From Interoperability to Full Integration – the ITA NTN Project Vision

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***Abstract*—This paper describes the integration of Terrestrial and Non-Terrestrial Networks, where space network entities cooperate with conventional and emerging terrestrial communication architectures to provide ubiquitous, resilient, and three-dimensional wireless connectivity around the world, supporting heterogeneous services (e.g., improving better coverage, user experience, system capacity, service reliability, and availability, as well as offering high-speed connectivity in remote sites or in disaster-affected areas). The view of all the possible architectures, considering the role both as backhauling and access for each layer of NTN systems and devices, is illustrated according to the studies of the Integrated Terrestrial And Non-Terrestrial Networks (ITA NTN) project, in the framework of the PNRR Research Program.**

***Keywords*—5G, 6G, Terrestrial, Non Terrestrial, GEO, MEO, LEO**

I. Introduction

It is well known that 5G [1] will allow exceptional performance for wireless communications; however the creation of adequate infrastructures will not be possible in every area either due to cost sustainability or because it is really impossible in areas such as the sea. But even territories where there are motorways or railways, which already provide telecommunications infrastructures, could require traffic peaks or other stringent services not foreseen at the beginning or which can occur in time situations limited to small intervals and located in points that vary continuously; this is, for example, the situation that the evolution of the *automotive industry* [2] will have to deal with by deploying networks that will have to support vehicular traffic well in the event of traffic congestion [3-6]. Hence the increasingly evident need to acquire mobile telecommunications infrastructures capable of positioning themselves where needed in particular time intervals such as in the case of disaster recovery or other emergencies. This is why the so-called *Non Terrestrial Networks (NTN)* are becoming increasingly important [7-9], to distinguish them from *Terrestrial Networks (TN)* in the sense that the antennas are mounted on structures that are on the mainland.

One of the most important challenges in the coming years will be the unification between TN and NTN, and this will be also one of the main themes of the 6G building on the initial integration achieved in 5G systems, [7], [8]. NTNs include spaceborne and airborne network nodes (unmanned aerial vehicles, aircraft, drones) cooperating with conventional and emerging terrestrial communication architectures to provide ubiquitous, resilient, wireless connectivity around the world, while supporting enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC), massive Machine Type Communications (mMTC), and Human-Centric Services [6-11], improving coverage, user experience, system capacity, service reliability and availability, and environmental sustainability of next-generation communication infrastructure for several potential verticals and in particular for transportation, public safety, and high-speed connectivity in remote sites or disaster-affected areas.

The NTN segment is composed by satellites (Geostationary Earth Orbit, GEO, Medium Earth Orbit, MEO, or Low Earth Orbit, LEO) and aerial devices, including drones and High Altitude Platform Stations (HAPS), operating at lower altitudes. The different combination and interconnection among the NTN nodes allows for a wide number of architectures, also defined by the role assumed by each device, *i.e.*, backhaul or access node. In this framework, the management of the whole network might become particularly challenging, also considering the high dynamicity of the network when it comes to non-GEO systems, which calls for the adoption of advanced solutions, such as Software Defined Network (SDN) and Network Function Virtualisation (NFV), as well as Open Radio Access Network (O-RAN) approaches.

A network composed by so many systems and devices offers many surfaces to receive attacks and therefore the security issue requires many attentions.

The aim of this paper is to report a review of the all architectures combining TN and NTN elements with the vision proposed by the ITA-TNT project in the framework of the RESTART Program. The paper is structured in the following way: after this introduction, in Sect. II the main current satellite and telecommunication platforms are described, in Sect. III the role of the 3GPP for the first integration among TN and TNT is summarized, in Sect. IV the aspects of such integrations are described and in Sect V the vision of the ITA-TNT is reported. Sect, VI is dedicated to security issues for such networks and in VII the conclusions are drawn.

II. Overview on the Current Satellite and Aerial Telecommunication Platforms

In fig. 1 we show a schematic example of integration of NTN and TN, with their own nodes.

