ETHER: A 6G Architectural Framework for 3D Multi-Layered Networks

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***Abstract*— Due to the fact that large swathes on Earth still lack broadband communication coverage, especially in remote/rural areas and developing countries, there have been several attempts, starting from 3GPP Release 17, to lay out the architectural amendments needed for the integration of terrestrial networks with their non-terrestrial counterparts. Such attempts have led to recent projects regarding such integration that consider either 5G/5G-Advanced networks or more revolutionary approaches for the forthcoming 6G networks. In this manuscript, we give an overview of the architectural framework, technical innovations, and considered use cases of the Horizon Europe ETHER project.**

***Index Terms*—3D architecture, non-terrestrial networks, artificial intelligence, management and orchestration.**

I. INTRODUCTION

6G networks are inherently considered to be *3-dimensional (3D) networks*, meaning they will integrate an aerial layer (including, for instance, high altitude platforms (HAPs), unmanned aerial vehicles (UAVs), and aeroplanes), and a space layer (comprising satellites in different orbits, such as low earth orbit (LEO), medium earth orbit (MEO) and geostationary earth orbit (GEO)) to the existing terrestrial infrastructure. The main reason for this integration is that, in an era where broadband connectivity should be ubiquitous regardless of the location of users, big parts of the world still lack it. This is due either to the difficulty of rolling out such infrastructure in hard-to-reach areas, such as remote islands, or the lack of economic viability for operators to densify remote and rural areas with terrestrial small cells.

With the realisation of 3D multi-layered networks, a range of new services can be facilitated, such as smart agriculture and forestry, asset tracking, remote telehealth and sensing, immersive communications, secure communications via quantum key distribution, and navigation of remote vehicles. Regarding their integration, efforts in current 5G and envisioned 5G-Advanced 3rd Generation Partnership Project (3GPP) releases (i.e., Releases 17–19), target the integration of non-terrestrial networks (NTNs) with a minimum impact to the already optimised terrestrial networks. However, 6G's 3D network vision, starting from the anticipated 3GPP Release 20, departs from this approach by considering the joint three-layer optimisation for an optimal network functionality and performance.

For accommodating a variety of new services, a key characteristic of the envisioned 3D networks is the inclusion of mega-constellations of LEO satellites equipped with regenerative payloads that act as flying base stations. This is expected to notably increase the size and the functionalities of the integrated networks, compared to terrestrial-only ones. In particular, beyond facilitating data transmission, satellites in mega-constellations are expected to also act as computing and storage units to alleviate the processing burden in the terrestrial cloud. There are commercial deployments of LEO mega-constellations by private entities, such as the European Eutelsat OneWeb or SpaceX's Starlink, and plans for further deployments by other entities (most notably, Amazon's Kuiper, China's GW, Telesat's Lightspeed, and Inmarsat's Orchestra). The proliferation of LEO mega-satellite constellations is assisted by technological advancements that, in the last years, drive the trend towards manufacturing very small satellites with high antenna gains that notably reduces cost.

Over the last years, there have been a number of Horizon Europe projects that focus on the architectural aspects that will govern future 3D integrated networks, such as the Horizon SNS JU sElf-evolving terrestrial/non-Terrestrial Hybrid nEtwoRks (ETHER), 6G-Non-Terrestrial Networks (6G-NTN) and 5G-Satellite and Terrestrial Access for Distributed, Ubiquitous, and Smart Telecommunications (5G-STARDUST) projects, and the 5G+ evoluTion to mutioRbitAl multibaNd

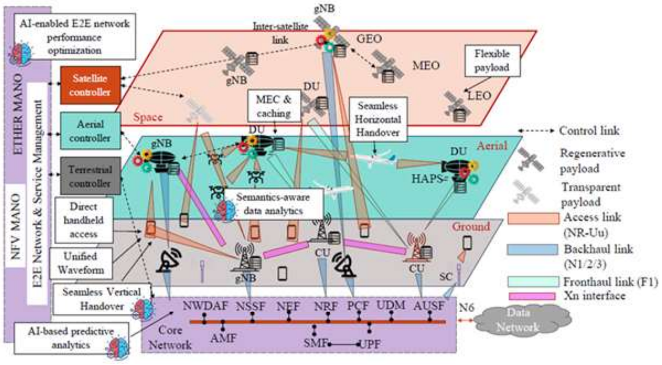

Fig. 1: ETHER's 3D network vision.

