ETHER: Energy- and cost-efficient framework for seamless connectivity over the integrated terrestrial and non-terrestrial 6G networks (draft)

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Abstract

Several use cases already proposed for 5G networks cannot be facilitated by terrestrial infrastructure, either due to its small penetration in remote/rural areas or the harsh propagation conditions due to the terrain. Indicative applications include forestry, mining, agriculture, semi-autonomous control of long-range vehicles, industrial services, logistics, asset tracking, telemedicine, beyond visual-line-of-sight drone operations, and maritime insurance. Hence, such use cases necessitate the integration of terrestrial with non-terrestrial networks, which gives rise to several challenges to overcome. The project ETHER aims to provide a holistic approach for energy- and cost-efficient integrated terrestrial-non-terrestrial networks. To achieve this goal, ETHER develops solutions for a unified Radio Access Network and for Artificial Intelligence-enabled resource management across the terrestrial, aerial, and space domains while creating the business plans driving future investments. To that end, this paper discusses a series of key technologies that ETHER combines under a unique 3-Dimensional (3D) multi-layered architectural proposition that brings together: i) user terminal antenna design and implementation for direct handheld access in the integrated network, ii) a robust unified waveform, iii) energy-efficient seamless horizontal and vertical handover policies, iv) a zero-touch network/service management and orchestration framework, v) a flexible payload system to enable programmability in the aerial and space layers, vi) joint communication, compute, and storage resource allocation solutions targeting at end-to-end network performance optimisation leveraging novel predictive analytics, and vii) energy-efficient semantics-aware information handling techniques combined with edge computing and caching for reduced latency across the distributed 3D compute/storage continuum. The 3D ETHER architecture and the targeted use cases are also discussed, paving the way toward 6G networks.

Index Terms

5G, 6G, terrestrial, non-terrestrial, mobile network, satellite, GEO, MEO, LEO, HAPS, drone, UAV, Ka band, handheld terminal, unified RAN, MANO, ZSM, NFV, SDN, MEC, cloud continuum, vertical handover, horizontal handover, MIoT, eMBB, URLLC, semantic communications, aviation, safety, IoT

Acronyms

The following acronyms are used in this manuscript:

3D	3-Dimensional
3GPP	3rd Generation Partnership Project
5G	5th Generation
5GS	5G System
6G	6th Generation
AI	Artificial Intelligence
API	Application Programming Interface
ATS	Air Traffic Services
CAA	Civil Aircraft-Assisted
CN	Core Network

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CP Control Plane

E2E End-to-End
EASA European Union Aviation Safety Agency
ESA European Space Agency
ETSI European Telecommunications Standards Institute

GEO Geostationary Earth Orbit

HAPS High Altitude Platform System
HEO High Elliptical Orbit

IoT Internet of Things

KPI Key Performance Indicator

LEO Low-Earth Orbit

MANO Management and Orchestration
MEC Multi-access Edge Computing
MEO Medium-Earth Orbit
ML Machine Learning
mMTC Massive Machine Type Communications
MNO Mobile Network Operator

NB-IoT Narrow Band IoT
NFV Network Function Virtualisation
NGMN Next Generation Mobile Networks
NR New Radio
NTN Non-Terrestrial Network

OFDM Orthogonal Frequency-Division Multiplexing
OTFS Orthogonal Time Frequency Space

QoS Quality of Service

RAN Radio Access Network
RATs Radio Access Technologies

SAGIN Space-Air-Ground Integrated Network
SDN Software-Defined Networking
SDR Software-Defined Radio
SNR Signal to Noise Ratio

TN Terrestrial Network

UE User Equipment
UP User Plane

VNF Virtual Network Function

I. Introduction

A. Background and related work

Although the deployment of 5th Generation (5G) networks is currently ongoing, research on the 6th Generation (6G) use cases that can be facilitated by such networks has already been initiated. One important problem not expected to be solved by 5G networks is the ubiquitous coverage, especially in remote areas. This is due to the fact that the straightforward solution of heavily densifying Terrestrial Networks (TNs) with small cells is prohibitive both in terms of cost and energy consumption. In addition, in terms of revenues, such a strategy is not viable for Mobile Network Operators (MNOs) for remote/rural areas that have a low density of users. Therefore, non-urban areas are generally undercovered – in terms of either supported Quality of Service (QoS) or service availability in general. In particular, several rural applications of growing social and economic importance, such as telemedicine, agriculture/forestry, shipping and freight tracking, cannot be appropriately served.