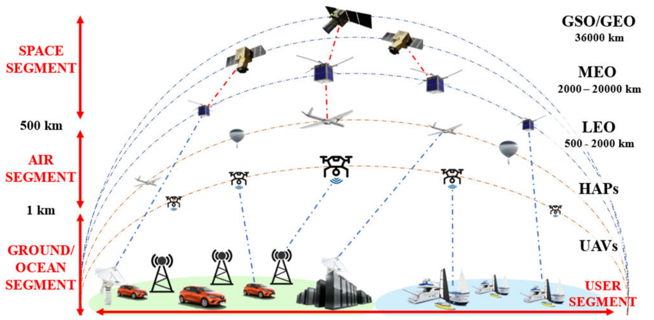

Figure 1 – Integration of T and NT network segments.

There are currently more than 6500 active satellites around the Earth. Generation 1 of SpaceX's Starlink will, by itself, consist of 11,926 satellites, and generation 2 will have 30,000 more. OneWeb, Amazon's Kuiper, and China's SatNet combined will deploy over 20,000 satellites. Together with active satellites, there are currently an estimated 330 million pieces of space debris, including 36,500 objects bigger than 10cm, such as old satellites, spent rocket bodies and even tools dropped by astronauts orbiting around Earth. Space surveillance networks now track more than 23,000 objects in Earth orbit.

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; 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; and Telesat LEO network with 300 satellites in orbit with a global service in 2022.

This crowded situation poses several challenges:

- interference to astronomical observations;
- radio frequency interference to other communication systems and challenging spectrum management;
- challenges in space operations as the margin of error for maintaining separation between satellites gets reduced;
- higher probability of collisions which leads to an increase of the debris.

The resulting T/NT 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.

III. The Pillars of the Upcoming T-NT Networks According to 3GPP

It is globally recognized that a Non-Terrestrial (NT) component will be fundamental in achieving the ambitious requirements that are now being set forth for 6G communications, largely building on their integration with terrestrial infrastructures achieved in 5G.

In this context, starting from Rel-15 the 3GPP [12-14] has been focusing its efforts on the integration of the NT component in the 5G network infrastructure, by initially assessing the impact of the peculiarities of the NTN link on the New Radio (NR) Air Interface and procedures, reported in TR 38.811; such analyses also allowed to identify a wide range of use cases in which the introduction of NTN would be beneficial, including automotive applications [10]. Of the valuable outcomes of the 3GPP NTN study phase led to the first-ever standardized NTN component in Rel-17 of 3GPP (March 2022). This standard specifies the features enabling 4G and 5G systems to support a satellite component, in particular focused on S-band (i.e., below 6 GHz) for handheld terminals. More than technical specifications, it also enables the integration of the satellite industry in the 3GPP ecosystem, involving more than 700 organizations at worldwide level to ensure a global market. However, the current standardized architecture is essentially based on integrating the NTN component in the 5G network, based on interfaces and protocols still optimized for the terrestrial segment, *i.e.*, with a minimum impact on the 5G standard. As such, the NT and terrestrial components appear to be loosely integrated and based on a specific adaptation of the Terrestrial architecture and radio access network to the specificity of the Non-Terrestrial link. Differently, 5G-Advanced (Rel. 18-Rel. 20) and, in particular, 6G (Rel. 20+) will target a much more ambitious vision, according to which T and NT networks will be fully unified in a novel architecture, commonly denoted as 3D architecture in which terrestrial and non-terrestrial nodes at multiple orbits seamlessly contribute to the global connectivity [7]. In Rel. 18, the 3GPP studies are focused on further enhancements focusing on both GEO and NGSO deployments, supporting Frequency Range 2 (i.e., Ka-band) for fixed or moving Very Small Aperture Terminals (VSAT), coverage enhancements, and NTN-TN/NTN-NTN mobility aspects. Rel. 18 (the first related to 5G-Advanced) will freeze the radio protocol specifications in June 2024, while the content of Rel. 19 will be frozen in December 2023 aiming at finalising the radio protocols by December 2025 [11]. The identification of the Rel. 19 package is on-going and several topics are being discussed aiming at improving the service experience and introducing new capabilities. As of today, it can be expected that Rel. 19 will address: i) coverage enhancements both on the uplink and on the downlink; ii) NTN-TN mobility enhancements in connected mode; iii) support of Reduced Capability (RedCap) User Equipment (UE) below 6 GHz; iv) the support of regenerative payloads with Inter-Satellite