neTwORks (TRANTOR) one [1–4]. This manuscript gives an overview of the ETHER project. In particular, Section II presents ETHER's 3D network vision, together with the main technical innovations it brings forward. Subsequently, in Section III the ETHER reference architecture is introduced. The use cases considered in ETHER and the target key performance indicators (KPIs) are presented in Section IV. Finally, Section V concludes this manuscript.

II. 3D NETWORK VISION AND TECHNICAL INNOVATIONS

A. 3D Network Vision

ETHER brings together key technologies for the integration of NTNs to offer 6G services, exploiting the air and space assets in the best possible way and providing seamless solutions for different scenarios. The evolution of mobile networks towards multi-domain software-defined network (SDN) control and automation aims to cover radio access, transport and core network. End-to-end 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 application programming interfaces to relevant systems for the management of the domain functionality with regard to such factors like radio access network (RAN) nodes' high 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 terrestrial network (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 ETHER architecture satisfying the above principles is shown in Fig. 1.

B. Technical Innovations

This section presents the main technical innovations brought forward in ETHER. as seen in Fig. 1.

1) Distributed LEO swarms for direct handheld device access at the K_a band and device antenna design: Direct handheld device access from NTN platforms is feasible and has already been demonstrated in the S band (2–4 GHz). However, due to the congested spectrum, there is a notable gap between the user rates that can be offered by TNs operating in bandwidth-rich millimeter-wave 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 LEO satellite and direct handheld device access at the K_a band (27–40 GHz) [5]. According to the findings, broadband handheld device access from LEO satellites is feasible under certain conditions, such as the satellites being almost vertical above the handheld device (smallest distance) and absence of detrimental weather conditions (e.g., rain, fog).

To counteract the mentioned strict and limiting satellite position and weather requirements, in ETHER the increase in the antenna gain in space by enabling distributed beamforming via satellite swarms is considered. Literature has shown that this has the potential to offer significant virtual array gains from space, provided that the challenges of time, frequency, and phase synchronisation among the satellites in the swarm are adequately tackled [6]. This will be target of ETHER. Moreover, ETHER also targets the design and fabrication of cost-efficient and high performing handheld device array for communicating with a TN or a LEO-based gNB.

2) 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 arise from the communication of ground terminals with 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 like LEO satellites [7]. Hence, the first step in ETHER would be to identify potential scenarios incorporating communication with LEO satellites, where OTFS is much more beneficial than OFDM. Choosing between OFDM and OTFS through artificial intelligence (AI) means is also going to be considered.

3) Flexible payloads: The orchestration of multiple applications in a satellite system is a challenge that needs to be addressed not only in ground infrastructure, but also in satellite systems. A framework that abstracts hardware heterogeneity would simplify and enhance these procedures.

ETHER envisions to tackle this challenge with the technical innovation called *flexible payload*, which is aligned with the concept of software-defined satellites [8]. This concept represents a framework integrated in a software (operating system) and hardware (satellite platform) environment, enabling the deployment of software-controlled payloads. The framework offers mechanisms to expand or update satellite functionalities while in-flight, by executing third party software-based applications and services. This approach adds an abstraction layer to services, that become platform-independent and can be optimally deployed based on different premises such as geographic area, resources occupancy, number of users or expected energy consumption [9]. To deploy the concept in a real scenario, the framework runs on an embedded software-defined radio (SDR) platform based on field-programmable gate array (FPGA) technology as its core. This technology offers an excellent balance between high computation and power consumption, at a lower cost when compared to application-specific integrated circuits (ASICs) or other market alternatives. As services' requirements are different depending on their complexity, the framework offers up to three levels of flexibility: (i) Hardware exchange relying on logic cells reconfiguration, (ii) Software reprogramming using modern virtualisation techniques and (ii) Service orchestration to manage remote deployment of virtual network functions (VNFs) from within ground stations. A prototype of this flexible payload framework will be developed and demonstrated in ETHER.

