Chapter Title: Terrestrial/Non-Terrestrial Integrated Networks for Beyond 5G Communications

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I. Introduction

In the framework of EU initiative defined as Italian National Resilience and Restart Programme, the ITA NTN project is focused on a 6G-oriented scenario, where space network entities (such as low-Earth orbit mega-constellations of nano-satellites, High-Altitude Platforms (HAP), and unmanned aerial vehicles) cooperate with terrestrial networks to provide a 3-dimensional (3D) wireless connectivity. Indeed, it targets the ambitious goal of conceiving novel methodologies and effective solutions able to provide pervasive, ubiquitous, and flexible 3D on-demand wireless broadband connectivity and edge computing services through the effective integration of Terrestrial (T) and Non-Terrestrial (NT) wireless networks. To this end, research activities will cover architectural aspects, protocols, and functionalities operating at the different levels of the communication stack (including the physical layer and more specifically transmission system performance), and orchestration algorithms.

I.I Motivation and Chapter contents

ITA NTN has the ambition to produce a significant impact on the advancement in the field of the integration of space and terrestrial networks for the ubiquitous provision of connectivity and computing services supported by terrestrial operators. Therefore, in this chapter the description of the integrated scenario and an overview of the 3GPP technical specifications about terrestrial and non-terrestrial systems and subnetworks are provided. Finally, the main basic conditions that have to be realized in order to allow full exploitation of the main features of ITA NTN are presented.

I.II NTN Goals

ITA NTN introduces five main project goals, as summarized in what follows.

- Design a 3D multi-layered communication architecture for integrated terrestrial/non-terrestrial networks supporting seamless high-capacity demanding applications and massive access by heterogeneous devices. Particularly, starting from the reference use cases and the accurate analysis of their communication and computational requirements, ITA NTN will provide a high-level definition of the overall 3D multi-layered communication architecture and the involved terrestrial and non-terrestrial network elements.

- Evaluate the link budget of free-space, optical, and radiofrequency communication links available in such a 3D multi-layered communication architecture. This consists of the investigation and development of technologies related to communication systems that are adopted in each link.

- Design of advanced transmission techniques for integrated terrestrial/non-terrestrial networks based on novel (e.g., optical) antennas and electronic technologies, optical wireless system solutions, waveforms, multiple access techniques, MIMO schemes operating in the mmWave and optical bands, multicarrier waveforms for time-varying channels.

- Conceive innovative methodologies for the dynamic, energy-efficient, and QoS/QoE-aware orchestration of communication and computational resources exposed in the considered 3D multi-layered communication architecture.

- Evaluate the performance of the conceived approaches in some reference use cases through computer simulations (also carried out via open-source tools) and Proof of Concepts. It will assess the network coverage synergy, considering the possible interfering effects arising from coexistence issues with other wireless systems as well as operational impairments.

II. **From Interoperability to Full Integration**

Next-generation network architecture aims at providing global communication coverage, i.e., 3D coverage, especially to support ubiquitous communication for a massive number of devices as in the IoT scenario.The current terrestrial legacy cellular networks have (i) a prohibitive cost to develop dense cells to provide connectivity on a global scale, and (ii) an inability to achieve communication at high altitudes and in deep waters scenarios where future services can be envisaged.

The 3GPP, in Release 17, initiated the study to evaluate and confirm solutions to address the minimum specifications needed for NTN to support terrestrial networks such as LTE-M and NB-IoT, i.e., related to massive IoT scenarios and to provide satellite access to 5G systems in FR1 bands for a global service continuity. In Release 18, the work of the group continues for further enhancements focusing on satellite backhaul with changing delay for 5G Advanced.

II.I Interoperability of Space and Terrestrial Segments

Mainly, the interworking of satellites with the terrestrial network can make feasible 5G promises such as ubiquitous connectivity, eMBB, and mMTC while the future 6G proposes a fully integrated satellite-terrestrial network where the users must interface in a transparent way both with terrestrial and satellite networks.

The integrated satellite-terrestrial network architecture (Figure 1) can:

- expand the coverage area through satellite backhaul transmission;
- increase network reliability by using terrestrial relays in satellite networks;
- improve resource allocation and guarantee service continuity.