Links (ISL); and v) the support of UEs without Global Navigation Satellite System (GNSS) capabilities for the uplink time and frequency synchronization (in idle/connected mode).

Finally, it is expected that Rel-20+ of 3GPP (beyond January 2025) will promote a new architecture where TN and NTN will be truly unified into the above-mentioned 3D architecture, as also shown in Fig. 1. The view of the ITU about the integration of satellite systems into Next Generation Access Technologies can be seen in [15].

IV. A NEW PARADIGM: INTEGRATING MULTILAYERS

Mainly, the interworking of satellites with the terrestrial network can support service continuity, scalability, and availability for eMBB and mMTC services, while future 6G networks build on a fully unified satellite-terrestrial network where the users must interface in transparent way both with terrestrial and satellite networks.

The integrated satellite-terrestrial network architecture can:

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

Regarding to the satellite segments we can consider:

1) Satellite can provide broadband Internet access services comparable to the ones supported by terrestrial cellular systems in terms of pricing and bandwidth, but currently most of their communications regard GEO at an altitude of 35.786 km, involving an excessive delay for a direct integration with terrestrial mobile networks.

2) The NGSO 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 2000-20000 km for MEO and 300-2000 km for LEO. Their typical radius footprint size ranges from 100 km to 1000 km. 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.

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 signals 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 Adjacent-Channel Interference (ACI). 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, a mitigation to the interference from different layers and orbital constellations with different propagation delay can be achieved by using an 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 or 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, as, e.g., the macro cell. Cell-free operation decreases the needs of 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 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 full 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. SDN architecture can be used for an efficient and intelligent network management into the integrated satellite terrestrial system. The SDN control plane include both the terrestrial and the satellite controllers, allowing a unified control of the integrated network. This flexible and scalable control keeps divided 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 performed on the ground and on the satellite, forwarding the data packets according to flow tables.
- Cloudification: it plays a vital role in optimizing resource usage, reducing operational costs, and ensuring network flexibility for the extensive number of clients and servers in 6G NTN. Multi-access Edge Computing (MEC) is a pivotal technology that minimizes processing latency within NTN systems. To fully harness the benefits of MEC, it is crucial to develop appropriate solutions for MEC service provisioning to NTN User Equipment (UEs) and direct task processing at the NTN level. The concept of a Cloud-native vision brings new opportunities to the space business, enhancing the competitiveness of NTN systems.

Virtualization techniques enable hosting Digital Twins (DTs) for satellites, orchestrated within a federated multi-tenant Ground Station Network (GSN). Ground Stations (GSs) function as edge nodes in a global terrestrial-satellite network, enabling the delivery of sophisticated 6G services by orchestrating and integrating microservices associated with different satellite DTs.