A fundamental requirement of 6G networks is to provide unlimited access on the globe, covering land, sea, and sky [1]. This is achieved through Non-Terrestrial Networks (NTNs) in the mobile communication ecosystem. However, while the direction of efforts initially was to integrate non-3rd Generation Partnership Project (3GPP) NTNs with a 5G System (5GS), the 6G is characterised by a unified access composed of TN and NTN [2]. 3GPP has been working on NTN integration since 2017. The vision of a few satellite use cases has been defined [3] together with delay Key Performance Indicators (KPIs) targets for various orbits satellites (and the latter have been further incorporated to the general service requirements of 5GS [4]). The issues of the New Radio (NR) support for NTNs [5] and solution proposals [6] have been analysed and reported. Currently, 3GPP identifies Low-Earth Orbit (LEO), Medium-Earth Orbit (MEO), Geostationary Earth Orbit (GEO), and High Elliptical Orbit (HEO) satellites, drones, and High Altitude Platform Systems (HAPSs) among the NTN platforms; 5GS is required to support both 3GPP and non-3GPP NTN access nodes [4], [7]. The new study on satellite access in 5GS [8] with new use cases, i.a., store-and-forward operation, delay-tolerant Internet of Things (IoT) data collection, drones with satellite access, is at an early stage.

Several advancements regarding the identification of requirements, challenges, and enabling technologies for the efficient integration of TN with NTN have also been proposed by academia. Novel architectural solutions are being proposed, such as a Space-Air-Ground Integrated Network (SAGIN) focused on supporting ubiquitous coverage and expected 6G services [9] or Civil Aircraft-Assisted (CAA)-SAGIN [10] aiming to reduce launching costs of airborne communications platforms by installing base stations and relays on already operating civil aircraft. The TN-NTN integration is expected to aggravate the complexity of the service management and orchestration due to the mobility and heterogeneity of the NTN infrastructure [11]. Potential solutions to these issues have been proposed and include the usage of hierarchical multi-layered management architecture with global and local controllers to reduce the complexity of network control [12] or exploitation of specific enablers within service management and orchestration framework such as Temporospatial Software-Defined Networking (SDN) [13], [14] – enhanced SDN concept facilitating application-driven network control based on the location, motion, and orientation of assets in space.

Among different Horizon 2020/Horizon Europe projects, several are dedicated to various aspects of NTN access. In particular, the EU-KR project "5G-ALLSTAR" [15] has demonstrated multiple access based on TN and satellite links, providing 50 Mbps expected user data rate, 10 ms latency and 99.999% reliability, especially to support critical applications. The project "SaT5G" has developed and demonstrated a cost-effective plug-and-play solution to integrate satellites with SDN, European Telecommunications Standards Institute (ETSI) Network Function Virtualisation (NFV) and Multi-access Edge Computing (MEC)-enabled 5G networks [16]. At the beginning of 2023, three other projects started. The project "Hexa-X II" [17] will work on the European 6G vision from use cases, services and requirements for 6G, through platform and system design, to proofs of concepts. The project "5G-STARDUST" [18] is aimed at a fully integrated 5G-NTN autonomous system for enabling ubiquitous radio access through, i.a., deeper TN and NTN integration, unified radio interfaces, Artificial Intelligence (AI)-driven management, and O-RAN architecture. The project "6G-NTN" [19] plans to design and validate key technical enablers for the integration of NTN and TN components into 6G. Moreover, the project "TRANTOR" [20] targets the in-orbit validation of a complete satellite value chain involving automated management of satellite resources across multiple bands, satellites, and orbits, and a converged radio access network. Furthermore, concerning European Space Agency (ESA)-related projects, the "5G-GOA project" [21] investigates direct radio access of User Equipment (UE) devices via satellites, while the objective of the "5G-LEO" project is to extend the OpenAirInterface5G software stack to support non-GEO satellite systems in non-geostationary orbits [22].