Regarding the satellite segments we can consider:

1) High-Throughput Satellite (HTS) systems provide broadband Internet access services comparable to the ones supported by terrestrial cellular systems in terms of pricing and bandwidth. Most communications satellites are in GEO at an altitude of 35.786 km, involving an excessive delay for direct integration with terrestrial mobile networks.
2) The NGEO is proposed to provide lower latency (with respect to GEO) and high bitrate. They have a circular or elliptical orbit with an altitude that varies between 7000-25000 km for MEO and 300-1500 km for LEO. Their typical radius footprint size ranges from 100 km to 1000km. However, each LEO satellite, being much lower, illuminates only a fraction of the area covered by a GEO satellite, and therefore a LEO network requires a much greater number of satellites than a GEO network.

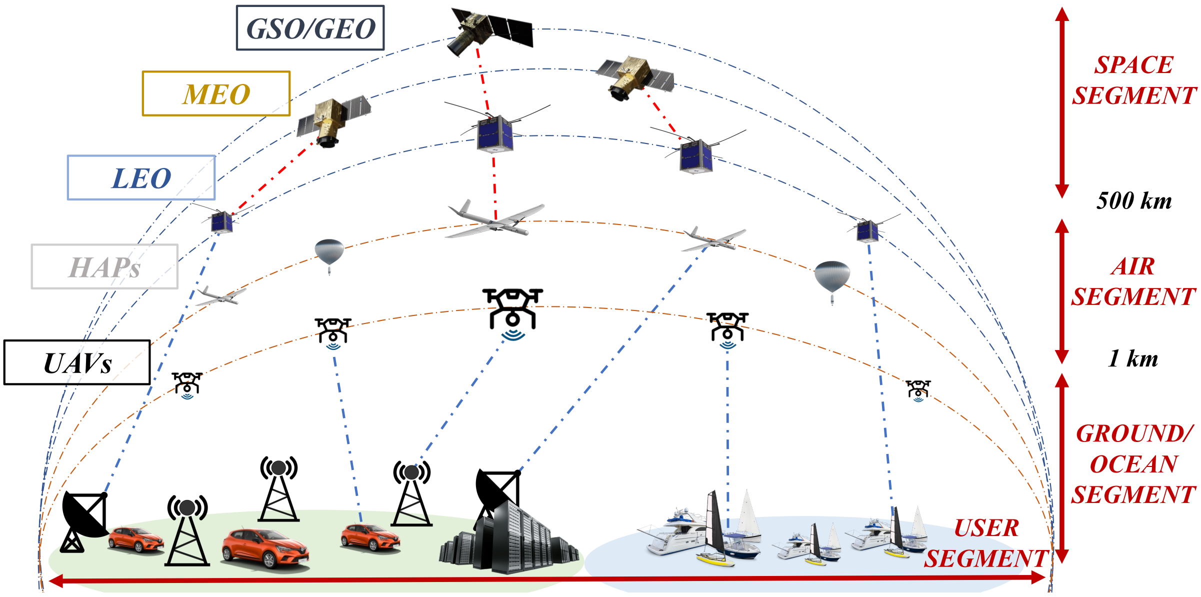

Figure 1. The integrated satellite-terrestrial network architecture

Historically, the first LEO satellite networks were operated in the nineties by Motorola with the Iridium satellites network consisting of 66 LEO satellites in six orbit planes on the orbit of 780 km and by the Loral Corporation and Qualcomm with 48 LEO satellites in eight orbit planes on the orbit of 1400 km.
Recently, due to the reduction in the cost of satellite launches, the introduction of new technologies, such as free space optical communications (FSO), new satellite systems starts for marketing, such as Starlink by the American Space X, a constellation of 4,425 LEO satellites and 7518 VLEO satellites in orbit of about 340 Km, fully deployed in 2027; OneWeb which launched its first six satellites into orbit on 2019, with respect to a total of 720 LEO satellites for this constellation; Hongyan by the Chinese Aerospace Science and Technology Corporation (CASC) with the launch of nine LEO satellites of the total 320 satellites in orbit by 2025; Telesat LEO network with 300 satellites in orbit with a global service in 2022.
Open issues and challenges for the interoperability of Space and Terrestrial networks can be mainly addressed in the following:

- Propagation Delay: latency communications of LEO systems with laser and RF routing mechanisms can be comparable to terrestrial fiber optic networks when communication distances are greater than about 3000 km.
- Satellite Interference: The use of higher frequencies of future 6G system, e.g. at the Ku band and Ka band typical of satellites, and consequently higher available bandwidths, can allow to an integrated 6G/ LEO network to provide higher data rates and enhance the traffic capacity. However, the presence of thousands of LEO satellites causes significant ASI (Adjacent Satellite Interference). Moreover, if the integrated terrestrial/satellite network uses the same higher frequencies in coexistence even more consequences may turn out due to LoS interference received from space to the terrestrial segment. Consequently, mitigation of interference from different layers and orbital constellations with different propagation delays can be achieved by using accurate network management.
- Multi-mode and Cell-free communication: 6G devices should support a certain range of different frequencies, for example, sub-6 GHz, mmWave, THz, optical and in particular Visible Light Communications (VLC). Multi-connectivity methods already enlarge the current boundaries of terrestrial cells, resulting in cell-free operation since the devices are not more served by a single cell, e.g., the macro cell. Cell-free operation decreases the need for user handovers and scheduling, which are hard issues for mobile scenarios. The devices should switch in transparent mode between different heterogeneous links depending on the availability of terrestrial or satellite nodes. Satellite cells, providing large coverage areas, could operate as megacells and control resources, and assist in handovers. Increasing the number of satellites, as in the LEO constellation, each terrestrial location will naturally be served by more beams from several satellites. Due to the high altitude of satellite networks, it is possible to serve a small area on the ground from many independent spatial directions and consequently, spatial multiplexing is required for cell-free communication.
- Orchestration of heterogeneous resources: a fully integrated satellite/terrestrial network needs the management and orchestration of heterogeneous resources both from the satellite system and the radio access and core network as well as computational resources from the cloud to the network edge. Software Defined Networks (SDN) architecture can be a solution for efficient and intelligent network management in the integrated satellite-terrestrial system. The SDN control plane should include both the terrestrial and the satellite controllers with the definition of novel procedures in terms of orchestration, allowing a unified control of the integrated network. This flexible and scalable control keeps separated the decision for the procedures of handover, routing, traffic offloading, and resource allocation from the data plane where processing and transmission of data are carried out. Data service access, service aggregation, and data flow transmission are in charging to LEO satellites and base stations, while switches are performed on the ground and on the satellite, forwarding the data packets according to flow tables.
- Channel propagation: due to the altitude of satellites the satellite communications signals have to pass through the atmosphere before arriving at the ground stations. As a consequence variable weather factors, such as rain, clouds, water vapor, and fog,

impact the satellite communications paths. This can outage the communication link. Moreover, due to the high speed of MEO/LEO satellites with respect to the ground, faster time variation, larger Doppler shift, and larger phase shift make channel conditions highly dynamic. Consequently, a more complex and accurate CSI is required by considering the effect of propagation delay.

- Hierarchical architecture: this is a multi-connectivity architecture composed, for an instance of a space backbone network of satellites, a space Based Access from LEO and MEO satellites and a RAN from the terrestrial network providing two transparent access networks in the integrated satellite-terrestrial system. The satellite backbone can increase the coverage and ensure reliable space-to-ground connectivity while the satellite access is essential for integration with terrestrial networks to support ubiquitous access in remote areas or when terrestrial infrastructures are overloaded.

II.II A Full-Fledged 3D (Integrated) Multi-Layer Network

With 5G networks already bringing benefits to our economy and society, research and development initiatives are already directed towards the design of enhanced 5G-Advanced features and novel technologies for 6G communications. While the former is expected to unleash the full potential of the 5G infrastructure, the initial vision for 6G is already being defined in the framework of the ITU, at both the Radiocommunication sector (ITU-R) and Telecommunication Standardization sector (ITU-T) level, [ITU20, Wei20]. In order to satisfy the demanding requirements of both 5G-Advanced and 6G systems, it is commonly recognized that a NT component will be a key enabler in the global communication infrastructure. In this context, it shall be noticed that, before 5G, the terrestrial and NT components were independently optimized and their inter-working was addressed a posteriori, leading to difficult integrations; 5G and, more recently, 5G-Advanced introduced a radical shift in this paradigm by integrating the two components, but still optimizing the terrestrial part aiming at minimizing the impact to support the NT segment. Only with 6G the terrestrial and NT components will be jointly optimized and unified in a fully integrated multi-layered infrastructure [GVS22].

