Review article

Multi-layer NTN architectures toward 6G: The ITA-NTN view

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ABSTRACT

This paper describes the integration of Terrestrial and Non-Terrestrial Networks, wherein space-based network entities collaborate with traditional and emerging terrestrial communication frameworks to furnish pervasive, resilient, and three-dimensional wireless connectivity worldwide toward the 6th Generation of communication networks. This integration supports heterogeneous services, such as enhancing coverage, user experience, system capacity, service reliability, and availability, while also providing high-speed connectivity in remote or disaster-affected areas, improving existing 5th Generation technologies. Various Use Cases are detailed, highlighting the pivotal roles that Non-Terrestrial Networks play in distinguishing between urban/suburban and rural environments, with particular emphasis on transportation ecosystems. Through this analysis, Key Performance Indicators and requirements are delineated to characterize the requisite service quality for these diverse Use Cases. The paper further presents an overview of potential and standards-compliant integrated Terrestrial/Non-Terrestrial architectures, delineating their roles both in backhauling and access across different layers of Non-Terrestrial systems and elements. These insights are derived from studies conducted within the Integrated Terrestrial And Non-Terrestrial Networks (ITA-NTN) project, part of the European Union initiative defined as the Italian National Recovery and Resilience Plan (NRRP) RESTART Research Program.

Contents

1. Introduction

5th Generation (5G) technology has been a revolution in the telecommunication field since has given enormous advantages in several vertical sectors [1]. However, some aspects require further improvements and changes that are at the base of 6th Generation (6G) technology, which will try to support better ubiquitous coverage and massive-capacity global connectivity [2,3]. In particular, to overcome the coverage limitations of 5G, 6G technology will explore NTNs. NTNs can help in dynamically offloading traffic from TNs components and also in reaching unserved areas. Thus, Non-Terrestrial stations such as drones or Unmanned Aerial Vehicles (UAVs), High-Altitude Platform Systems (HAPSs), and satellites are likely to complement TNs [4]. While 5G optimizes terrestrial network design to allow the integration of satellites for coverage and availability extension, 6G will introduce new technologies and capabilities and optimize network design, implementation, and operations considering the characteristics of terrestrial and satellite communications to create unified and integrated networks.

1.1. Motivation of the work: Project vision

Even areas already equipped with telecommunication infrastructures, like motorways or railways, may encounter unexpected surges in demand or require services not initially anticipated, especially in dynamic scenarios like those in the automotive industry. This underscores the growing necessity for mobile telecommunication infrastructures capable of adaptively deploying where needed, particularly during disaster recovery or emergencies [5]. In this context, NTNs are emerging as vital solutions, distinct from TNs by utilizing antennas mounted on structures not limited to the mainland.

A pivotal challenge in the forthcoming years is the integration of TNs and NTNs, which represents a fundamental pillar also in the evolution toward 6G, building upon the initial strides made in 5G systems [4]. NTNs encompass aerial devices like drones and High-Altitude Platforms (HAPs) and satellites, i.e., Geostationary Earth Orbit (GEO), Medium Earth Orbit (MEO), or Low Earth Orbit (LEO). The spaceborne and airborne network nodes collaborate with terrestrial architectures to deliver ubiquitous, resilient, and 3D wireless connectivity around the world. In fact, this synergy supports various communication paradigms like enhanced Mobile BroadBand (eMBB), Ultra-Reliable Low Latency Communications (URLLC), and massive Machine-Type

Communications (mMTC), enhancing coverage, user experience, and environmental sustainability across diverse sectors, notably transportation, public safety, and high-speed connectivity in remote sites or disaster-affected areas [5–7]. Specifically, eMBB aims to enhance the speed, capacity, and coverage of mobile broadband networks, URLLC prioritizes low latency and high reliability for real-time communication in critical applications, and mMTC focuses on providing connectivity for billions of devices with diverse requirements, including low power consumption and low data rate transmission [5]. The interplay between TNs and NTNs supports higher data rates and guarantees a large service availability, reliability, and lower latency values [5], by offering diverse architectural possibilities, which vary in roles such as backhaul or access nodes. Managing such a dynamic network poses challenges, necessitating advanced solutions like Software-Defined Networking (SDN), Network Function Virtualization (NFV), and Open Radio Access Network (ORAN) approaches [8]. SDN and NFV are key technology enablers for 5G and Beyond 5G networks, representing the paradigms that make networks programmable and virtualize classical network functions, respectively [9]. The new ORAN paradigm promotes virtualized RANs with disaggregated and interoperable components, which are connected via open interfaces and optimized by intelligent controllers [10].

The aim of this contribution is to report a review of the main Use Cases of the ITA-NTN project, with the Key Performance Indicator (KPI) and requirements and all the possible architectures combining TN and NTN elements in the framework of the RESTART Program. The paper is structured as follows. After this introduction, Section 2 describes the main network elements characterizing TN and NTN. Section 3 reviews the Use Cases of interest in the ITA-NTN view. Then, KPI and requirements are highlighted in Section 4, while in Section 5 all the possible architectures for integrated TN and NTN are described and analyzed. Finally, Section 7 concludes the paper and draws future research directions.

For readers' convenience, the list of the employed acronyms is reported herein.

2. Network elements

The architectures of NTN are designed to provide communications on a global scale or in specific scenarios, relying on many different network elements. In what follows the network elements that typically constitute a Non-Terrestrial system are reviewed.