4) Data analytics, edge computing, and caching including 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 of information [10]. More specifically, by leveraging semantics in NTNs, ETHER will allow generating and transmitting 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 targeted are 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 [11]. Furthermore, adapting those metrics to capture the unique characteristics of NTNs is crucial. The development of caching schemes and cooperative computing techniques will enable us to outperform the current schemes by achieving lower latency and higher energy efficiency. These metrics will be further utilised in data analytics schemes where the current approaches neglect the importance and relevance of information, thus making them cumbersome to be applied directly in NTNs.

5) Seamless horizontal/vertical handover mechanisms: In such complex 3D networks, seamless horizontal/vertical handover procedures between the same and different radio access technologies without any service disruption are needed. ETHER targets the development of both horizontal and vertical handover strategies that will be transparent to the UE (i.e., the end users will not be aware whether they are connected to a TN or an NTN platform), enjoying seamless network connectivity. Towards this, ETHER will design novel machine learning (ML)-based algorithms for horizontal/vertical handovers in the integrated network that will balance a variety of network criteria, such as latency, rate, traffic, while targeting at 70 % higher energy efficiency than state of the art [12]. Towards this, both NG and Xn handovers, as defined in 5G, will be considered [12].

6) Automated MANO for the integrated network: The coordination of the resources (i.e., computation, communications, and caching) in the heterogeneous 3D network requires complex solutions. In this way, the adoption of MANO approaches would benefit from (i) integrating current terrestrial solutions and operations, and (ii) automatising operations to efficiently use the NTN resources. However, the integration of MANO approaches into this novel network poses multiple challenges that need to be faced.

Among the challenges mentioned above, ETHER addresses the most relevant ones: (i) closed-loop automated execution of the service life cycle would ensure a quick response against network events, as well as to reduce human intervention; (ii) service coordination procedures shall integrate NTN mobility patterns, which in some layers can impact in the continuity of the service provision; (iii) service life cycle executions shall include geo-localisation information, due to the provision on specific target areas; and (iv) connectivity and dynamic route definitions according to traffic demands shall be conducted by means of SDN technologies. The alignment of these technical innovations with the incorporation of AI/ML techniques to achieve an optimised end-to-end performance becomes crucial. Details of this integration are presented in Sec. II-B7.

The conducted development contributes to the resulting ETHER MANO, which integrates the novel functionalities needed to manage and orchestrate applications in 3D networks.

7) AI-driven E2E network performance optimisation: The E2E MANO framework builds upon the architectural specifications already presented above, for the RAN and core network (CN), and does not introduce further requirements from an architectural viewpoint. Yet, it introduces a need for original mechanisms capable of meeting the following targets: (i) real-time network monitoring and key performance indicator (KPI) prediction; (ii) online (for run-time self-configuration) and offline (for long-timescale self-configuration) end-to-end (E2E) cross-layer optimisation procedures that build on the monitoring and prediction tools above. Given the complexity of these tasks, data-driven models based on state of the art (SOTA) AI paradigms, tailored to the ETHER context, are going to be developed to meet the requirements.

III. ETHER REFERENCE ARCHITECTURE

A. Overview

The overall ETHER system architecture, which is depicted in Fig. 2, is composed of:

- *The 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 Network Function Virtualisation (NFV) infrastructure layer of European Telecommunications Standards Institute (ETSI) NFV [13] extended by non-virtualised resources, i.e., physical network functions (PNFs).

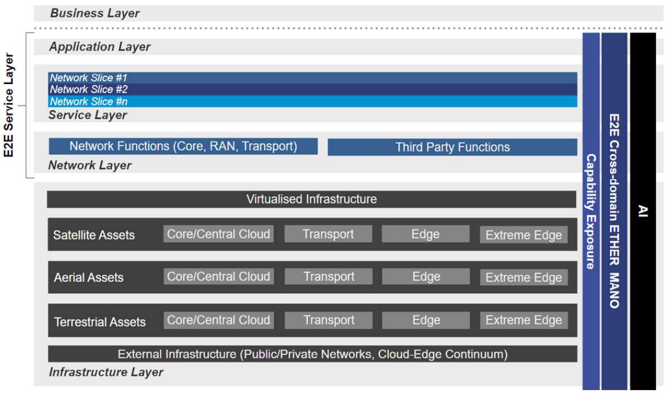

Fig. 2: High-level ETHER architecture diagram.