B. Motivation, pillars, and objectives

Despite the abundance of literature works and projects related to TN-NTN integration, there is a lack of an architectural framework that deals with efficient smart management of the numerous resources of the highly heterogeneous and dynamic 3-Dimensional (3D) network to support diverse foreseen use cases in an automated, "zero-touch" way. Also, the proposed solutions have not provided adequate schemes to robustly meet the QoS requirements for constrained avionic communications and networking. ETHER aspires to close this gap and provide a complete roadmap for a multilayered 3D flexible and sustainable unified Radio Access Network (RAN) architecture that leverages proposed essential air interface technical innovations and manages its resources in an automated way via data-driven methods. To achieve that, the project relies on the following pillars:

I. Unified RAN advancements that enable broadband connectivity from every corner of the world, even with handheld devices and in challenging frequency bands, such as the Ka band;
II. Intelligent management of the 3D network resources for meeting predefined KPIs, allowing the network to self-adapt to rapidly evolving traffic conditions and situations on the ground without human intervention;
III. A distributed 3D computing and caching continuum enabling the reduction of response delays by alleviating congestions towards cloud data center.

ETHER will address the pillars above by targeting the following objectives:

1) Provide solutions for a unified and sustainable RAN for the integrated TN and NTN (Pillar I) – direct access of user devices (particularly handheld ones, e.g., smartphones), from aerial and space platforms, like HAPS and LEO satellites, in mmWave bands, i.e., the Ka band; development of a unified waveform for the hybrid TN/NTN continuum; development of seamless horizontal/vertical handover procedures between the same and different Radio Access Technologies (RATs) without any service disruption, while targeting high energy efficiency.
2) Provide an AI-based framework for the self-evolving network slicing management and orchestration of the integrated network and the onboarded services, automatically adjusting its management policies and allocated resources based on stimuli corresponding to unknown environments and situations (Pillar II) – full, zero-touch, predictive analytics learning-based automation of the integrated 3-layer network resources under highly dynamic and complex conditions.
3) Architect a viable, highly energy- and cost-efficient, flexible integrated TN/ NTN 6G network offering seamless and continuous connectivity (Pillars I, II, and III) – flexible and scalable multi-layered architecture relying on flexible payloads (connectivity, compute, and storage resources) on board NTN platforms, employing an SDN cross-layer distributed controller placement-based approach, for intelligent network management and orchestration.
4) Demonstrate the effectiveness of ETHER solutions by experimentation activities targeting practical applications (Pillars I, II, and III) – showcasing the technical innovations of ETHER, relevant to key use cases arising from societal needs, through in-lab emulations.
5) Identify the key benefits that will drive the investment in the integration of NTNs with TNs (Pillars I, II, and III) – driving forces behind involvement and investments towards the integration of NTNs into existing TNs on the grounds of reduced costs and revenue opportunities.

II. ETHER ARCHITECTURE OVERVIEW AND TECHNOLOGICAL ENABLERS

A. ETHER architecture

The ETHER system architecture is presented in Fig. 1. The heterogenous 3D architecture is composed of terrestrial, aerial, and satellite access layers integrated with a common 5GS Core Network (CN) [23]. To provide End-to-End (E2E) control and automation of network and service management, which extends to all network domains – from the radio access through transport to the CN, the hierarchical ETHER Management and Orchestration (MANO) is envisioned. The domain MANOs will expose standardised functionalities through Application Programming Interfaces (APIs) covering domain complexities, namely the satellite ones (especially in complex multi-orbit, multi-system networks). The integrated terrestrial/aerial/space orchestrator, ETHER MANO, capable of interfacing the 5GS CN, will enable a single telecom network to make use of both TN and NTN assets in an optimal and seamless manner. Regarding service orchestration, the envisioned framework will integrate and extend existing advanced edge orchestration platforms for cloud-native service life cycle management, introducing novel interfaces, features and functionalities to efficiently exploit the mix of cloud/edge computational capabilities offered by the ETHER infrastructure. In addition, one of the main goals of ETHER is to design an edge platform — based on open-source solutions. This will enable the Edge-for-AI concept, i.e., the execution of AI/optimisation algorithms in a closed-loop manner.

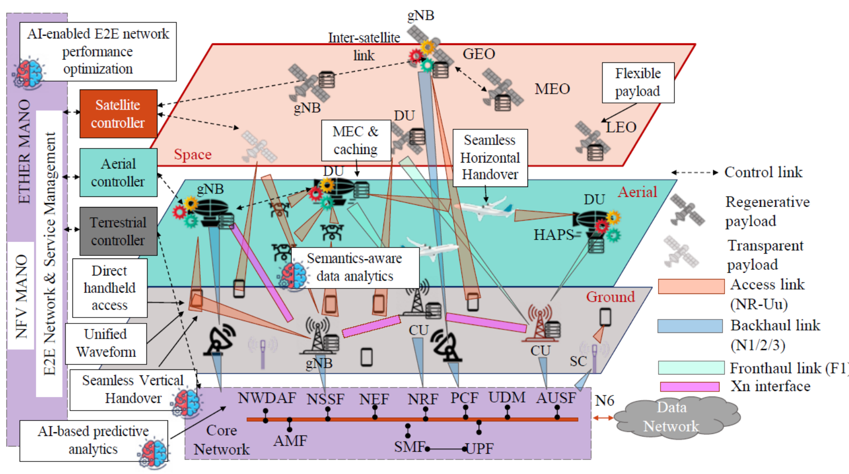

Fig. 1. High-level 3D multi-layered ETHER architecture.