- 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 non-limiting examples, variable wheatear factors, such as rain, cloud, water vapor, and fog, impact to the satellite communications paths. These can produce deep fading events and thus 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, more complex and accurate Channel State Information (CSI) is required by considering furthermore the effect of propagation delay.
- Terahertz (THz) communications: it offers the high capacity needed for 6G applications, but they face challenges such as path loss, molecular absorption, and blockage. Despite advancements in THz device manufacturing, developing end-to-end THz networks is still a significant task. THz communications have potential for enabling unmanned aerial systems (UAS) and HAPS with lower latencies than other platforms at higher altitudes, but optimized positioning and beam management are essential for reliable air-to-ground connections. While the THz band has been studied for inter-satellite communications, its feasibility for space-to-Earth links requires further investigation. Compact and efficient THz sources and amplifiers remain a key challenge, but Ultra-massive MIMO (UM-MIMO) and reconfigurable electronic surfaces show promise in addressing these obstacles.
- Intelligent Reflecting Surfaces (IRS): offer passive and energy-efficient solution to enhance communication performance in integrated T/NT systems while adhering to size, weight, and energy constraints. The integration of IRS in NTN systems holds promise for various applications. Studies propose using Reconfigurable Intelligent Surfaces (RIS) and the THz band in LEO Inter-Satellite Links (ISLs) to enhance communication security through secure cooperative jamming. Additionally, optimizing IRS operation with predictive mobility compensation can increase the Signal-to-Noise Ratio (SNR) in IRS-assisted LEO satellite communications. However, addressing current limitations related to channel models for NTN systems and understanding the impact of harsh environmental conditions on RIS design and operation requires further research.

Therefore we can say that a complete T-NTN is a multi-connectivity architecture composed of space backbone network of GEO satellites and a space Based Access from LEO, MEO satellites and HAP and UAV for the NTN part, and a RAN from the terrestrial network.

V. T/NT Networks

6G promises to enlarge the boundaries of current wireless Terrestrial Networks to NTN made up of multiple tiers (which include, for example, spaceborne 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.

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, GEO, and 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 wireless 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., on-board 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 (B-)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.
According to the role of each layer of the 3D network, we can distinguish different types of architecture, depicted in fig. 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.
The first configuration (case A) is a drone-based relay network between the user segment and the 5GC on the ground, typically consisting of UAVs or HAPs deployed in the air segment and a ground control station, which can be embedded in the gNB. A key aspect defining the overall architecture is the option to deploy transparent or regenerative payloads onboard the drone. In the transparent mode, the network node operates solely amplifying and forwarding received data to its intended destination (i.e., the gNB). Conversely, in the regenerative mode, the network node processes incoming data, makes decisions based on the analysis, and then regenerates the signal before forwarding it to the gNB. The gNB responsible for serving the on-ground UEs is conceptually positioned at the system GW. To adhere fully to the 3GPP NTN standard, all CP/UP protocols are terminated at the on-ground gNB. As a result, the feeder and user links necessitate the implementation of the NR-Uu Air Interface.
Satellite-based architecture (case B) is purposefully designed for long-term operation, ensuring consistent and uninterrupted connectivity, as well as providing extensive coverage across wide areas. Two distinct configurations involving satellites can be distinguished: i) satellite-based direct access, and ii) satellite-based backhauling. Satellite-based direct access refers to the utilization of satellites to directly connect end-user devices, establishing a direct link between the satellite and the UE. It should be noted that a functional split option is also feasible, with an onboard gNB-DU and an on-ground gNB-CU. Satellite-based backhauling solution, instead, is facilitated through the implementation of Integrated Access and Backhaul (IAB) specifications [11]. Clearly, the number of entities involved may vary. It encompasses multiple UEs and satellites concurrently, which raises concerns regarding the orchestration of networks and management of radio resources. Moreover, when multiple satellites are employed, inter-satellite communication often represents a viable solution to cover large areas.
In the 3D single-connectivity architecture (case C), the UE has the capability to establish communication with intermediary transparent nodes at low altitudes, such as a swarm of drones or HAPs. These intermediary nodes are responsible for routing the traffic towards a gNB entirely present onboard the satellite, and subsequently, to the Core Network hosted on the ground. Similar to other configurations, the NT nodes can adopt either a transparent or regenerative approach. This scheme proves to be highly advantageous, especially in emergency situations, where UEs lack the necessary technology or capabilities to directly communicate with the satellite or the gNB.

