Integrating Terrestrial and Non-Terrestrial Networks to Bridge the Digital Divide and Advance Sustainability

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***Abstract*—This paper analyzes the key characteristics of the integration among Terrestrial Networks (TN) and Non Terrestrial Networks (NTNs) that could have an important role to eliminate the digital divide and to make environments more sustainable. This is due to the many NTN devices, consisting of both high-altitude elements as satellites GEO and LEO, and lower-altitude elements as drones and aerial platforms, that allow us to reach unserved areas and have a fine control of any ambient. However, managing, orchestrating, and controlling for TN-NTN networks requires sophisticated procedures, and here we consider the main recommendations coming from organizations as 3GPP and ETSI, including also approaches based on Artificial Intelligence, necessary to define a suitable network behavior with so many elements.**

Keywords*—*NTN, 5G, 6G, SDN, 3GPP, ETSI

I. INTRODUCTION

Despite the immense progress in the field of telecommunications, unfortunately there is still a large population in the world that still does not have access to the Internet, and this happens even in some areas of the most industrialized countries. And because of this *digital divide* there are areas that have great difficulties in both social and economic growth and even some essential services are often absent. Furthermore, today there is a strong interest in how telecommunications can give a strong boost to the improvement of life by acting on those phenomena that today are terrible threats such as pollution, desertification and climate change. From other points of view, telecommunications could give a strong support to the development of more efficient and at the same time more sustainable industrial and agricultural processes. Clearly the solution cannot be based on bringing expensive telecommunications infrastructures everywhere, because the deployment of optical fibers and radio bridges in some areas would not only be economically unsustainable but also harmful to some environments.

For several years it has been understood that Non-Terrestrial Networks (NTNs) [1-3] can be an excellent solution for eliminating the digital divide and for creating a more sustainable world and the clearest example in this area is the coverage of the Amazon with the Starlink satellite network.

The NTNs consist of satellites (Geostationary Earth Orbit, GEO, Medium Earth Orbit, MEO, or Low Earth Orbit, LEO), but also and airborne devices, including drones and High-Altitude Platform Stations (HAPS), operating at lower altitudes. Different combinations and interconnections among NTN nodes enable a range of possible architectures, defined by the specific role assumed by each device, whether it be a backhaul or access node.

But the proper functioning of NTN will depend on how it is connected, or more precisely integrated, with the Terrestrial Network [4-9].

Within this context, managing the entire network can be particularly challenging, especially considering the high dynamism of the network in non-GEO systems. This dynamicity necessitates the adoption of advanced solutions, such as Software Defined Networking (SDN) [10] and Network Function Virtualization (NFV), along with approaches like Open Radio Access Network (O-RAN) [11].

Generally, different network domains have been defined and managed through standards perfectly tailored for them. Future heterogeneous networks will necessarily have to integrate various systems that have so far worked independently. In this context, this work deals with the individuation of a possible contact point between these standards, to create layers that can unify different local solutions through a global orchestration. For such an aim it is necessary to clearly understand where this global orchestration must operate including all NTN architectures, Use Cases (UCs), and protocols concerning the multi-accesses and multi-connectivities.

There is another fundamental aspect of the integration between terrestrial networks and that is that these networks will be made up of an immense number of channels in which information will transit, made up of wireless connections with different carriers, from sub-millimeter to THz, up to wireless optical channels.

These propagation channels combined with massive antenna arrays can allow us also to make precise measurements of different physical effects by analyzing wave transmissions, reflections, and scattering [12-14]. In particular, services such as high-accuracy localization, recognition, passive object detection, as well as imaging, and environment reconstruction can be obtained by exploiting these principles. In fact, it has already been extensively proposed how a telecommunications system operating with these frequencies could also be used for sensing, for instance by adopting time intervals dedicated either to data transmission or sensing [14] obtaining the so-called Integrated Sensing And Communications (ISAC).

In the ISAC framework, TN-NTNs appear particularly suitable for exploring the sensing world both for their dimensions and the presence of several high-frequency channels operating on many different bandwidths. Furthermore, NTN can include specific subnetworks based on the Internet of Things (IoT) [15] specifically designed for sensing. Therefore, the integration of T/NTNs, in addition to being used for the purpose for which it was created, namely telecommunications, could be used for environmental monitoring purposes and therefore to make further contributions towards environmental sustainability.