ETHER envisions a cross-domain SDN architecture with distributed SDN controllers across all three layers. In particular, due to the challenging conditions and limited capabilities in fast-moving platforms such as LEOs and drones, the placement of distributed controllers is considered in GEOs and HAPSs, and the coordination of the rest of the components of each layer through them or the terrestrial domain. ETHER also adopts the communication network softwarisation based on NFV to allow efficient and flexible provisioning of services and network on demand. Given that satellite networks use different dedicated hardware, adopting the NFV concept in the satellite layer will enable better support of beyond 5G and 6G requirements as well as seamless integration with TN via the use of standard 3GPP network interfaces in the satellite network. Through the proliferation of softwarised 3GPP TN functional solutions in the commodity hardware-based NTN domains, the deployment of satellite systems and their components will be faster and more cost-efficient.

B. Technological enablers

To realise the vision of a 3D unified TN-NTN, several enabling technologies are essential [24], [25], [26], [27]. ETHER targets the following innovations (cf. Fig. 1):

1) **Integrated architecture** composed of terrestrial, aerial (HAPSs, drones), and satellite (LEO, MEO, and GEO) access layers integrated with a common CN, with distributed SDN-based transport and storage/compute capabilities in each layer. Virtualisation- and softwarisation-based architecture is expected to provide network reconfiguration flexibility (flexible NTN nodes payload) to accommodate the changing service demand. The unified, multi-layered RAN will provide seamless handovers to support service continuity. The distributed computing and storage capabilities will enable the ETHER nodes to pre-process and store large sets of information for elastic delay-tolerant services, which contribute to latency reduction below 5 ms.
2) **Direct handheld terminal access in the Ka band from LEO satellites** enabled by integrated antennas instead of external 20–50 cm square flat panels, and distributed beamforming from LEO swarms. In the case of antennas integrated with UE, the compact phase array antennas (compatible with the size constraints of handheld devices, able to target satellites' trajectory through electrical beamsteering, and providing the gain for sufficient radio link budget) will be designed and fabricated. The link budget will be further enhanced through distributed beamforming from a virtual large array of multiple LEO satellites.
3) **Uniform waveform design for high channel impairment robustness** to provide context-aware waveform adaptation. For different communication scenarios, an Machine Learning (ML)-based decision on whether to apply either Orthogonal Frequency-Division Multiplexing (OFDM) or Orthogonal Time Frequency Space (OTFS) multiplexing scheme will be

used, including trade-offs between different factors, such as saturation of power amplifiers, sufficient Signal to Noise Ratio (SNR), Doppler shift sensitivity, or channel estimation complexity.