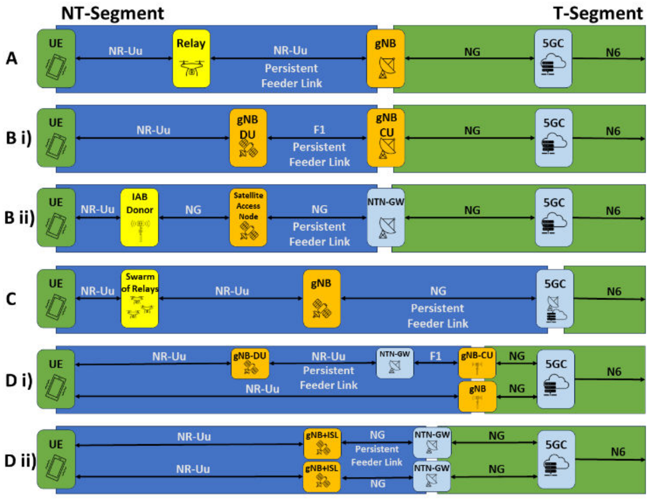

Figure 2-Possible T/NT architectures of interest in the ITA NTN project.

The 3D multi-connectivity architecture (case D) enhances network capacity through the utilization of multiple layers or tiers of connectivity, including terrestrial, aerial, and satellite networks. It can be deployed either i) between a T node and a NT node or ii) between two NT nodes. In the latter scenario, the NT nodes have the flexibility to function as either transparent or regenerative. This approach favors network reliability and resilience significantly. Indeed, in case one layer of connectivity faces interruptions, the other layers can serve as backup or alternative routes, ensuring uninterrupted communication. However, the heightened complexity involved in managing and coordinating the network may be a significant concern. Integrating and synchronizing different layers of connectivity necessitates sophisticated algorithms and protocols to optimize resource allocation effectively.
These features can introduce the opportunity to operate autonomous rescue and emergency vehicles in remote locations without any telecommunications infrastructure. Additionally, not using UAVs and introducing higher intelligence and autonomy into the satellite may reduce delays that can occur during the relaying process. Nonetheless, this setup also leads to an increase in the payload design's complexity. Such a scenario proposes a real challenging and innovating breakthrough, by hosting the whole network (gNB and CU) onboard the satellite, so offering the opportunity to ITA NTN to completely skip the ground segment of the network. Not to say of the opportunity offered by the Local Break-Out of data plane traffic, allowing direct delivery of IP services at the network's edge and the Software Defined Network (SDN) and Network Function Virtualization (NFV) opportunities. Of course, an extra effort is required to really implement a similar scenario.

Concerning transmission techniques, links could be implemented also in terms of Optical Wireless Communication (OWC) link, as far as it is concerned with the first step of the Uu interface between the UE and the gNB-DU, that is the UE-UAV (or the HAP) link, so that also cyber-security issues can be successfully faced, provided a certain level of transmission performance, in terms of throughput (100 Mbs to say at least), Bit Error Rate and reduced signal latency for "mean" Line of Sight distances, is at hand.

Anyway we should be flexible when defining restrictions. Not to be overlooked the second step of the Uu interface between the UE and the gNB-DU (onboard the satellite), that is the UAV (or the HAP)-gNB-DU link which could be implemented in terms of a RF link, that is a THz, or a mmWave communication (to be deeply investigated concerning their practical aspects), or equivalently a sub-6 GHz communication. So the 3D T/NT network architecture, thanks to ITA NTN challenges, could be a real innovative unified radio access network, also thanks to new transmission techniques at physical and data-link layers exploiting the OWC pillar. At the same time, innovation shall be pursued without losing sight of the North Star of reliability and of performance for the same communication.