Moreover, the integration of T/NTNs can have an important role for the Sustainable Development Goals (SDGs), for example by reducing energy consumption thanks to SDN, NFV, and Artificial Intelligence (AI) paradigms.

All these aspects should be analyzed in a management and control framework proposed for cross-domains by different Standardization organizations, and this is the aim of this paper obtained in the framework of the Italian Project "Integrated Terrestrial And Non-Terrestrial Networks (ITA-NTN)", in the context of the "*RESearch and innovation on future Telecommunications systems and networks, to make Italy more smart (RESTART)*" program, funded by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of Next Generation EU.

Therefore, this paper is structured in the following way. Section II provides an overview of the state of the art about the NTN architectures, while Section III describes the principal UCs of applications of these architectures in different environments. Section IV illustrates where the TN-NTN can have an important role in the United Nations' SDGs of the 2030 Agenda. Section V enters in the details for the role of TN-NTN for a space sustainable. Section VI reports the main proposals at the standardization level concerning high-level cross-domain management and control operations. Section VI reports our main conclusions.

II. TN-NTN Architectures

The ITA-NTN project is focused on a 6G-oriented scenario for 3-dimensional (3D) wireless connectivity, as shown in Fig. 1. Specifically, 3D refers to terrestrial, low altitude flying devices (i.e., drones, balloons, air platforms, ...) and satellites. The aforementioned project targets the challenging goal of conceiving novel methodologies and effective solutions to provide pervasive, ubiquitous, and flexible 3D on-demand wireless connectivity and edge computing services through the integration of TN-NTN [12]. By considering that each layer of the 3D network architecture can have different transmission roles, four different architectures are crucial: i) Drone-based Relay Network, ii) Satellite-based Architecture, iii) 3D Single-Connectivity Architecture, and iv) 3D Multi-Connectivity Architecture [8]. Note that in the 3D scenario the intermediary node and the satellite can operate in transparent and regenerative mode, giving rise to various architecture subtypes.

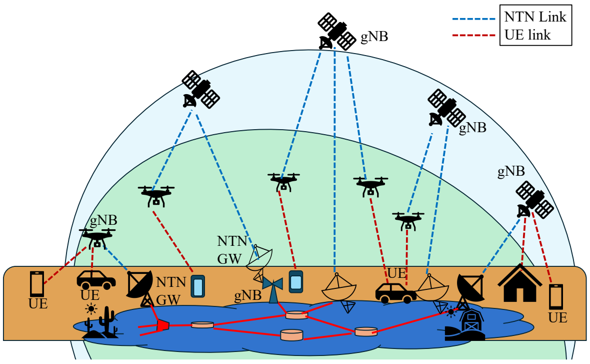

Fig. 1: The TN-NTN scenario.

The architecture of a *drone-based relay network* consists of three main components: User Equipments (UEs)/Ground Users (GUs), drones, and a ground control station (NTN Gateway, NTN GW), which can be embedded in the gNB (e.g., the drone on the left in Fig. 1). Indeed, drones equipped with communication systems can act as flying base stations or relays, enabling communication between distant locations.

Satellite-based architecture enables communication via Earth-orbiting satellites, offering broad coverage that connects distant and remote areas. However, it faces challenges like signal latency due to the long distances, high setup and maintenance costs, and sensitivity to weather conditions. Unlike drone-based designs, satellite systems effectively bridge gaps in regions where laying terrestrial cables or direct fiber connections is difficult or expensive. There are two key configurations: satellite-based access and satellite-based backhauling. The latter, involving Integrated Access and Backhaul (IAB) nodes as introduced in 3GPP Rel. 16, connects remote ground nodes to the core network.

The *3D single-connectivity architecture* combines all the entities of the previous schemes represented in the middle of Fig. 1. Different possibilities can be adopted as a fully transparent option, regenerative satellite (full gNB) and transparent drone, transparent satellite and regenerative drone (full IAB-Donor), and regenerative satellite (full IAB-Donor) and regenerative drone (IAB- node).