4) **Flexible payloads** of satellite nodes, which is the ability to orchestrate the satellite hosts resources for proper service provisioning. To this end, the interface between orchestration systems and satellite payloads should be defined, exploiting Software-Defined Radio (SDR) technology for free adaptation of payload to the orchestrated service.
5) **Data analytics, edge computing and caching for low-latency energy-efficient aerial and space layers** – edge computing and caching have the potential to reduce E2E latency drastically. When equipped with processing capabilities, aerial nodes and satellites can take the communication and networking functionalities from ground stations and eliminate unnecessary round-trip control signals delays, hence reducing the E2E delays. Utilising the semantics of information [28], [29] in NTNs combined with edge computing and caching will further increase the efficiency and reduce the E2E latency without affecting the amount of conveyed information. The development of caching schemes and cooperative computing techniques will be enabled.
6) **Horizontal/vertical handovers** – efficient handovers, inter-layer and intra-layer, respectively, are crucial for seamless connection continuity. While 5GS supports two basic mechanisms – with and without control by CN [30], the project will balance a variety of handover criteria in hybrid TNs/NTNs, leveraging the process autonomy with AI-based algorithms, in order to consider proactively the E2E context and network evolution over time (including latency, rate, traffic, satellites trajectory) as well as minimisation of handovers-related energy consumption.
7) **Automated MANO for the integrated network** – resource-constrained and highly changing satellite systems are capable of serving a large number of heterogeneous users in a single coverage area. Integration of current operational MANO technologies, designed for TN, with NTN infrastructure, remains a technological challenge. Dynamic and constant path reconfiguration becomes crucial for connection sustainability. The project will advance the following aspects: unified management and orchestrator framework for satellite systems and aerial platforms (able to manage satellite mobility and its intermittent connectivity with ground systems) and AI-based adaptive resource orchestration optimisation mechanism for service provisioning (able to cope with the diverse latency, computing and operational requirements of TN and NTN UE access).
8) **E2E integrated TN and NTN performance optimisation** – contemporary communication networks evolve towards "networks of networks" with constantly growing complexity, thus making the E2E performance optimisation of such a complex network a challenging task. Integration of NTNs imposes the additional challenges and constraints associated with the components belonging to the aerial and space layers for performance optimisation of communication, computation, and storage resources. Particularly, the project will focus on low-complexity algorithms for energy-efficient user association, traffic routing, Virtual Network Function (VNF) placement and caching, with regard to the constraints imposed by terrestrial/aerial/space layers and required QoS. In addition, the project will elaborate the efficient predictive analytics for E2E service-level network optimisation through algorithms that target capacity prediction needed for demands of specific applications and ensure QoS guarantees.

III. Demos of ETHER architecture and technologies

To prove the effectiveness of the ETHER vision, three use cases showcasing the capabilities of the developed system mechanisms and related enablers will be demonstrated. The planned tests involve the aspects of delay-tolerant IoT communication (Section III-A), unified RAN access for handheld UEs (Section III-B) and air-space safety-critical operations (Section III-C). All of the above-mentioned subjects align with the 3GPP study documents related to NTN use cases.

A. UC1: Horizontal handovers for delay-tolerant IoT applications

Important future applications will require global connectivity even in distant rural and offshore areas. In such areas, a significant part of UEs will be dedicated to typical Massive Machine Type Communications (mMTC) applications exploiting Narrow Band IoT (NB-IoT) technology. Such delay-tolerant applications can be efficiently deployed using LEO satellites and be supported by regenerative and flexible payloads offering diverse services at different points in time. Nonetheless, two major issues should be tackled: service link discontinuity due to the low density of LEO constellations and a limited number of available feeder links between satellites and the ground, which necessitates the implementation of regenerative payload architecture, and a store-and-forward mechanism for both User Plane (UP) and Control Plane (CP). Therefore, it is essential to provide solutions such as discontinuous NB-IoT backhauling, standard 3GPP interfaces for service providers to use the same LEO constellations and mobility management mechanisms. This use case aims to demonstrate the provisioning of the NB-IoT service by a low-density constellation of LEO satellites. Due to the constant satellite constellation changes, efficient horizontal handovers (cf. Fig. 2) are crucial. Service continuity is planned to be maintained by the ground NFV MANO that will coordinate the ETHER flexible payload among the satellites to provide the correct services to the UEs on time (perform activation/deactivation of services, status and context exchange between the satellites, etc.). Two other IoT services will also be deployed in parallel to prove the ability of the developed flexible payload solution to autonomously manage software-based payloads and propagate their status among the satellites. Such capability enables the provisioning of global connectivity, ultimately contributing to the reduction of vendor and technology lock-in as well as market growth.

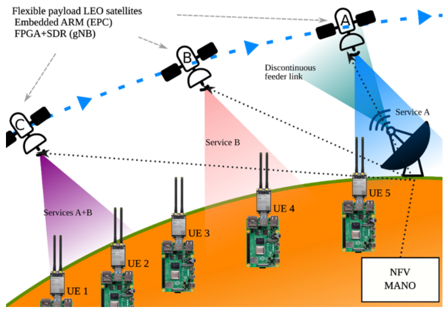

Fig. 2. Horizontal handovers for latency-tolerant IoT services.

B. UC2: ETHER unified RAN for direct handheld device access in the Ka band

The currently used sub-6 GHz bands are envisioned to be supplemented by mmWave ones, offering much larger bandwidths but more susceptible to blockages. Deployment of 100% mmWave broadband terrestrial coverage with TN is not economically feasible, so the coverage by both TN and NTN platforms will be used with necessary UE handovers to provide service continuity.