- *E2E service layer*, consisting of *Network*, *Service*, and *Application* layers. The former, that can be seen as an ETSI VNF-based one with dedicated PNF support functions, includes network functions (NFs) – i.a., 3GPP CN and RAN, as well as transport-related functions – and third-party functions (any functions external to the ETHER scope but supporting the network operation). The middle one is 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. The latter contains applications that exploit the capabilities provided by NSI or several NSIs.
- *Business layer* constituted by the relevant business actors' environments interacting with the ETHER system framework and exploiting its capabilities (outside of the scope of further considerations).
- *E2E cross-domain ETHER MANO*, coordinating the above-mentioned layers on multiple levels. Additionally, the capabilities provided by the cross-layer *Intelligence mechanisms*: internal ones (e.g., AI-based MANO enablers) or those external to the ETHER system, e.g., exposed to the framework via AI as a service (AIaaS) mechanisms – all together leverage both ETHER MANO and layers of the ETHER system listed above.

B. Intelligence in the ETHER MANO and E2E service layer

1) Intelligence in the ETHER MANO: In line with current trends towards automated network management, the ETHER MANO supports operations that are driven by AI. Therefore, it is designed to be natively compatible with emerging architectural models that integrated artificial intelligence (AI) in mobile network infrastructures. In particular, the ETHER MANO aligns with the vision proposed by the 5G PPP and 6G-IA Architecture Working Groups of a network intelligence stratum (NIS) [14], that is posed to coordinate AI-based decision-making across the network infrastructure. To this end, the AI models developed in ETHER come with network monitor-analyse-plan-execute over a shared knowledge (N-MAPE-K) representations [15] and the ETHER MANO blueprint includes *Nio-Mano* interfaces that allow an exchange of information with the NIS [16].

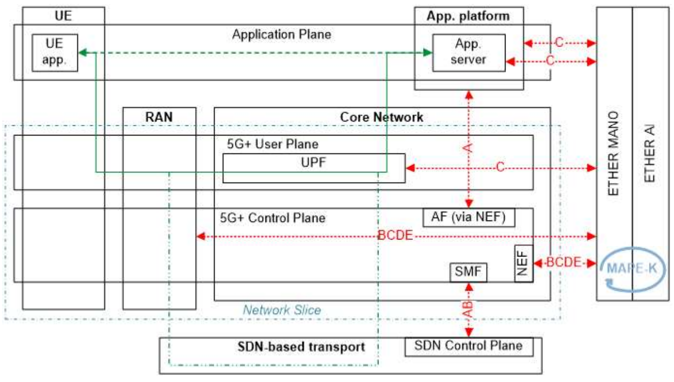

Fig. 3: ETHER E2E service layer architecture and support of specific ETHER mechanisms.

2) E2E service layer: This layer comprises application plane (AP), user plane (UP), and control plane (CP) that are orchestrated and managed by the ETHER MANO and intelligence layer. The two latter planes are based on the 3GPP vision [17]. The roles of these planes are as below:

- AP hosts the application-level services. It is localised at the UE side (the user equipment (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 depend on the solution specificity.
- UP provides connectivity service for AP with predefined quality of service (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.

The simplified ETHER E2E service layer architecture is presented in Fig. 3. The AP interactions are served by the 5G+ UP composed of a service-specific user plane function (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). Selected ETHER entities are indicated in the figure to emphasise their role in the support of fundamental ETHER mechanisms presented in Fig. 1 – indicated as (A) edge computing & caching, (B) Seamless vertical/horizontal handover, (C) Semantic-aware data analytics, (D) AI-based predictive analysis, and (E) AI-enabled E2E network performance optimisation. Distribution of both UP and CP parts of CP in the terrestrial and non-terrestrial domains is assumed.

