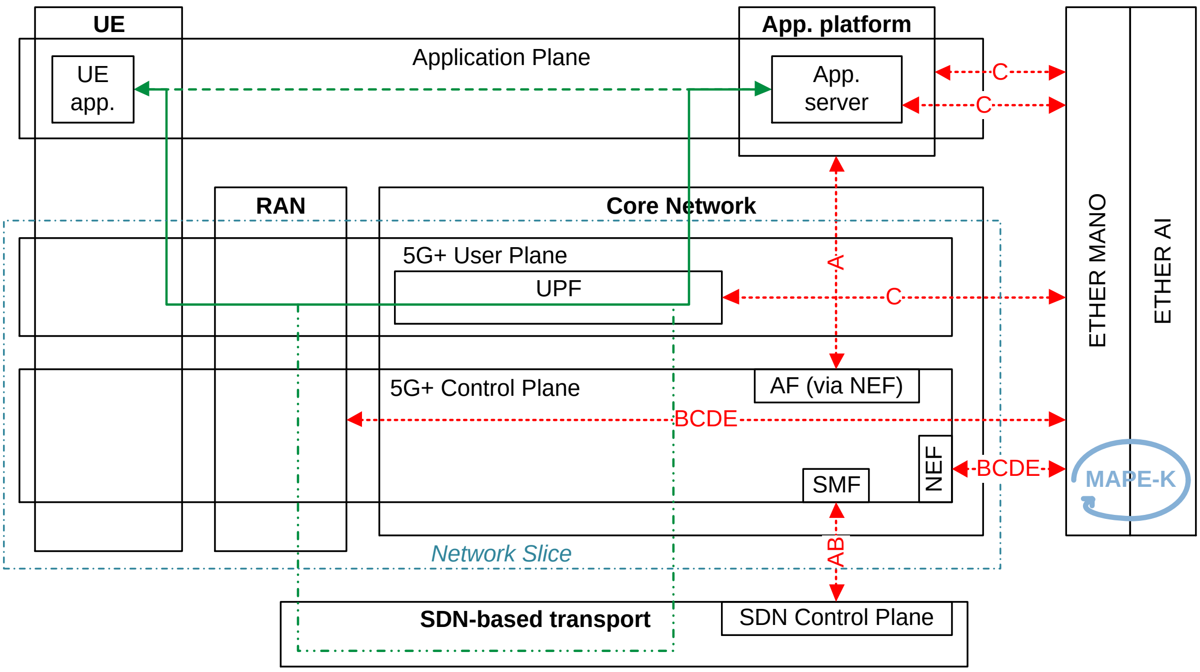

Figure 5-11: ETHER E2E Service Layer architecture and support of specific ETHER mechanisms

Selected ETHER E2ESL entities are indicated in Figure 5-11 to emphasise their role in the support of fundamental ETHER mechanisms presented in Figure 4-2 (cf. interactions indicated as A, B, C, D, and E), namely:

A. MEC & caching: the application platform (e.g., MEC), integrated as AF, requests via NEF UE-related data from the CP services or redirection of specific UE traffic fraction to the application server. The latter request is further processed by SMF and sent to the SDN CP in SD-WAN through the N4 interface [78] (N4-SDN CP NBI mediator to be potentially developed). In case of caching mechanism, it can be embedded in UP only or also use AP. For the latter case, an interaction with SDN CP may be also used. The SDN CP interfaces can be either accessed directly or via MSDNO/SDNO APIs. The deployment configuration and potential benefits of both approaches will be investigated within WP3 activities.

B. Seamless vertical/horizontal handover: the AI-based handover logic controls upgraded AMFs via NEF and upgraded gNBs in RAN (cf. proposed solution for ETH-REQ-UC2-NF-01 in Table 5-1). The details of the handover control solution will be defined by WP3.

C. Semantic-aware data analytics: the interaction of semantic data analytics is provided with all planes: both application server and platform in AP, dedicated entities in the UPF chain (to be further studied by WP3), and relevant core CP functions via NEF or directly from gNBs in RAN (here, the data may be also acquired via RAN OSS). At this stage, no need for interaction via SMF with SD-WAN CP in the context of UP analytics has been identified.

D. AI-based predictive analysis: the data for analytics are exposed by core CP functions via NEF or directly from gNBs in RAN (here, the data may be also acquired via RAN OSS). Defining the details of the analytics solutions will be performed within WP3 activities.