The *3D multi-connectivity architecture* is a variant of the single-connectivity type where a UE can connect simultaneously to two NTN accesses (the car on the right side of Fig. 1). This scheme offers several advantages. For example, it enhances network capacity by leveraging multiple layers or tiers of connectivity, i.e., terrestrial, aerial, and satellite networks. This allows for efficient utilization of available spectrum resources and enhanced coverage in various areas. Moreover, it is possible to improve network reliability and resilience. Within 3GPP, Multi-Radio (MR) Multi-Connectivity (MC), and in particular Dual-Connectivity (DC), was analyzed to simultaneously transmit Protocol Data Unit (PDU) sessions to the same UE over multiple Satellite Access Node (SAN)/ Radio Access Network (RAN) nodes, with more analysis still underway (Rel. 18 and Rel. 19).

III. ITA-NTN USE CASES

The ITA-NTN project has identified six different UCs (Fig. 2), by considering all the possible multi-connectivities and the multiple roles in 5G/6G of NTNs and in particular Satellite Communication networks, acting as RAN and as backhaul connection for remote 5G/6G deployments:

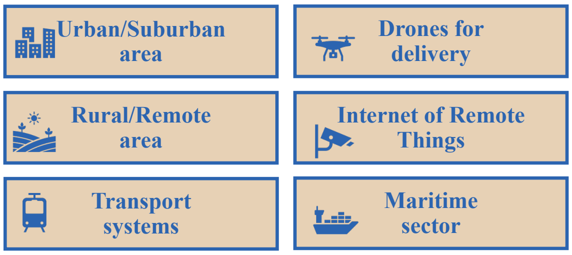

Fig. 2: ITA-NTN UCs.

- Urban/Suburban area UC: An NTN component can be beneficial for offloading data, where the satellite network offers an additional connection to manage traffic surges and maintain the performance of sensitive flows and coverage.
- Rural/Remote area UC: Aerial and space platforms can help close the digital divide by providing high-speed connectivity to remote areas lacking terrestrial infrastructure. Moreover, HAPs and satellites play a crucial role in disaster response by ensuring resilient emergency communication networks during disruptions to terrestrial infrastructure.
- Transport Systems UC: These include a range of functionalities such as supporting railway operations and providing wireless connectivity for passengers during train services. This involves managing signaling and critical voice and data traffic for train safety, real-time critical video to support train operations, and both critical and non-critical data related to train and infrastructure issues that affect passenger safety and travel efficiency [16-17].
- Drone Delivery UC: Drones can revolutionize logistics by facilitating communication with control centers for real-time updates on parcel location, traffic conditions, and weather, leading to faster and more efficient deliveries. Additionally, drones equipped with high-resolution cameras can transmit live video feeds, improving situational awareness and enabling operators to identify potential hazards.
- Internet of Remote Things UC: This includes IoT networks capable of collecting data from sensors and sending control messages to actuators, thereby enhancing situational awareness and operational efficiency. These networks pave the way for revolutionary applications in Smart Agriculture, Environmental Monitoring, Remote Control and Monitoring of Critical Infrastructures, and Smart Goods Tracking.
- Maritime UC: These involve critical communications, such as those related to Global Distress and Search & Rescue operations, where coverage and reliability take precedence over broadband and real-time features [5].

In particular, by considering that the integration of TN and NT networks can ensure connectivity and continuity of services everywhere, the ITA-NTN project will extend Internet access to unconnected peoples and places, to eliminate the digital divide.

IV. TN-NTN AND THE SDGS OF THE 2030 AGENDA

The integration of TNs and NTNs can give a fundamental contribution for sustainability. For example, it will be possible to reduce energy consumption directing data transmissions in areas with less energy impact and reducing hardware usage through SDN, NFV, and AI paradigms, as well as the potential reduction of space debris, all in line with the 17 United Nations' SDGs of the 2030 Agenda[1].