In this framework, a Multi-Band Multi-Layer Multi-Dimensional (MB-ML-MD) network architecture will be a fundamental part of future infrastructures. The bi-dimensional terrestrial infrastructure, also including the 6G Core network (6GC), will be augmented by a third dimension (MD) provided by the NT component, which encompasses: (*i*) an airborne network, including drones, HAPS, and UAV; and (*ii*) a spaceborne network, including satellite payloads on multiple orbits (ML), which can be GEO, NGEO, or HEO.

The air-/space-borne platforms, referred to as nodes in the following, will operate in Frequency Range 1 (L/S/C bands) or Frequency Range 2 (Ku/Ka bands) depending on the type of service, terminal, and specific architecture implementation. The nodes in the NT segment can be organized in swarms to foster the implementation of advanced distributed techniques, such as coherent or non-coherent joint transmission and MC. To provide global connectivity, the Inter-Node Link (INL) is needed both intra-layer (i.e., for nodes at the same orbit altitude) and inter-layer (i.e., for nodes at different orbit altitudes); as for the former, inter-constellation nodes can also be foreseen to enable cooperation and enhance the system performance, subject to proper coordination among different SNOs. Depending on the considered platform, different benefits are provided to the overall MB-ML-MD architecture: (*i*) GSO satellites can provide fixed continental or regional coverage with large propagation delays and, thus, can be exploited for non-delay-critical and broadcasting communications, as well as to support the management of network elements orbiting at lower altitudes; (*ii*) NGSO satellites can provide a fixed (through digitally steered beams) or moving coverage with lower latencies, to support delay-sensitive applications; (*iii*) HAPS can provide quasi-static regional or spot coverage with latency comparable to that of terrestrial networks; and (*iv*) UAVs and drones are particularly fitted to provide coverage in small areas based on the current users' needs.

III. Integrated Architectures

Satellites can be effectively utilized to enhance performance and expand the reach of 5G services, without impacting end users [LQR23]. The efforts of 3GPP reflect the cutting-edge trend in this regard, as they have introduced support for Non-Terrestrial Networks, with a particular focus on satellite networks, starting from Rel-16. However, it is important to note that the specific role of satellites in the context of 5G is continuously evolving. Currently, the utilization of satellites in 5G-based services holds great promise for optimizing performance and expanding coverage seamlessly for end users.

The utilization of a Non Terrestrial (NT) component in 5G networks presents a significant opportunity. A recent article published by 3GPP [JC21] highlights a clear direction towards integrating NT networks into 5G, initially with a limited role focused on NB-IoT and eMTC-based satellite access to address the requirements of massive Internet of Things (IoT) deployments. However, there is potential for an expanded role in the future.

To achieve this integration objective, extensive investigations and testing activities have been undertaken by specialized working groups as well as standardization processes [DKY22]. As a result, dedicated 3GPP Technical Reports (TRs) have been developed specifically for Non-Terrestrial Networks (NTN), along with updates to several existing specifications that did not initially consider NTN and SatCom requirements. These efforts have been essential in laying the foundation for incorporating NTN into 5G networks. It facilitates synergy between terrestrial and satellite operators, leading to improved market penetration for SatCom services. This collaboration between different communication mediums enables a more comprehensive and robust network infrastructure capable of meeting the diverse needs of various industries and sectors. By leveraging the strengths of both terrestrial and satellite-based communication systems, 5G networks can effectively extend their coverage, enhance reliability, and overcome geographical limitations. This integration opens up new possibilities for delivering connectivity to remote and underserved areas, supporting critical applications, and enabling seamless communication in challenging environments.