E. AI-enabled E2E network performance optimisation: the data for analytics are exposed by core CP functions via NEF or directly from gNBs in RAN (here, the data may be also acquired via RAN OSS), and the control feedback may go exactly the same way (RAN OSS mechanisms will probably be used for actuation in RAN). Decision about either direct interaction with core CP NFs or via NSSMF/NFMF (cf. Figure 5-10) is implementation-dependent (to be further investigated by WP4).

It should be emphasised that the mutual relations/interactions of the ETHER MANO and AI layers will be further investigated by WP4. The ETHER E2ESL exposes data and mechanisms that can be used by both layers.

5.5 ETHER AI LAYER

According to the general vision of the overall ETHER architecture (cf. section 5.1), the ETHER AI layer has been defined as an implementation of a separate AI Stratum, embedded as a native element of the ETHER system, which role is to expose its services to the ETHER MANO as well as applications, communication, and steering mechanisms.

At the current stage of the project, it is assumed that the ETHER AI layer will be designed according to the SBA principle. ETHER will also monitor and take inspiration from ongoing efforts by SDOs in the integration of MLOps frameworks in the mobile network architecture [79], [80] as well as from proposals from other collaborative projects such as the Network Intelligence stratum proposed by H2020 ICT-52 DAEMON [81]. Further developments of the ETHER vision for an independent AI Stratum will be described in D2.4, also driven by feedbacks from WP3 and WP4.

The vision of the ETHER AI layer will be further developed and presented in the final ETHER architecture design (D2.4).

5.6 INTER-LAYER INTERACTIONS

At the current stage of the project ETHER development, the following inter-layer interactions and related issues have been identified for further study:

- **SBA and REST API for inter-layer interactions** – a general principle for all inter-layer interactions design will be the design of all interfaces between layers based on the SBA approach and REST API. A potentially possible exception from this principle may be the existence of an industrially standardised interface at the specific reference point or not standardised interfaces left by 3GPP for implementation, thus developed as proprietary. These issues will be further studied, in the cooperation with WP3 and WP4, during the preparations of the final ETHER System architecture (to be delivered in D2.4).

- **Interaction between CP of E2ESL and ETHER MANO layer –** these specific interactions will follow the 3GPP approach presented in Figure 5-10, i.e., utilisation of the interfaces standardised by ETSI NFV ISG at the ETSI NFV MANO reference points *Os-Ma-Nfvo*, *Ve-Vnfm-em*, and *Ve-Vnfm-em*. The issue whether these interfaces need additional modifications is for further study in the cooperation with WP3 and WP4.

- **Cross-layer control loops** – the border between CP of E2ESL and the ETHER MANO layer can be fluid, especially when dealing with either the NFMF mechanism or agent of an external NFMF being embedded in CP NF for the case of the fastest, local MAPE-K control loops. In the case of slower, higher level of management hierarchy control loops, they may span multiple layers, including the ETHER MANO layer, ETHER AI layer, and in extreme cases also AP in E2ESL (including 3rd party ICT environments). The detailed vision of these interaction chains starting and ending back in CP, in terms of the ETHER project use cases and their demonstrations, is a matter of WP3 and WP4 concerns, and feedbacks from these work packages may influence the final overall architecture of the ETHER System to be presented in D2.4.

- **Handover considerations** – details of the horizontal/vertical handover management mechanism and optimisation aspects are not known at this stage of the project – they will be worked out by WP3. While gNB and AMF will remain the executive entities, the issue of managing handover policies and enforcing these policies in the executive entities remains open. The handover management architecture in the ETHER System may potentially impact the overall architecture, however, this issue remains for the further concern.

- **Dynamic RAN topology considerations –** in the case of base stations and AMF instances, their constant awareness of the dynamically changing RAN topology (non-geostationary satellites/other NTN base station bearers) will be crucial for the proper UE mobility management. The basic mechanisms for the exchange of information about neighbour base stations are defined by 3GPP (NGAP, gNB-AMF N2 interface [82] and XnAP, gNB-gNB Xn interface [83]). However, the issue of global management of the entire process coordination should be also considered from the point of view of the overall ETHER system architecture, taking into account the location of knowledge source of the trajectory of individual satellites, the times of their stay in individual Tracking Areas, the properties of the entire constellation, etc. Further studies on the ETHER System overall architecture should be synchronised with the activities of WP3 and also with current 3GPP work on this issue.