Some important examples of how the ITA-NTN project could impact the SDGs are reported in what follows:

- *SDG 9 - Industry, Innovation, and Infrastructure*: By extending Internet access to remote and underserved areas, the ITA-NTN project contributes to building resilient infrastructure and promoting inclusive and sustainable industrialization. This supports innovation by providing more people with access to various digital tools and platforms.
- *SDG 10 - Reduced Inequality:* The ITA-NTN project will extend Internet access to remote and underserved areas. Thus, it is possible to reduce inequalities within and among countries, focusing on ensuring equal opportunities and reducing income disparities.
- *SDG 11 - Sustainable Cities and Communities*: The ITA-NTN project supports the development of smart cities by providing reliable connectivity for IoT devices and sensors, which can improve urban planning, traffic management, and public safety.

The integration of TN-NTNs will also have an impact on other SDGs:

- *SDG 4 - Quality Education*: Improved connectivity in remote areas facilitates access to online educational resources, enabling distance learning and digital literacy programs. This can help reduce the education gap between urban and rural areas, promoting lifelong learning opportunities for all.
- *SDG 3 - Good Health and Well-being*: The integration of TN-NTNs can enhance telemedicine services, allowing people in remote areas to access healthcare professionals and emergency services more easily and improving health outcomes and reducing health disparities.
- *SDG 7 - Affordable and Clean Energy*: Using energy-efficient technologies such as SDN, NFV, and AI, the ITA-NTN project can help reduce the overall energy

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[1] https://international-partnerships.ec.europa.eu/policies/sustainable-development-goals_en

consumption of communication networks. This contributes to the goal of ensuring access to affordable, reliable, sustainable, and modern energy for all.

- *SDG 13 - Climate Action*: By minimizing the need for physical infrastructure and reducing energy consumption, the ITA-NTN project supports efforts to combat climate change. Additionally, the emphasis on reducing space debris aligns with broader environmental protection efforts.
- *SDG 8 - Decent Work and Economic Growth*: Enhanced connectivity can stimulate economic growth in remote areas by enabling access to markets, creating new job opportunities, and supporting Small and Medium-sized Enterprises (SMEs).
- *SDG 12 - Responsible Consumption and Production*: The adoption of sustainable practices in network deployment and maintenance, including the reduction of space debris, aligns with the challenging goal of ensuring sustainable consumption and production patterns.

Note that space sustainability is a new key aspect to be considered in order to balance exploration with responsible resource use, according to ITU guidelines[2], by managing current space activities while anticipating future developments and challenges. In this context, it is highlighted that ITU's first Space Sustainability Forum took place in Geneva, Switzerland, in September 2024.

V. TN-NTN AS ENABLER FOR SPACE SUSTAINABILITY

6G aims to contribute to the SDGs. Whitin this framework, the integration of TN and NTN is widely recognized to play a crucial role. The integration can reduce the ecological footprint of network expansion. Traditional terrestrial networks often require extensive land use and significant energy consumption for infrastructure deployment and maintenance. In contrast, non-terrestrial networks, particularly those utilizing LEO satellites, can cover vast areas with fewer physical installations on the ground, reducing land disturbance and habitat fragmentation. Moreover, the deployment of integrated TN-NTNs can optimize resource usage and energy efficiency. Advanced technologies such as AI and Machine Learning (ML) can manage network traffic dynamically, ensuring efficient utilization of bandwidth and power. This can lead to lower operational energy consumption and a reduced carbon footprint. However, it is worth outlining that the recent growth of space systems has occurred in an uncontrolled manner, posing an urgent challenge to long-term space sustainability [18, 19]. Therefore, sustainable design and operation of TN-NTNs must include measures to mitigate space debris, such as satellite deorbiting plans and the use of reusable launch vehicles. The ITA-NTN project aims to design future TN-NTNs with a focus also on preserving. By enabling the use of the same space infrastructure for communication sensing and positioning, it is possible to reduce the number of satellites This approach can significantly help in preserving the orbital environment. Furthermore, the above integration could help in additional ways such as:

- *Improvement in the space debris management* - the ISAC paradigm can enhance space debris detection and tracking capabilities. Traditional systems often rely on separate infrastructures for communication and debris tracking, which can be both resource-intensive and limited in capability. By integrating sensing and communication, ISAC systems can utilize communication signals to concurrently detect and monitor debris. This dual functionality allows for real-time updates and more precise tracking, enabling better collision avoidance and debris mitigation strategies.
- *Improvement of satellite operation efficiency* - ISAC can optimize satellite operations by providing simultaneous communication and situational awareness. For instance, a satellite equipped with ISAC technology can continuously monitor its surroundings and communicate with ground stations, ensuring it operates within safe parameters and adjusts its trajectory as needed to avoid potential collisions. This integration reduces the need for multiple separate systems, saving weight, power, and cost while enhancing the overall reliability of satellite operations.
- *Improvement in the efficient use of spectrum resources* - with integrated systems, the frequency spectrum can be more effectively utilized, reducing interference and optimizing bandwidth allocation. This efficiency helps mitigating the risk of signal congestion, which is becoming increasingly important as the number of satellites and other space assets grows.
- *Improvement in space traffic management* - as space becomes more crowded, effective space traffic management becomes essential to avoid collisions and ensure the safety of space operations. ISAC can play a key role in this area by providing real-time, accurate data on the position and velocity of various space objects. This information is crucial for coordinating the movements of satellites and other space vehicles, preventing accidents and maintaining orderly traffic flow in space. By combining sensing and communication, ISAC systems can share this data seamlessly between satellites and ground stations, fostering a collaborative approach to space traffic management.

ISAC can thus be considered an enabler of space sustainability and its effectiveness in the in-space hardware rationalization can take great advantage from flexible and resilient T-NTN architectures. The latter, in turns, are tightly related to an extensive use of software-driven and software-defined paradigms, where the challenge is more and more becoming the achievement of truly hardware-free and energy

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[2] https://www.itu.int/hub/2024/10/space-sustainability-balancing-exploration-with-responsible-resource-use/

efficient software, with a very low cost – in terms of hidden hardware mass/weight and requested energy – per code line.

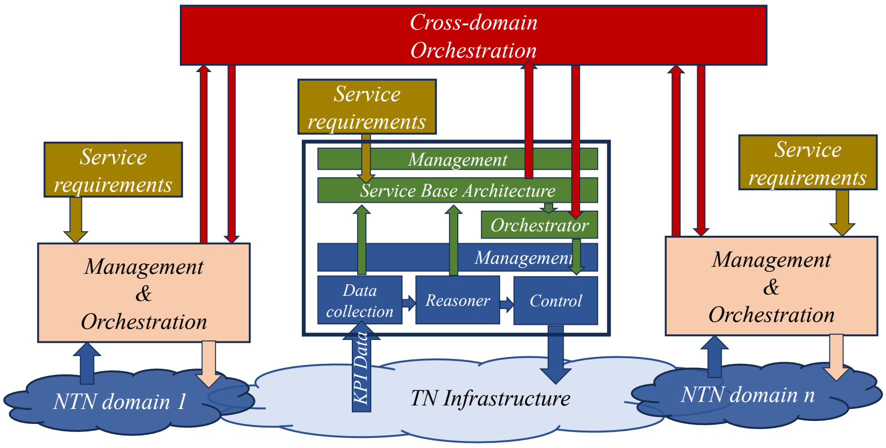

Fig. 3: Functional architecture of integrated network control for TN-NTNs.

VI. CROSS-DOMAIN ORCHESTRATION AND MANAGEMENT

As previously affirmed, the dimension of TN-NTNs can permit in principle to forward the traffic in areas where either the power consumption can be more convenient, especially in a specific time interval, or time intervals where the energy is produced in a greener way. For such an aim it is required a complex integrating control, orchestration, and management across TNs and NTNs and it presents a multifaceted challenge.