List of acronyms

3D	3-dimensional
3GPP	3rd Generation Partnership Project
5G	5th Generation
5GC	5G Core Network
6G	6th Generation
AI	Artificial Intelligence
AMF	Access and Mobility Management Function
AR	Augmented Reality
BS	Base Station
CP	Control Plane
CU	Centralized Unit
DC	Dual-Connectivity
DU	Distributed Unit
eMBB	enhanced Mobile BroadBand
eMTC	enhanced Machine-Type Communication
GEO	Geostationary Earth Orbit
gNB	gNodeB
GPS	Global Positioning System
GU	Ground User
GW	Gateway
HAP	High-Altitude Platform
HAPS	High-Altitude Platform System
HARQ	Hybrid Automatic Repeat reQuest
HF	High Frequency
IAB	Integrated Access and Backhaul
IoRT	Internet of Remote Things
IoT	Internet of Things
ISL	Inter-Satellite Link
ITA-NTN	Integrated Terrestrial And Non-Terrestrial Networks
KPI	Key Performance Indicator
KVI	Key Value Indicator
LEO	Low Earth Orbit
LoS	Line-of-Sight
LTE-M	Long Term Evolution for Machine-Type Communication
MC	Multi-Connectivity
MEO	Medium Earth Orbit
MF	Medium Frequency
MIMO	Multiple-Input Multiple-Output
mMTC	massive Machine-Type Communications
MR	Multi-Radio
N3IWF	Non-3GPP Inter-Working Function
NAS	Non-Access-Stratum
NB-IoT	NarrowBand Internet of Things
NFV	Network Function Virtualization
NG	Next Generation
NG-U	Next Generation User Plane interface
NR	New Radio
NTN	Non-Terrestrial Network
ORAN	Open Radio Access Network
PDU	Protocol Data Unit
QoS	Quality of Service
R&D	Research and Development
RAN	Radio Access Network
RF	Radio-Frequency
RLC	Radio Link Control
RT	RadioTelephony
SCG	Secondary Cell Group
SDAP	Service Data Adaptation Protocol
SDG	Sustainable Development Goal
SDN	Software-Defined Networking
SMF	Session Management Function
SRI	Satellite Radio Interface
TN	Terrestrial Network
UAV	Unmanned Aerial Vehicle
UC	Use Case
UE	User Equipment
UP	User Plane
UPF	User Plane Function
URLLC	Ultra-Reliable Low Latency Communications
VHF	Very High Frequency
VSAT	Very Small Aperture Terminal
WSAN	Wireless Sensor and Actuator Network

2.1. Ground user — User equipment

End-users are usually called Ground Users (GUs) or, more in general, especially in the context of 5G networks, User Equipments (UEs). UEs refer to devices on the ground that require wireless connectivity or communication services, such as smartphones, laptops, Internet of Things (IoT) devices, or even drones. Similarly, GUs denote those terminals that typically have zero altitude, at least with respect to the other entities of the 3D network. In general, these devices are characterized by constrained energy, which in turn leads to limited network resources and computational capabilities. In the framework of 3rd Generation Partnership Project (3GPP) NTNs there are two categories of UEs [11]: (i) Very Small Aperture Terminal (VSAT), which are allowed to operate in Frequency Range 2 (FR2, i.e., above 10 GHz, typically Ka-band) and are equipped with a parabolic antenna with 60 cm diameter; and (ii) handheld terminals, equipped with omni-directional antennas (there are two radiating elements providing a 3 dB gain to compensate the depolarization loss on the NTN link) and are allowed to operate in Frequency Range 1 (FR1, i.e., below 6 GHz in S-band). It is worthwhile highlighting that currently frozen 3GPP NTN specifications (Rel-17) only allow S-band operations for handheld terminals; the specification of FR2 systems for VSAT receivers is on-going in Rel-18.

2.2. Base station — gNB

The gNB is responsible for transmitting and receiving wireless signals, managing radio resources, and facilitating data transfer between user devices and the core network. It employs advanced technologies, such as massive Multiple-Input Multiple-Output (MIMO) and beamforming, to enhance network capacity, coverage, and data rates. In the context of this architecture, the gNB serves also as the command and control center for the drone-based relay network. It can also integrate with other network management systems to optimize the overall network performance.

2.3. UAV — Drone

UAVs, also known as drones, play a crucial role in NTNs by acting as airborne relays or nodes for communication networks. UAVs can be equipped with communication payloads, thus acting as flying Base Stations (BSs) or relays, transmitting and receiving data between GUs

Fig. 1. The UCs of interest for the ITA-NTN project.

and the gNB. They can also establish connectivity between ground-based and satellite networks, fill coverage gaps, and enable seamless communication in challenging or inaccessible environments. UAVs can facilitate data transmission, support emergency response operations, and provide connectivity for remote sensing or monitoring systems. Their mobility, flexibility, and ability to quickly deploy in remote areas make UAVs valuable assets in establishing and maintaining reliable communication.

2.4. HAP

HAPs, also known as stratospheric platforms, refer to special un-manned systems floating in the stratosphere at altitudes ranging from 20 km to 50 km. These platforms can be also equipped with propulsion systems, such as electric motors or jet engines, thus allowing them to move to different locations. This capability also allows them to be deployed and redeployed as needed, providing coverage to specific areas or addressing changing communication demands. Indeed, lever-aging their high-altitude positions, HAPs can offer wide coverage and great Line-of-Sight (LoS) and enable reliable communication links in previously inaccessible regions. Moreover, such platforms can establish wireless links with terrestrial networks, other HAPs, or satellites.

2.5. Satellite

Satellites are deployed in orbit around the Earth and act as relay nodes or gNBs. They are equipped with transponders, antennas, and other communication systems to receive signals from the ground BSs or UEs and transmit them to other ground terminals. Satellites can be categorized into different types:

- GEO satellites are positioned at a fixed location in the geosta-tionary orbit, approximately 35 786 km above the ground on the equatorial plane and rotate at the same speed as the Earth's rotation, allowing them to remain stationary relative to a specific location on the Earth's surface. They provide continuous coverage over a large geographic area, making them ideal for applica-tions such as television broadcasting, telecommunications, and weather monitoring. However, the high altitude of GEO satellites introduces higher latency due to the longer signal travel time;
- LEO satellites orbit the Earth at lower altitudes, typically be-tween a few hundred to 2000 km above the Earth's surface. LEO satellites move at high speeds relative to the Earth and complete orbits in a relatively short time. This orbital configuration enables lower latency communication and supports various applications such as broadband internet access, Earth observation, and Global Positioning System (GPS).
- MEO satellites operate at altitudes between those of GEO and LEO satellites, typically around 8000 to 20 000 km above the Earth's surface. MEO satellites offer a balance between the coverage area of GEO satellites and the lower latency of LEO satellites. They are commonly used for applications such as navigation systems.