IV. ETHER USE CASES AND KPIS

A. *Use case 1: Flexible payload-enabled service provisioning to semantics-aware and delay-tolerant Internet of things (IoT) applications*

Provision of network coverage from LEO satellites with service and feeder link discontinuity will bring global coverage to delay-tolerant massive machine-type communication (mMTC) applications. Furthermore, providing service with multiple technologies by means of flexible payload allows for a higher number and variety of supported devices and applications, which opens up for a bigger market impact and reduces vendor and technology lock-in. The combination of these technologies enables to demonstrate a use case in which satellites can provide narrow-band Internet of things (NB-IoT) service, by deploying dedicated software-defined payloads through the flexible payload framework and by using the store-and-forward protocol.

Fig. 4 presents an overall view of this use case, where the provision of, e.g., a NB-IoT service from a satellite system will be achieved by means of the flexible payload. This payload will have a crucial role in the execution of the demonstration. Specifically, the payload will enable to manage the NB-IoT service over a target region among the different satellites, managing their mobility. This management will be orchestrated by the ETHER MANO (deployed on ground), that will instruct the satellites to activate and deactivate services in a coordinated manner, exchanging status and context with satellites to come. To this end, it is performed through the developments of different capabilities in three main scopes: (i) management of infrastructure resources from different domains such as registration of cloud/edge and RAN resources, (ii) resource management capability by allocating and optimising resources leveraging the semantics of information, and (iii) management of network services including service instantiation/termination/migration, service update, and service recovery. With this execution, it is expected to verify that the design and development of the flexible payload is capable to autonomously manage internal software-based payloads, and propagate their status among the satellites to ensure service continuity. This use case is envisioned to demonstrate the feasibility to achieve 100 % coverage, and > 75 % higher energy efficiency leveraging the semantics-aware information handling combined with edge computing and caching.

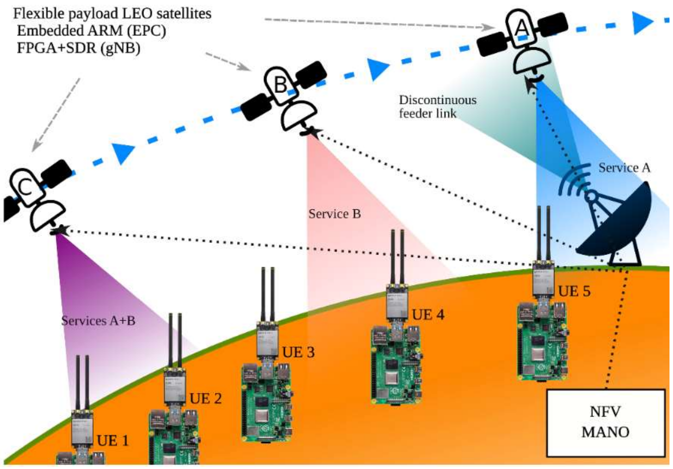

Fig. 4: Representation of ETHER's use case 1.

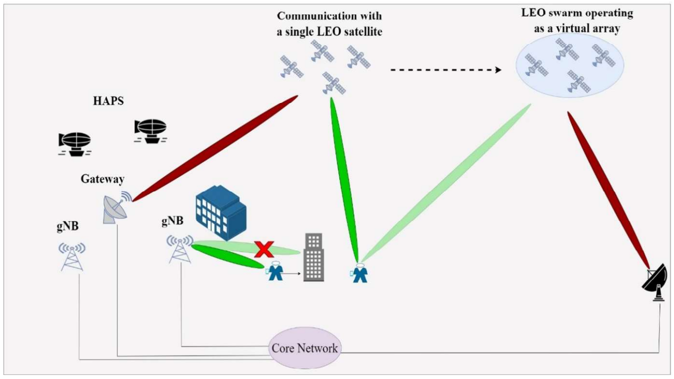

Fig. 5: ETHER use case 2's direct-to-handheld device access.