Several high-level specific issues related to cross-domain control plane, orchestration, and management in integrating TN and NTN can be listed:

- Heterogeneous Technology Integration: it includes reconciling differences in network architectures, communication protocols, and transmission mediums; it clearly appears looking for example at satellite, optical fibers, cellular, and IoT technologies.
- Dynamic Resource Management: NTN environments, such as satellite networks, exhibit dynamic characteristics due to factors like satellite mobility, variable propagation conditions, and handovers between different satellites. Coordinating resource allocation and management across these dynamic environments, and taking into account also the connection with NT, while ensuring seamless handovers and QoS provisioning is a challenging task.
- Service Orchestration and Lifecycle Management: Orchestration platforms must facilitate end-to-end service creation, provisioning, and lifecycle management across TN and NTN domains, including dynamic service chaining, policy enforcement, and resource optimization.
- Inter-Domain Routing and Traffic Engineering: Effective routing and traffic engineering between TN and NTN domains require optimized path selection, considering latency, bandwidth, and congestion, and developing protocols for inter-domain routing.
- Policy and Governance: Harmonizing policies and governance across TN and NTN domains is critical for ensuring compliance, security, and regulatory alignment.
- Unified Performance Monitoring: Managing network performance and detecting faults across TN and NTN domains necessitates unified platforms that can aggregate and correlate data from diverse sources.
- Spectrum Management: Establishing regulations and standards for efficient spectrum allocation in TNs and NTNs is essential to ensure equitable access and optimal use of the spectrum.
- Sustainability: cross-domain orchestration and management can play a key role in enhancing the sustainability of integrated TN NTN. By seamlessly coordinating various network domains, these systems optimize resource allocation and improve overall network efficiency. Key benefits include:
    - energy efficiency: dynamic resource management can minimize energy consumption by allocating bandwidth and power where needed, reducing both waste and operational costs.
    - reduced infrastructure footprint: efficient orchestration can allow optimal use of existing infrastructure, minimizing the need for additional terrestrial installations and the reducing land use and associated environmental impacts.

Recent research and development efforts worldwide have initiated the exploration of novel technologies to enable TN and NTN convergence, as for example in [5] [29-30]. On the other hand, Standards Development Organizations (SDOs) such as ITU- T [31], ETSI [33] and 3GPP [1-3] have proposed different approaches to address various challenges associated with a unified management and control both for TN and NTN. However, no definitive solutions have been addressed yet and convergence and interoperability remain critical gaps to be further investigated.

First of all, the proposals are much different if we refer either to the core architecture, that is mainly related to the TN part, or to the access one the mainly refers to the NTN [20]. Concerning the NTN, that can be related to the Radio Access Network, currently there is much interest for the Open RAN (ORAN) approach [21-22].

In Fig. 3 we illustrate the different M&O approaches for the TN and the NTN segments, that must be controlled by a Crossdomain orchestration. In the figure we report in more detail the NT area since it is the one that has to operate with the higher bit rate devices operating also on very long distances. In particular, it recalls the proposal in [23], inspired to ITU-T Study Group 13, where a two-layer control system is depicted. The upper layer (green) oversees an End-to-End (E2E) service, while the lower layer (blue) consists of individual network domain control systems. These systems collectively feed data into a central monitoring system, facilitating a comprehensive analysis of the network's status from an E2E perspective. This analysis serves as the foundation for optimizing E2E resource management and control according to service level requirements and user intents. The primary objective is to dynamically allocate resources to ensure high-quality E2E communication services.

The challenge lies in detailing the characteristics and transmission protocols of all devices across different domains and determining which processes should remain domain-specific versus those managed by the integrated network control system, ideally centralizing control as much as possible. Achieving effective orchestration and management requires advanced analytics, enabling adaptive control and automation. The 3GPP SA5 introduced the Management Data Analytics Function (MDAF) to facilitate cross-domain data gathering from sources like OAM systems and intelligent elements within the 5G core and access networks. However, the specific design of functional components, interfaces, protocols, and algorithms still needs further exploration and standardization, especially in line with ETSI's Zero Touch Network and Service Management (ZSM) vision for AI-driven automation [24-25].

VII. CONCLUSION

In this paper, describing the TN-NTNs, we underline how such infrastructures can make an important contribution to either reducing or eliminating the digital divide and making the world more sustainable. However, the complexity of such networks, especially in controlling all the devices composing the TN-NTNs, requires complex methodologies for orchestration and management which are still to be investigated.

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