3. Use cases and applications

The goal of this section is to provide a description of the UCs of interest for the ITA-NTN project (see Fig. 1). In order to facilitate the definition of the communications and positioning requirements and the selection of possible 3D architectures, the considered UCs are classified in different categories which encompass specific applications that are described as well. It is worth outlining that the final selection should not only take into account traditional KPIs of communication systems but also KPIs measuring the "level" of sustainability of the proposed solution, as better explained in the following.

3.1. Urban/suburban areas

Thanks to their intrinsic ubiquity and broadcasting/multicasting capabilities, NTN, and in particular Satellite Communication networks, can play multiple roles in such scenarios, acting as RAN and as backhaul connection for remote 5G deployments. An NTN component that relies on HAPs and satellites component may be useful for:

- data offloading: users select a primary connection to send/receive data. The satellite network may provide an additional connection aimed at addressing traffic peaks and preserving the performance of specific sensitive flows.
- coverage: NTNs have the potential to significantly improve con-nectivity in areas that are traditionally difficult to cover, where deploying traditional terrestrial infrastructure is challenging and costly and offer benefits in terms of disaster recovery, rapid deployment, and scalability. Also, the backhauling could involve connecting the NTN technology to the central network infras-tructure on the ground, enabling data to be relayed between the Non-Terrestrial component and the core network.

3.2. Rural/remote areas

In the rural/remote scenarios, the considered applications are ori-ented to specific situations and to a reduced number of users that are likely to perform complex and risky operations. In particular, the following applications can be envisaged:

- Emergency operation management: in the aftermath of natural disasters, when terrestrial communication infrastructure might be damaged, Non-Terrestrial networks can be deployed to restore connectivity quickly. NTN can offer a resilient and quickly de-ployable communication solution to support relief efforts and coordinate emergency responses. The requirements for this UC, for example in terms of latency and reliability, must be the same of the ordinary services (Internet Connectivity, Transport system, IoT, Media Distribution, Agriculture, etc.).
- Interactive Aerial Telepresence: aerial telepresence becomes pow-erful when Augmented Reality (AR) is used which can offer 3D visuals and real-time tele-interaction with the environment. Such haptic guidance enhances UAV capability, opens up new applications and, perhaps most importantly, provides access to experts from anywhere at any time [2]. The communications ground-UAV are in LoS and the distance is 500 m–1 km.

3.3. Transport systems

As for the UC which is related to Transport systems, the main applications are identified in the following for the main fields, namely trains and cars (i.e., automotive field):

- Trains: Mobile networks represent a powerful instrument to simultaneously support railway operations and passengers' wireless connectivity but pose new challenges to the harmonization and efficient management of the available resources. Furthermore, due to some criticisms mainly related to coverage, bandwidth scarcity, and latency, the realization of smart railways may not always be achieved by resorting to pure terrestrial systems. So, the investigation of integrated Space–Air–Ground solutions has attracted particular attention since potentially tailored to address the problem of Quality of Service (QoS) diversification [12]. In the field of railways, it is possible to define different services and applications that can be related to pure transport activity, passengers' on-board activity, train facilities, and so forth. Rail communication performance is significantly influenced by the environment, which may be characterized by free-space, railway corridors in hilly terrain, tunnel/underground paths, forest areas, shunting yards, and so forth. Moreover, the variability of the scenario represents a further element to be taken into account when implementing solutions for meeting the requested QoS requirements. In this regard, the mainline scenario is considered as the most challenging one since voice, video, and data traffic must be handled with the train traveling at very high speed [13].
- Automotive: Vehicle Operations Management category encompasses UCs that deliver operational and management value to vehicle manufacturers, such as sensor monitoring, electronic control units (ECUs) software updates, and remote support. These three UCs do not require significant data rates and latency is not a critical factor, so a satellite network composed by GEO, MEO, or LEO would bring a significant advantage in remote areas where terrestrial networks are unable to provide sufficient service coverage . Moreover, the NTN ability to provide connectivity without the need for time-consuming deployment of terrestrial infrastructure across borders, and without incurring roaming costs, can further enhance the appeal.

3.4. Drone for delivery

The use of drones for delivery has gained significant attention in recent years due to their potential to revolutionize logistics. The communication between drones and control centers is fundamental to achieve such an objective, since it allows updates on parcel location, traffic conditions, and weather, resulting in faster and more efficient deliveries. Moreover, to enhance reliability and accuracy, drones have to access real-time mapping and geolocation data, thus optimizing their navigation paths to avoid obstacles and ensure accurate and safe deliveries. In addition, drones equipped with high-resolution cameras can transmit live video feeds, enhancing situational awareness, and thus allowing operators to monitor operations, identify potential hazards, and intervene if necessary, ensuring the safety of both the drones and the delivered parcels. The communication with the drones for delivery is beyond LoS and hence, they will occur through satellites or HAP. The involved distances are the ones from drone to HAP (around 20 km) and drone-satellite (around 600 km to 1000 km).

3.5. Internet of remote things

In Internet of Remote Things (IoRT), satellite communications provide a more cost-effective solution with respect to other terrestrial technologies to their interconnection and communication with the "the rest of the world". IoRT nodes are remote or they are dispersed over a wide geographical area or they are inaccessible.