III.I Baseline Architectures

Architectural variants

The utilization of satellite technology in 5G networks is driven by the service requirements, presenting both needs and opportunities. This influence extends to all the corresponding 3GPP Technical Specifications (TS). Specifically, 3GPP TS 22.261 [TS22.261] emphasizes that satellite access should be considered a compulsory option, either as an alternative or the sole

option, in upcoming 5G systems. The document further highlights that the initial set of significant applications benefiting from satellite integration includes massive Internet of Things (IoT) networks and data offload/multimedia broadcasting.
The evolution of SatCom technology, including the development of high-throughput platforms and mega-constellations, along with enhanced NTN support in future 3GPP specifications, will contribute to the growing potential and capabilities of satellite-enabled services in 5G networks.
By conducting a thorough examination of 3GPP documentation, reference architectures, and relevant research and development (R&D) projects, a careful selection of meaningful and 3GPP-compatible SatCom integration options has been made. In this process, configurations that are unfeasible, unsupported, or unlikely to be implemented have been excluded. These include scenarios such as utilizing different SatCom systems for the fronthaul and backhaul, or placing the entire 5G Core (5GC) or a portion of it on-board without the Radio Access Network (RAN) component. Such configurations lack practical viability and do not hold significant interest for implementation purposes. The chosen integration options, on the other hand, demonstrate compatibility with 3GPP standards and are deemed relevant and feasible for further exploration and implementation in practical 5G networks.

IV. ITA NTN Architectures

According to the role of each layer of the 3D network, there are different types of architecture (Figure 2), depending on the roles allocated to the space/air segment (e.g., UAVs, HAPs, or satellite), such as Integrated Access and Backhaul (IAB) nodes, gNB-Distributed Unit (DU)/Central Unit (CU), gNB, and 5G Core Network (5GC) mode.

Case A - Drone-Based Relay Network
In the Drone-Based Relay Network, there is a network that uses drones or high-altitude platforms (HAPs) in the air to relay data between users and the 5G Core (5GC) on the ground. These drones can either simply pass on data they receive (transparent mode) or process and enhance the data before sending it to the ground (regenerative mode). The main ground station for serving users is located at the system's gateway (GW), and all communication protocols are terminated there, using the NR-Uu Air Interface for feeder and user links.

Case B - Satellite-Based Architecture
In the Satellite-Based Architecture, there is a satellite-based network designed for consistent and broad coverage. It has two configurations: one directly connects end-user devices through satellites, i.e., (i) satellite-based direct access, while the other uses satellites for backhauling data, i.e., (ii) satellite-based backhauling. The backhauling method employs Integrated Access and Backhaul (IAB) specifications. It is worth noting that different numbers of entities can be involved, and sometimes inter-satellite communication is used to cover larger areas.