VI. Security Aspects of T/NT Networks

To integrate 5G and NT networks, the Third Generation Partnership Project (3GPP) launched a Release 15 study [11] on channel models and deployment scenarios, followed up with a Release 16 study [13] on solutions for adapting 5G NR to support NTNs and a Release 17 report, addressing architecture issues for using satellite access in 5G, [14]. Also, ITU-R describes key elements for the integration of satellite systems into next generation access technology [15]. However, in standardization activities security issues for integrated T/NT communication networks have not yet been addressed in a structured way, even if a growing attention is animating the technical-scientific community of the sector. In most cases, security issues relate to limited segments of the integrated T/NT network. To meet security requirements of confidentiality, integrity and availability, security challenges traditionally embodied for each technology separately are not sufficient, but it is necessary to consider security concerns and complexity, arising from their interoperability and integration. In fact, a specific security feature in a segment may not allow to adopt similar security measures and approaches when implemented in other segments. It is noteworthy that 5G and NT networks, both individually and integrated, are complex and strategic infrastructures also supporting other strategic and critical infrastructures or supporting critical services. Therefore, identifying the security peculiarities of spatial and terrestrial networks is relevant to their integration.

Without any ambition to be exhaustive, main challenges to be considered impacting the security of integrated T/NT systems refer to:

- Open network environment: satellite networks operate in space orbit of hundreds to thousands of kilometres that make them vulnerable not only to adverse natural conditions (e.g. solar flares, coronal mass ejections, unfavourable weather conditions etc.), but also to kinetic attacks, which can damage or destroy satellites and other space-based system. Moreover, due to link openness, malicious attacks, as jamming, eavesdropping, hijacking, and spoofing, can occur at different layers, so that space ground communication can be interfered or interrupted.

- Resource constraints: the evolution towards reduced-in-size satellites sets limitations in terms of storage, power, and processing capability. This restricts the ability to implement security measures, such as strong cryptographic techniques, firewalls and IDPS, that require significant resources. It is to highlight that broadcast communication need strong encryption. Moreover, the emergence of edge and multiaccess edge computing requires higher computing resources and security techniques for ground station, particularly challenging for on board satellite gNB.

- Long Distance: Non-terrestrial networks span long distances, which makes it challenging to detect and respond to cyber-attacks in real-time. The time delay between the transmission and reception of signals, together with noisy channels and asymmetric band channel, can also impact the effectiveness of secure transmission control measures usually adopted in terrestrial networks (e.g., TCP based).

- Dynamic network topology: the mobility of satellite network nodes, joining or leaving the integrated network, can change the network topology, leading to the need of an update of authentication policy and renegotiation of IPsec / TLS tunnel.

- Key management: cryptographic key management is a vital part of any security system dealing with data encryption, user/node authentication and used in communication and security protocols. The mobility and different altitude of GEO, LEO and HAPS nodes, wide coverage and long propagation delays, dynamic topology, relatively high BER, and resource constraints, make it not simple to implement a key management solution. Different key management schemes (e.g., centralized, distributed, identity-based, topology based, hierarchical based, preconfigured key based etc.) have been proposed, but each of them has its own advantages and specific objectives, so further investigations are still required.

- Handover management: due to the long latency and the rapid change in the relative positions among different layers of satellites, HAPS, and ground terminals and long latency, handover occurs frequently and signaling information might be eavesdropped, falsified, or fabricated.

- Programmability enabled by Software defined Networking (SDN) and Network function Virtualization (NFV): the SDN-NFV programmability is present not only in 5G core networks and in radio access networks, as proposed in ORAN, but also satellite networks are evolving in this direction (i.e., software defined payload). These technologies provide many benefits in terms of flexibility and scalability, but on the other hand can expose networks to injections of malicious software and allow privileges to application avoiding security control, if not securely protected.

- Complexity: T/NT networks are complex and involve multiple many different components, constraints and features, service characteristics requiring different security measure and technologies. This complexity makes it challenging to implement and manage cybersecurity measures across the entire integrated network.