There are two modes of interoperability between satellites and sensors/actuators: direct access and indirect access. The direct access mode allows sensors and actuators to directly communicate with the satellite, in uplink with the sensors and in downlink with the actuators. In the indirect access mode, each sensor and actuator in a Wireless Sensor and Actuator Network (WSAN) may communicate with the satellite through a sink node; therefore, the data flow between the satellite and the WSAN is bidirectional. The advantage of exploiting the indirect access is that a lower number of expensive satellite terminals is required for the same number of sensors/actuators. Furthermore, in the indirect access mode, the sink is provided with a satellite terminal (expensive and power-hungry) and with a WSAN radio interface, while all the other nodes of WSAN are only provided with a WSAN radio interface. This solution allows to decrease the system costs and the complexity of the installation (in terms of antenna pointing and power generation facilities). However, this approach has the typical drawbacks of a centralized solution with respect to a decentralized solution.

Smart Agriculture, Environmental and wildlife monitoring, and Disaster and Critical Infrastructure remote control are some of the possible applications that could be envisaged in this UC.

3.6. Maritime sector

A maritime networked system consists of interconnected assets making use of radio-based communications to interoperate. Their main goals can be identified in the following ones:

- Distress, Safety, Urgency, and Security Communications: the communications systems that can be exploited are Terrestrial communications in Very High Frequency (VHF), Medium Frequency (MF), and High Frequency (HF) (also) with Digital Selective Calling (DSC) capability and RadioTelephony (RT), Satellite communication systems using geostationary and non-geostationary satellites, Cospas-Sarsat satellite service for search and rescue based on emergency position-indicating radio beacons, i.e., Emergency Position Indicating Radio Beacons (EPIRBs), Maritime Safety Information (MSI) via NAVigational TEXt Messages (NAVTEX), Localization services based on radars and Automatic Identification System (AIS) transmitted via VHF;
- General Purpose Communications: in this second class, all other services are considered, notably those framed in the so-called e-Navigation concept. Although a rigid classification is not yet normative, maritime services include Vessel Traffic Services (VTS) information, Navigational assistance, Traffic organization, port support, pilotage, tug, vessel shore reporting, meteorological information, real-time hydrographic, and environmental information.

4. KPIs and service requirements

4.1. Functional KPIs

Here below is the list of functional KPIs that are relevant for communications in NTNs:

- End-to-end latency;
- Reliability;
- User Experience Data Rate;
- Speed limit;
- Payload Size;
- Availability;
- Area Traffic Density;
- Service area dimension.

The definition of those KPIs can be found in [12] and they are related to the specific end-to-end communications. However, it must be noted that the service will be provided by an integrated architecture,

which will involve several specific links (feeder link, Inter-Satellite Links (ISLs), inter-drone link, inter-HAP links, etc.). Therefore, in order to properly design each communication link, the communication requirements in terms of maximum data rate, reliability, and latency of each specific link have been identified.

4.2. Sustainable-related requirements

It is well recognized that space systems (for Earth Observation, navigation, and communications) will play a key role in attaining the Sustainable Development Goals (SDGs) defined under the Agenda 2030 for Sustainable Development by the United Nations (UN).[1] Moreover, the integration of NTNs with the TNs might open novel applications and services that could further improve the positive impact on the environmental sustainability. On the other hand, a new urgent challenge needs to be faced, as a consequence of the recent evolution of space systems, which has occurred in an uncontrolled and unregulated way, the issue of space sustainability. Nowadays space is extremely congested and soon it will no longer be a safe place to do business or support military operations. This crowded situation poses several challenges such as: 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. Several initiatives and projects are on-going to face the space sustainability challenge. Most of the initiatives are focused on mitigating the damages caused by the wild use of satellite orbits and an uncontrolled generation of space garbage. However, just mitigating the already-made damages will not guarantee long-term space sustainability and safe use of space. It is imperative to initiate the process of designing novel systems with "sustainability" as a foundational principle. The focus should be on the maximization of reuse potential within already deployed infrastructure for forthcoming missions. Additionally, it is essential to conceive novel infrastructures characterized by "interoperability" and flexibility, allowing for their utilization across diverse missions and facilitating seamless upcycling. Furthermore, optimizing the utilization of the 3D NTNs, encompassing the TNs as well, demands the formulation of appropriate architectural frameworks.

Therefore, any technical solution or architecture should be evaluated not only in terms of functional KPIs but also in terms of some other non-functional KPI that "measures" or assesses the level of:

- Environmental sustainability, and hence how the proposed solution contributed to some SDGs. Also, considerations on manufacturing, operational energy consumption, recycling practices, and end-of-life treatment must be done;
- Space Sustainability, and hence how able is the solution to reduce the number of satellite nodes and the probability of collisions (thus producing less further debris), decreasing the level of interference to other systems.

New performance metrics need to be defined, which may involve weighing a set of KPIs based on evolving trends in a specific 6G use case or application. For example, for sustainability, the novel metric should weight KPIs that might include: energy efficiency, which is relatively well-defined for communication, but not for positioning and sensing; capital (e.g., deployment) and operational expenses (e.g., power consumption of components or systems); capability to reuse the same infrastructure for future novel missions. An interesting work has been presented in [14], where the need for the definition of Key Value Indicators (KVIs) has been expressed. There, the authors describe the KVIs for 6G in the context of positioning and sensing, reveal their synergies and conflicts, and propose ways to quantify them (thus effectively turning them into new KPIs). However, much work still needs to be done especially to consider also the space sustainability. Nevertheless, ITA-NTN will make this effort to assess each proposed architecture and solution under the "light" of environmental and space sustainability.