B. *Use case 2: Unified RAN for direct handheld device access in the K_a band*

In use case 2, depicted in Fig. 5, a mobile handheld device is initially connected to a terrestrial gNB via the K_a band for receiving broadband communication. As the device is moving, the received signal from the terrestrial site starts deteriorating due to an obstacle in its vicinity. Based on reported measurements from the handheld device about the signal strength from other terrestrial sites and from non-terrestrial platforms, such as LEO satellites, a handover process will be triggered through intelligent algorithms that target the maximisation of the energy efficiency subject to constraints related to time availability, flow conservation, power, and capacity constraints. In the case of connecting to a non-terrestrial platform, the ability to choose by AI-based means ofwhether to deploy OFDM or OTFS waveforms, according to the resulting Doppler spread and their impact on performance, is also going to be leveraged. Moreover, to counteract the higher spreading loss of the K_a bands compared to its sub-6 GHz counterparts and the more pronounced impact of atmospheric effects, distributed beamforming will be leveraged among LEO satellite swarms, as explained in Section II-B1, leveraging the time, frequency, and phase synchronisation algorithms developed in ETHER. In addition, the mentioned designed cost-efficient and high-performing UE antenna will also be incorporated into the demonstration of use case 2. The KPIs for use case 2 are: (i) 100 % outdoor coverage, (ii) 99.99999 % service continuity, (iii) 99.99999 % service reliability, and (iv) 70 % more energy efficient handover mechanisms compared to SOTA ones.

C. *Use case 3: Air-space safety critical operations*

Aircraft require reliable connectivity through TN, HAP, and LEO satellite-based space network platforms to maintain persistent communications with air traffic controls (ATCs) and air operation centres (AOCs) along their routes connect-

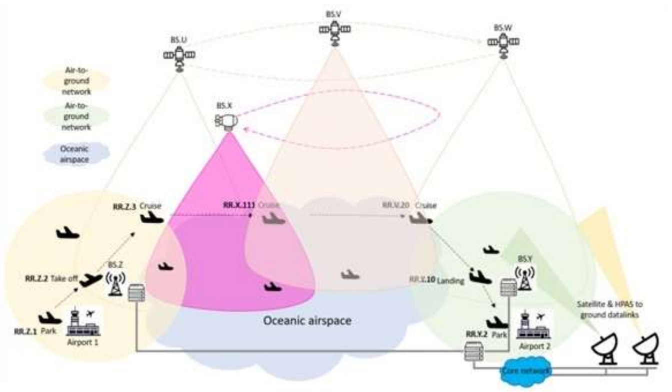

Fig. 6: ETHER use case 3's airspace safety critical operations.

ing different airports, possibly passing through the oceanic airspace as shown in Fig. 6. The operational requirements for the various technical options of aircraft communication systems in the various phases of flight are assessed against a set of values for some parameters denoted by the term "required communication performance (RCP) type". This is quantified in terms of communication delay, data rate, continuity, availability, and integrity, which will be primarily used to evaluate RCP in the provision of air traffic services. In this context, Collins proposes a use case that aims to demonstrate provisioning E2E resilient seamless aircraft communication services using the ETHER 3D network with required tailored development to support two objectives, namely: (i) meet RCP of the different aircraft flight phases and (ii) provide guaranteed E2E aircraft communication services subject to optimal network performance and efficient resource allocation. The use case is supported by key value enablers, namely: (i) ETHER network and satellite simulation or emulation technologies, (ii) 3D network communication links orchestration, and (iii) SDN-based traffic flows steering and users to cell association. Aircraft standard data communication, standard surveillance communication and strict data communication services require different communication performance, which is measured against the following metrics [18]: 100 % network coverage; 99.99999 % service continuity; 99.99999 % service reliability; 95 percentile delay of 250 ms; 99.9 percentile delay of 500 ms; Performance integrity 10^{-4} to 10^{-6}; > 80 % more energy efficient resource allocation than the SOTA.

V. CONCLUSIONS

A few Horizon Europe projects have recently started that focus on the seamless integration of TNs with NTNs under a 3D multi-layered jointly optimized 6G framework. Among these, in this manuscript we give an architectural overview of the ETHER project by presenting its main 3D network vision, technical innovations, reference architecture, and the targeted use cases and KPIs.

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