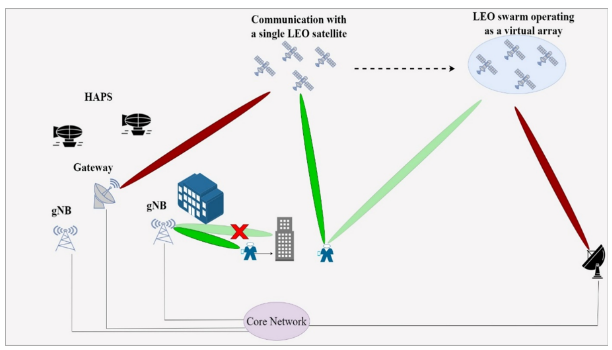

Fig. 3. Overview of unified RAN demonstration.

The primary objective of this use case is to demonstrate TN to NTN handover operation triggered by the intelligent algorithms maximising energy efficiency under the constraints of time, availability, power, capacity and flow conservation aspects. In this scenario (cf. Fig. 3), the handheld UE connected to TN moves towards the area with poor TN coverage. Based on the coverage measurement data reported by UE (TN and NTN platforms), the ETHER algorithms will trigger the handover operation and, in the case of NTN connection, select OFDM or OTFS modulation depending on the Doppler spread and its impact on performance. The ability to access the Ka band by the handheld UEs directly will massively contribute to the ubiquitous access to broadband communication for terrestrial users, even in distant rural areas.

C. UC3: ETHER architecture demonstration for air-space safety-critical operations

One of the key aspects of the integration of TN and NTN networks is conformance with the emerging aviation and space standardisation proposed, e.g., by EUROCONTROL or European Union Aviation Safety Agency (EASA). The specific domain needs will imply diverse requirements related to mobility management (horizontal and vertical handovers), service continuity maintenance (transmission redundancy), QoS enforcement, fault management, service performance, etc.

The main target of this use case will be safety-critical aircraft operations. In order to support these services and meet safety goals, multiple requirements have to be met, which involve reliability, resiliency and ubiquity of communication system, conformance with emerging aviation standards, e.g., related to Air Traffic Services (ATS) data communications, remote operation of unmanned aircraft, future reduced crew or single pilot operations, that provide network-specific KPIs (communication latency, integrity, availability, etc.). In the considered scenario (cf. Fig. 4), one or several aircraft move across the area with coverage provided by TN and LEO satellites. Therefore, multilink features and handover procedures (both horizontal and vertical) leveraging unified waveform and access technology will be exploited. Additionally, a smart multi-link capability will be deployed in the network layer to manage dissimilar data links and ensure service performance maintenance. The evaluation of the ETHER solutions will be supported by the MEC framework capabilities to deploy aviation-domain applications supporting safety-critical aircraft operations, and then assist with the collection of KPIs vital for pertaining service-continuity (latency, backhaul performance, data synchronisation, application mobility across the network, etc.). The trialled enablers are expected to contribute to the safety of aircraft operations and mitigate potential risks such as human injuries or property/environmental damage.

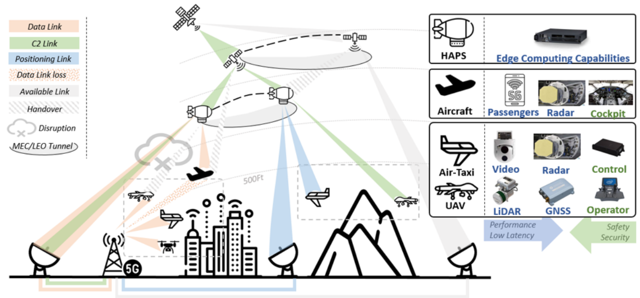

Fig. 4. Air-space safety-critical application within ETHER framework.

IV. Conclusions

In this paper, the ETHER project was presented, which targets an integrated 3D architecture consisting of the terrestrial, aerial, and space layers. Its objectives were discussed together with main ETHER technology enablers. In addition, the three use cases targeted by the project were analysed. Key technological enablers include the design of a user antenna for direct handheld access, the design of a robust unified waveform for the integrated network, seamless energy-efficient horizontal and vertical handovers, a zero-touch network/service management and orchestration framework to automatically adapt to rapidly varying traffic load conditions, a flexible payload system to enable programmability in the aerial and space layers, resource allocation solutions targeting at E2E network performance optimisation leveraging efficient and novel predictive analytics schemes, and energy-efficient semantics-aware information handling techniques combined with edge computing and caching for reduced latency across the distributed 3D compute and storage continuum of the 3D architecture.

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