5. Integrated T/NT architecture

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 NTN integration options has been made. In this process, configurations that are unfeasible, unsupported, or unlikely to be implemented have been excluded. The latter include scenarios such as utilizing different satellite communication systems for the fronthaul and backhaul, or placing the entire 5G Core Network (5GC) or a portion of it on-board without the RAN component. Such configurations lack practical viability and do not hold significant interest for implementation purposes. Besides, the chosen integration options demonstrate compatibility with 3GPP standards and are deemed relevant and feasible for further exploration and implementation in practical 5G networks.

With the advent of 3GPP Rel-17, significant progress has been made towards the consolidation of NTN New Radio (NR) support. While NTN architectures were initially introduced in Rel-16, Rel-17 builds upon this foundation by incorporating the findings and improvements derived from several study items focused on designing the necessary enhancements for satellite direct access. The most compelling use cases for NTN direct access, which have garnered attention from research projects and industry initiatives [11], revolve around LEO satellites and the widespread deployment of narrowband devices. Thus, a parallel standardization effort within Rel-17 has resulted in dedicated specifications tailored to IoT over NTN. These specifications are based on the legacy technologies of NarrowBand Internet of Things (NB-IoT), Long Term Evolution for Machine-Type Communication (LTE-M), and enhanced Machine-Type Communication (eMTC), with appropriate enhancements to address the unique requirements of NTN. Specifically, the utilization of NB-IoT satellite UCs offers notable advantages, including cost reduction, accelerated infrastructure deployment, and mitigation of latency-related challenges. By incorporating the outcomes of research projects and industry initiatives, combined with the parallel standardization activities within 3GPP Rel-17, a comprehensive understanding of the benefits and opportunities presented by NB-IoT satellite UCs can be attained. These advancements have the potential to reshape IoT connectivity, providing a viable solution that overcomes traditional limitations and facilitates the widespread adoption of satellite-enabled NB-IoT deployments.

There are also architectural approaches where the UE remains unaware of the presence of NTN as the NR-Uu air interface is exclusively terrestrial. Consequently, NTN can serve as a substitute for one or more terrestrial physical links, whether for user plane data transfer, control plane data transfer, or both. However, integrating NTN into 5G networks is not a seamless or straightforward process, primarily due to two key reasons. Firstly, performance considerations play a crucial role. NTN may exhibit lower performance compared to traditional terrestrial backhaul technologies like fiber links. This disparity in performance can result in a subset of services being unavailable to the 5GC or the end-user devices, particularly in terms of very low latency requirements. The second reason pertains to operational challenges. Terrestrial and satellite network operators typically operate under distinct service models that require harmonization. Satellite operators have the option to adopt a Vertical Integrated Model, which grants them control over the entire business chain, spanning from infrastructure to service subscriptions. Alternatively, they can choose a Virtual Infrastructure Model, where their focus is primarily on managing the physical space infrastructure and Radio-Frequency (RF) building blocks. On the 5G operator's side, opting for the Vertical Integrated Model allows for a rapid integration process with limited control over satellite resources.
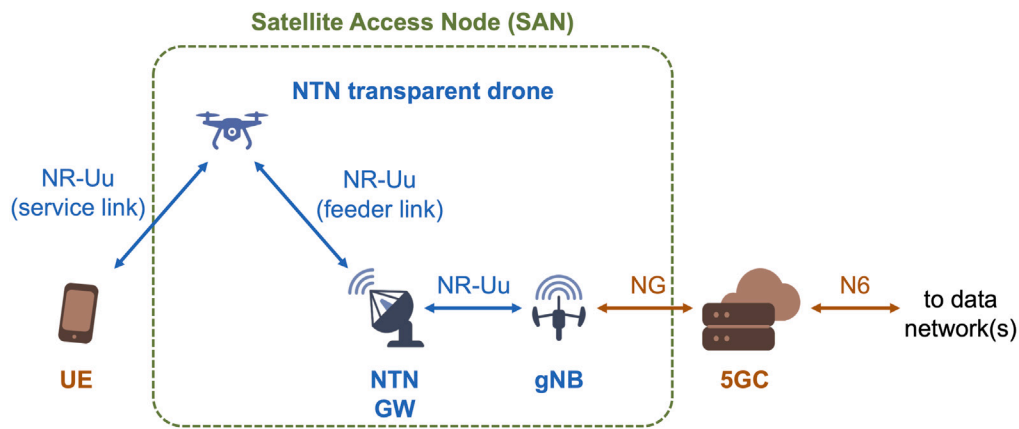

Fig. 2. NTN architecture with transparent drone and direct access.

Conversely, selecting the Virtual Infrastructure Model provides greater flexibility, albeit at the expense of more intricate procurement and custom configuration of the satellite technology.

In 3GPP Rel-15, provisions are made for Non-3GPP access to the 5GC by excluding the RAN portion and utilizing alternative access methods. This is accomplished through the Non-3GPP Inter-Working Function (N3IWF) component. One example of Non-3GPP access can be Wi-Fi (IEEE 802.11), as the majority of UE is equipped with both 3GPP NR-Uu and Wi-Fi interfaces. The role of the N3IWF is to adapt the access and authentication protocols of the Non-3GPP section to align with the 5GC. The term "untrusted" implies that the Non-3GPP access is assumed to be managed by a different operator than the 5G networks, such as an airport hotspot or a home Wi-Fi router. Consequently, an end-to-end security association between the UE and N3IWF must be established, and this security association is represented by the NWu reference point, which utilizes IPSec tunnels. The responsibility of managing this security association lies directly with the 5GC Network Operator. Once the procedures for Non-3GPP access are successfully completed, the UE has the flexibility to enable NR-Uu access via a gNB simultaneously or use Non-3GPP access as the sole method of connectivity. This allows for seamless integration of multiple access methods and provides users with options based on their specific needs and available network resources.