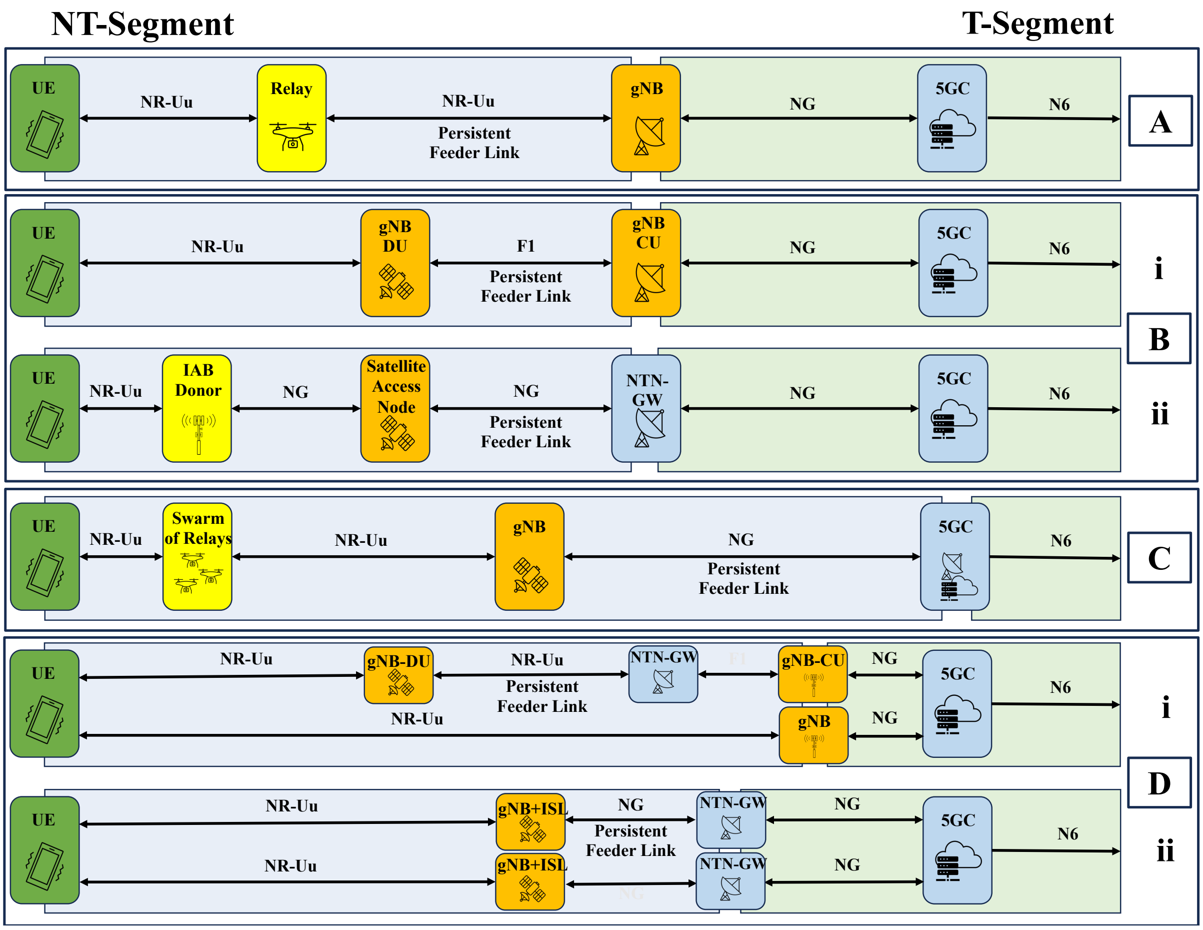

Figure 2. ITA NTN Architectures

Case C - 3D Single-Connectivity Architecture

In the 3D Single-Connectivity Architecture (Case C), users communicate with intermediary nodes like drones or HAPs at low altitudes. These intermediary nodes route the traffic to a gNB on a satellite, and from there, to the Core Network on the ground. These intermediary nodes can work in transparent or regenerative modes, making this architecture useful in situations where users can't communicate directly with satellites or gNBs, such as emergencies.

Case D - 3D Multi-Connectivity Architecture

The scenario of the 3D Multi-Connectivity Architecture enhances network capacity by using multiple layers of connectivity, including terrestrial, aerial, and satellite networks. This can be (i) between a terrestrial node (T node) and a non-terrestrial node (NT node), or (ii) between two NT nodes. NT nodes can operate transparently or regeneratively. This approach improves network reliability by providing backup routes in case of interruptions. However, it requires complex coordination and management of different layers.

In summary, these scenarios offer the opportunity to use autonomous rescue and emergency vehicles in remote areas without traditional telecommunications infrastructure. While this may reduce delays, it also adds complexity to payload design. In some cases, the entire network, including gNB and CU, can be hosted on satellites, eliminating the need for a ground network segment. This can enable local data delivery and opportunities for Software Defined Networking (SDN) and Network Function Virtualization (NFV), although it requires extra effort to implement.