Schematically, threats affecting T/NT networks can be referred as physical, operational or network threats. Physical threats include natural disasters, environmental disturbances, kinetics attacks, other cybersecurity attacks, as Denial of Services, eavesdropping, spoofing, jamming, data interception and interference. Malware and unauthorized accesses and use of network resources can lead to operational threats by, as an example, hijacking channel information, and even launching other attacks. Networks threats refer to unsecure transmission control and routing, unsecure handover, and key management. Finally, data leakage, interception and unauthorized use achieved by physical, network or operational attacks can exasperate security concerns. Some security countermeasures have been proposed in the literature. For example, at physical layer, multi beam satellite secure communication, directional antennas and spread spectrum techniques can help to resist against jamming attacks, even if resource constraints in terms of bandwidth, power consumption and processing can limit their practical applications. Authentication of terminals and network node is a key security requirement to prevent unauthorized access or illegitimate network function or transmission node embodiment by attackers. The 3GPP has developed a unified authentication framework for mutual authentication of terminals and service networks that can be adopted also for integrated T/NT networks. However, new alternative light-weighted authentication solutions should be considered when resource constraints and dynamic change in network topology in not terrestrial networks make it authentication more challenging. Secure transport protocols and routing for non-Terrestrial networks are investigated in literature, but most of them are derived from TCP adopted in terrestrial networks and effective solution of T/NT are still an open issue. Even for secure non link handover many solutions have been proposed, as new seamless handover scheme based on the predictability of satellite orbits, limiting service interruption due to periodic disconnection of satellite links, or other solutions based on adaptive handover for LEO satellite. At the current time, proposed solutions still require more effort to achieve practical applications in T/NT networks. In reference [15, 16], a taxonomy of threats is shown and schematically described with technical details and a comprehensive survey on attacks methodologies and proposed countermeasures for different layers of T/NT are reported.

Lastly, it is noteworthy to report an interesting strand of research in securing the T/NT networks relying on quantum technologies, aiming at playing a relevant role for physical security and cybersecurity schemes resistant also to quantum computing attacks. Basically, there are two approaches for quantum resistant T/NT communication networks: the first approach deals with quantum cryptography algorithms, which can be adopted whenever encryption algorithms are needed and when resource constraints allow their adoption. The second approach relates to Quantum Key Distribution (QKD) [18, 19], providing a way of distributing and sharing secrete keys for cryptographic protocols. It has to be highlighted that QKD over satellite networks can even overcame the limitation of QKD in terrestrial optical networks. The range of QKD in terrestrial optical fiber channel is limited to a few hundred kilometers, at least up to quantum repeaters become a viable realistic solution for overcoming fiber channel loss. After the launch of LEO Micius satellite, a series of key milestones for the space-scale quantum science experiments have been achieved among which the demonstration of QKD a satellite-to-ground-station distance of up to 1200 km and the first demonstration of intercontinental QKD among multiple ground station located in China and Austria, with a maximal separation of 7600 km [20]. Many other satellite based QKD satellite projects and extensive research studies also combining the use of commercial fiber optics with that of dedicated satellites are being implemented, or in the planning stages. The European Commission, including all EU Member State and the European Space Agency (ESA) is active to develop the European Quantum Communication Infrastructure (EuroQCI), which will be composed of a terrestrial segment relying on fiber communications networks linking strategic sites at national and cross-border level, and a space segment based on satellites, paving the way for the EU space-based secure communication system, [21]. In Italy the research conducted jointly between the University of Padua, and the Matera Laser Ranging Observatory (MLRO) of the Italian Space Agency (ASI), has demonstrated in 2015, [20], the exchange of qubits (based on the polarization of photons) between a ground station (the ASI telescope in Matera) and five satellites and, hence, the possibility of QKD, witnessing and encouraging future for security issues based on the advantages of a synergy of terrestrial and space networks.

VII. Conclusions

The ITA NTN project will contribute to the design and analysis of future 6G integrated T/NT networks. The research activities performed to this aim should have a strong impact for the advancement of knowledge of wireless networks, ensuring seamless connectivity, network resilience, reliable connections of mobile users and increasing the throughput under difficult propagation conditions. Moreover, the use of an integrated T/NT system will allow access to greater connectivity in areas where terrestrial networks are not available or have limited capacity, so it will have an impact on the digital divide and on digital transition, and will contribute to a more digital, green, sustainable, and resilient future. Particular attentions have to be considered for security aspects.

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