All the aforementioned architectural integrations need to be able to fit under specific UCs, as pros and cons emerge from them. According to the role of each layer of the 3D network, four different categories of architecture have been reviewed: Drone-based Relay Network, Satellite-based Architecture, 3D Single-Connectivity Architecture, and 3D Multi-Connectivity Architecture.

5.1. Drone-based relay network

The advancement of UAVs, commonly known as drones, has opened up new possibilities for various applications. One such application is the use of drone-based relay architectures, which have gained significant attention in the field of wireless communication networks. These leverage the mobility, flexibility, and reach of drones to extend wireless connectivity and bridge communication gaps, thus offering solutions for disaster response, remote sensing, and monitoring, among other domains. The architecture of a drone-based relay network typically consists of three main components: UEs/GUs, drones, and a ground control station, where the latter can be embedded in the gNB. Indeed, drones equipped with communication systems can act as flying base stations or relays, enabling communication between distant locations. By hovering at high altitudes, drones can cover a larger area and establish connections between UEs/GUs, providing Internet access and voice communication services. A fundamental aspect that characterizes the overall architecture is the possibility to implement transparent or

regenerative payloads on-board the drone. In the first case (i.e., transparent drone), the network node acts as a "transparent" entity, simply amplifying and forwarding the received data to their intended destination, i.e., the gNB. However, this inevitably affects the quality of the received information due to the noise sum of the involved paths. Moreover, this leads to the termination of all communication protocols at the gNB, leading to larger latencies in the end-to-end system. In the second case (i.e., regenerative drone), instead, the network node analyzes the incoming data, makes decisions based on that analysis, and then regenerates the signal before forwarding it to the gNB. The regenerative approach allows for various operations such as error correction, encryption/decryption, protocol conversion, traffic shaping, and QoS management. Moreover, it inherently mitigates the noise issue of the transparent approach. In this case, part or the entire gNB protocol stack can be implemented on-board, depending on the selected functional split option. This allows to reduce the latency in the end-to-end system, as for at least part of the protocols the termination is performed on-board, i.e., without the need to propagate the information through the feeder link. Notably, such a solution leads to an increased complexity and power consumption on-board, which shall be properly assessed on a case-by-case basis, i.e., depending on the specific service/mission of the NTN component. The reference architecture can be scaled up by increasing the number of UEs or UAVs in the same area covered by a single gNB. In both cases, it is necessary to take into account issues related to the orchestration of the radio and network resources, in order to mitigate or even avoid interference and packet collision.

Fig. 2 shows the high-level system architecture of the Non-Terrestrial component in which the connectivity to the users is provided through a drone equipped with a transparent payload. In this architecture, it is possible to highlight that the transparent payload, as previously discussed, only allows frequency conversion, filtering, and amplification, basically acting as an air-borne RF repeater forwarding the radio protocols received by the UEs to the gNB and vice versa. Furthermore, the gNB serving the on-ground UEs is conceptually located at the system GW. In order to be fully compliant and compatible with the 3GPP NTN standard, all CP/UP protocols are terminated at the on-ground gNB and, thus, the feeder and user links require the implementation of the NR-Uu Air Interface. Proper adaptations for the NR-Uu interface to operate on NTN links have been the main focus of NTN Rel-17 studies and agreements, as documented in the technical reports TR 38.821 and TR 38.811 [11,13]. Finally, in this context, it shall be mentioned that all adaptations were identified assuming LEO or GEO NTN payloads, which pose more challenging adjustments due to the longer slant path and larger Doppler shift for LEO compared to drone connectivity.

Fig. 3 illustrates the NTN architecture when the drone is equipped with a regenerative payload implementing the full gNB, i.e., no functional split option. In this case, all of the NR-Uu protocols are terminated on-board and, as such, only the user service link shall be
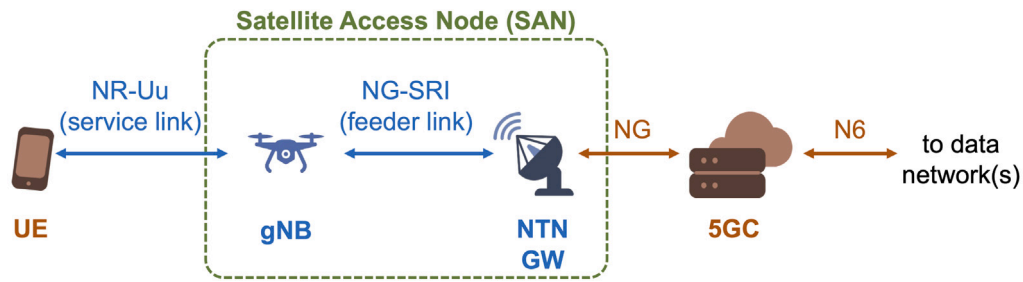
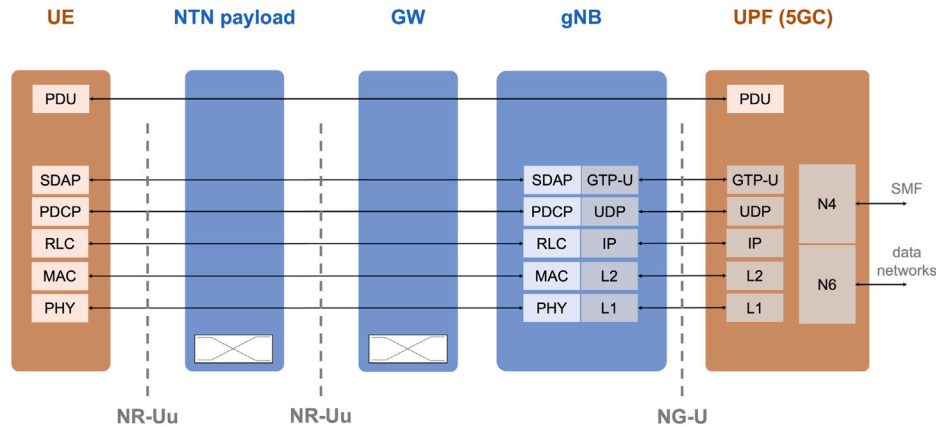**Fig. 3.** NTN architecture with regenerative drone (full gNB) and direct access.