V. Conclusions

V.I Project Vision

The rise of the 6G vision stimulated the worldwide research community to study the evolution of mobile networks, with the ambitious goal to realize a Ubiquitous Intelligent Mobile Society based on scalable and effective fruition of connectivity and services on demand. In this context, the challenging goal refers to the design of a novel communication infrastructure that integrates both Terrestrial (T) and Non-Terrestrial (NT) networks. As a huge amount of work is still needed to achieve a complete integrated infrastructure targeting sustainable, secure, global, ubiquitous, resilient, and broadband provision of information-processing and communication services, the ITA NTN project will focus on the integration of T and NT networks in future 6G deployments to conceive a novel 3D network architecture with a unified radio access network fully supported by new transmission techniques, communication protocols, and service orchestration methodologies exploting all the AI methodologies that will allow us to understand and foresee the whole network behaviours. Indeed, the resulting network architecture will appear as a mixture of space nodes that will be transparently integrated with the terrestrial segment for extending coverage, providing resilience and flexibility, offering backhauling services, and improving environmental sustainability [Sac23]. The project's activities will be successfully carried out sustaining the development and the dissemination of emerging services and applications belonging to Mobile Broadband Reliable Low Latency Communications, massive Ultra-Low Latency Communications, and Human-Centric Services service categories.

5G research has matured towards a global standard being commercially deployed, so that the R&D community is working on the development of beyond-5G solutions for the 2030 horizon, i.e., what is called now 6G – same time horizon as the one envisaged by RESTART [Gri23]. The 6G vision is a society increasingly i) digitized, ii) hyper-connected and iii) data driven. Many widely desired future services will be critically depending on real-time, virtually unlimited wireless connectivity. Mobile communication technologies are expected to progress far beyond anything seen so far, making everyday lives smoother and safer while dramatically improving the efficiency of businesses. 6G will not only be about moving data around, but it will become a framework of services, including communications, where all user-specific computation and intelligence may move from the cloud to the edge and vice-versa - from the 5G era of connected things to the 6G era of connected intelligence.

V.II Envisaged Road Map

6G promises to enlarge the boundaries of current wireless Terrestrial Networks to Non-Terrestrial Networks (NTN) made up of multiple tiers (which include, for example, satellite and airborne communication systems). Nonetheless the ambitious goal to realize a Ubiquitous Intelligent Mobile Society, based on scalable and effective fruition of connectivity and computing services on demand, and wherever needed can be successfully achieved by future 6G networks only thanks to the introduction of novel network architectures, transmission schemes, communication protocols, and service orchestration methodologies that go much beyond the conventional 5G enabling technologies.

Now, considering that the expected research on 6G poses several challenges in both academic and industrial realities, the ITA NTN project emerges - within the RESTART program – as an exciting, robust, and fruitful environment for formulating, testing, validating, and improving novel methodologies for the effective design of integrated T/NT wireless networks supporting seamless high-capacity demanding applications and massive access by heterogeneous devices. In its core vision, the ITA NTN project is fully convinced that the seamless integration of terrestrial and space wireless networks in future 6G deployments is fundamental for providing pervasive, ubiquitous, flexible, and on-demand wireless broadband connectivity. Therefore, it will support the deep definition of a novel 3D network architecture, able to exploit connections established (and dynamically configured) among ground and space network elements – such as Unmanned Autonomous Vehicles (UAVs), HAPs, aircraft, Geosynchronous (GEO) and Non-GSO (NGSO) satellites - and provide heterogeneous services and applications. ITA NTN is fully in line and consistent with the beyond-5G and 6G roadmap, as initially inferred from the NetWorld 2020 Strategic Research and Innovation Agenda and more recently supported by 3GPP documents, EU initiatives targeting both 2030 Digital Decade objectives, and EU Global Gateway strategy, ongoing ESA Calls for funding requests and industry white papers.

Regarding the definition of the 3D network architecture, ITA NTN will define a unified radio access network, exploiting new transmission techniques at physical and data-link layers. For instance, new wireless optical links will be merged with conventional wireless communication ones and novel antenna and electronic technologies will be conceived. Moreover, it will define new high-level protocols based on network softwarization and virtualization paradigms, and evaluate the pervasive integration (i.e., onboard satellites and at the ground level) of edge computing solutions and artificial intelligence techniques for the optimal orchestration of physical elements and network resources distributed across the 3D and multi-layer network architecture. What appears to be fundamental is performing a proper assessment of reasonable NTN (beyond-)5G service targets, and to devise the associated satellite network elements performance requirements to achieve acceptable system performance with a viable business model. This effort shall be pursued in addition to the support of all technologies that we have mentioned for NTN-friendly services such as IoT, back-hauling, broadcasting and multicasting.

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