- **Inherent delays in NTNs and their impact on the ETHER system performance and its design –** non-terrestrial systems are characterised by non-negligible delays due to the propagation distances. While the signal propagation distances in the case of stratospheric platforms are not drastically different from the distances in TNs, the satellite-based NTNs force grave propagation delays. Indicative delays are: LEO – 40 ms, MEO – 180 ms, GEO >250 ms [84]. These delays will affect not only the transmission of user data in UP, but all intra- and inter-layer interactions, especially for a distributed system. According to ITU-R [85], the IMT-2020 system (i.e., 5GS under 3GPP) is expected to support the following delays:

- UP (maximum): 4 ms for eMBB, 1 ms for URLLC.
- CP: 20 ms (firm maximum), 10 ms (suggested maximum).

The presented phenomenon must be taken into account, i.a., when designing the ETHER MANO layer procedures (the issue of procedures' dynamics, timeouts and coordination across different administrative and technological domains), CP procedures (especially dynamics of mobility management procedures, including the SD-WAN CP participation in maintenance of the path continuity and meeting SLA targets), function placement policies (including SDN controllers and distributed core functions placement), etc. These issues need to be studied and researched by WP3 and WP4, and their feedback may have an impact on the final overall architecture of the ETHER System to be presented in D2.4.

6 CONCLUSIONS

In this deliverable, the initial vision of functional ETHER network architecture, which enables the integration of terrestrial, aerial and space layers was presented. The architecture design has been driven by three main factors: the 6G architecture visions and trends in terms of implementation paradigms, capabilities, and targets, the most recent SotA-proposed approaches to the integrated 3D network architectures, and ETHER-specific requirements imposed by the demonstrated use cases (established within T2.1 activities) as well as ETHER technical innovations.

The 6G is envisioned as a highly distributed and modular ecosystem, composed of multiple self-contained, multi-access and multi-vendor environments, which are AI- and cloud-native by design. One of the emphasised challenges for the next-generation network is the significant reduction in overall system complexity, which can be achieved by network components and operations disaggregation and softwarisation. Moreover, the ETHER innovations impose specific requirements regarding the interworking between different architecture planes (e.g., CP and MP to manage the vertical handover operations or perform E2E network optimisation). To this end, the architecture decomposition into 4 primary layers, namely, infrastructure, E2E Service, MANO and AI layers has been proposed.

To address the specific requirements and challenges identified by ETHER, the proposed initial ETHER MANO architecture features a multi-level hierarchical and distributed multi-domain system composed of generic self-contained domains (ETHER MANO Domains) each containing a dedicated M&O component (DMOC) and domain-specific functions (SFs) implementing functionalities needed by the individual domains with a microservice-based approach (such as OSS/BSS functionality, components allowing integration with AI layer, optimisation of selection of infrastructure providers, etc.). The E2E M&O is accomplished by the EMOC component assisted with SFs, which coordinate the behaviour of each domain in an intent-driven manner (the umbrella MANO for the federation of domains). The generic MANO architecture proposal is followed by the example of instantiation using the well-established standardised solutions (ETSI NFV MANO, ETSI MEC, O-RAN), which are planned to be the foundation for the ETHER use cases demonstrations and solutions. Moreover, the concept of a lightweight Transport Network domains encapsulating the SDN-based WIM environment is proposed, allowing for fast data path reconfigurations. The overall architecture can be hence seen as the 3D mesh of domains (with terrestrial, aerial and satellite variants of each administrative domain variant) of specific types interconnected by the set of Transport Domains (the domain gateways visible from the E2E level).

As the standardisation of 6G has not yet started, the base communication system considered by ETHER is 5G Advanced. Therefore, the verification of support by the 5G components and its openness to extensions has been conducted. It has been proved that innate 5G capabilities such as SBA, generic AF or CP exposure mechanisms via NEF allow for tight integration with external systems such as MEC, ETHER MANO layer components, SDN-based transport or external AI components. The ways of implementation of ETHER technical innovations and their integration with the architecture have been established including: MEC & caching, seamless vertical/horizontal handover, semantic-aware data analytics, AI-based predictive analysis and AI-enabled E2E network performance optimisation. The impact on the architecture of the remaining technical innovations (network access in the Ka band, flexible payload) will be studied by joint efforts of WP2, WP3 and WP4 and will be provided in the D2.4.

The deliverable describes the initial version of the architecture, which will be updated with the progressing work of WP2, WP3 and WP4. The implementation activities of WP3 and WP4 and their outcomes will also provide the basis for the architecture evaluation and the definition of

ETHER framework interfaces and the preparation of Interface Control Documents. The updated and final version of the architecture will be included in D2.4

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