Fig. 4. UP protocol stack of the NTN architecture with transparent payload and direct access.

implemented with this interface. In this scenario, the Gateway (GW) acts as a Transparent Network layer node, as it terminates all transport protocols and connects the gNB to the 5GC through the Next Generation (NG) Air Interface. This interface can be implemented on the feeder link by means of any Satellite Radio Interfaces (SRIs), i.e., a transport link as Digital Video Broadcasting-Satellite 2nd generation (DVB-S2) or S2 Extensions (DVB-S2X) [13].

5.1.1. Protocol stack for drone-based relay network

Figs. 4 and 5 show the UP and CP protocol stacks for the transparent drone case represented in Fig. 2. As already mentioned, it can be noted that the NTN payload is acting as a transparent RF repeater. Moreover:

- on the UP, the Protocol Data Unit (PDU) sessions and the QoS flows are established between the User Plane Function (UPF) in the 5GC and the UE. The latter are transported over Next Generation User Plane interface (NG-U) tunnels between the 5GC and the gNB and, then, over radio bearers from the gNB to the UE. The N4 and N6 reference points represent the conceptual location of the interaction of the UPF and the Session Management Function (SMF) with the data networks, respectively. The SMF manages the dedicated sessions created for the UEs in the UPF, based on information exchanges via the N4 point. Then, the UPF connects to any internal/external data network through the N6 point;

- on the CP, the Non-Access-Stratum (NAS) signaling between the Access and Mobility Management Function (AMF) and the UE is transparently transported through the gNB, GW, and payload. This type of signaling involves Session Management (NAS-SS) and the Mobility Management (NAS-MM) operations. In this case, N11 is the reference point for the connection between the AMF and the SMF. This point allows the two functions to establish, coordinate, and terminate the PDU session types. When a UE is requesting a new service, the NG Application Protocol (NG-AP) provides NAS information to the AMF, which then interconnects to the SMF via N11.

To support the NTN component, the NR-Uu protocols have been enhanced in Rel-17 with several fundamental features related to Timing Advance (TA), Random Access (RA), Hybrid Automatic Repeat reQuest (HARQ), mobility management, and handover, including the extension of several timers to cope with the larger latency in NTN scenarios.

Figs. 6 and 7 depict the UP and CP protocol stacks for the regenerative case shown in Fig. 3. With respect to the above-discussed transparent scenario, it shall be noticed that:

- all of the protocols up to the Service Data Adaptation Protocol (SDAP) and the Radio Resource Control for UP and CP, respectively, are terminated on-board, thus reducing the latency;
- the GW and the drone must implement the protocol stack of the SRI, that is used to transport the CP/UP on the feeder link, in particular the upper layers of the NG interface;
- the UE's PDUs are transported over GTP-U tunnels between the UPF and the drone (including also the feeder link) and over radio bearers between the drone and the UE (only including the service link);
- routing schemes and algorithms involve the GW and the drone as nodes to be exploited for efficient networking;
- the NG-AP protocol timers might need to be adapted to deal with the larger latencies on the feeder link.

5.2. Satellite-based architecture

Satellite-based architectures facilitate communications through satellites orbiting the Earth. These communication systems are designed for long-term operations, offering stable and continuous connectivity. However, satellite-based architectures face challenges such as signal latency due to the long distance between satellites and GUs, high initial deployment and maintenance costs, and susceptibility to atmospheric conditions. Differently from the previously discussed drone-based ar-
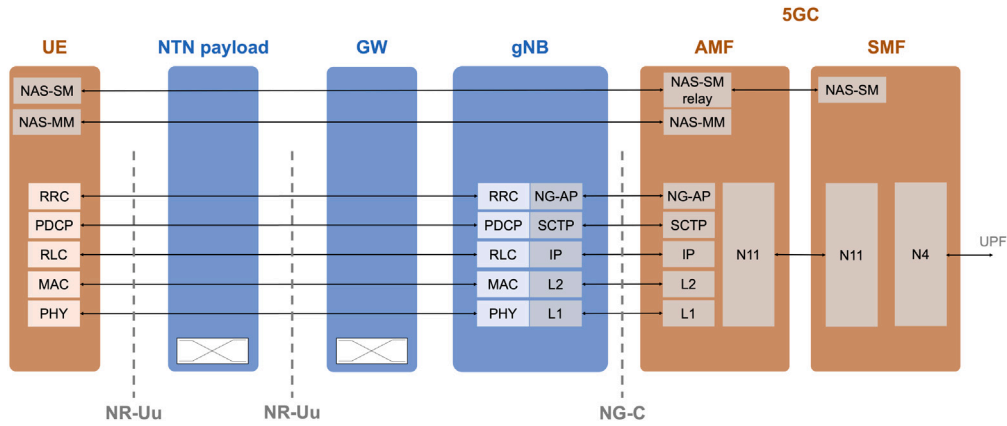
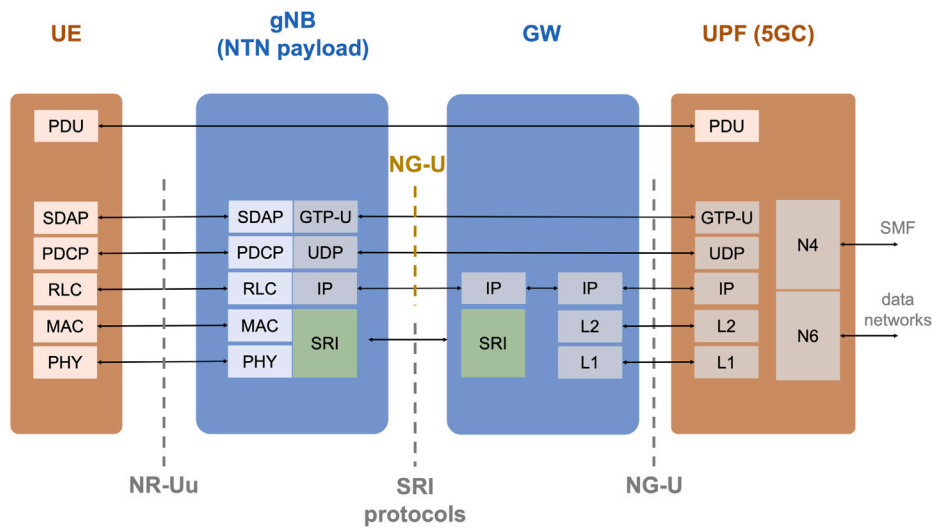**Fig. 5.** CP protocol stack of the NTN architecture with transparent payload and direct access.

Fig. 6. UP protocol stack of the NTN architecture with regenerative payload (full gNB) and direct access.
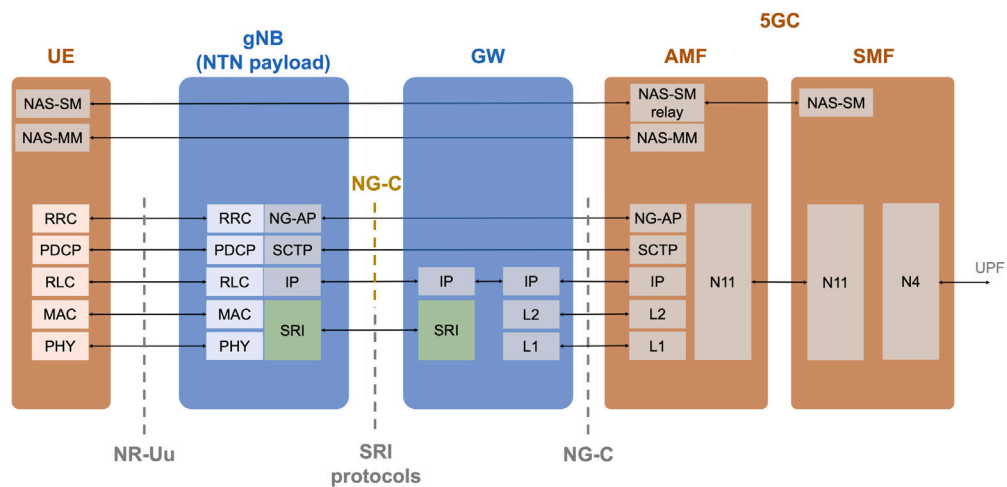

Fig. 7. CP protocol stack of the NTN architecture with regenerative payload (full gNB) and direct access.

chitecture, the satellite-based architecture provides ultra-wide coverage and is effective in connecting geographically dispersed areas, including remote or rural regions. It is important to note that both architectures have their unique advantages and limitations and their suitability depends on the specific UC and requirements. Two different configurations involving satellites can be identified: (i) *satellite-based access* (direct access in 3GPP terminology); and (ii) *satellite-based backhauling* (indirect access). Both configurations allow for connectivity to
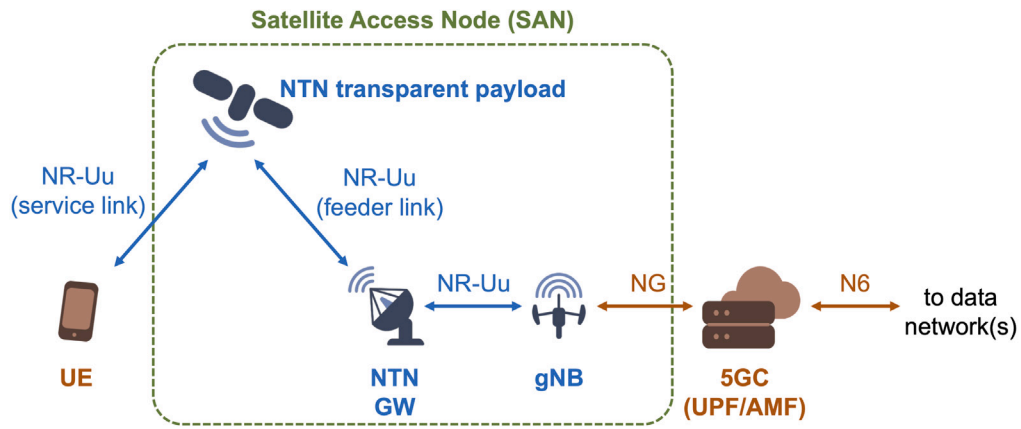
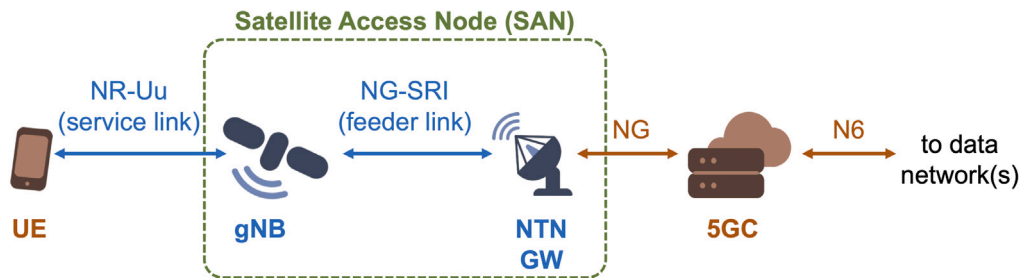**Fig. 8.** NTN architecture with transparent payload for satellite-based access.

Fig. 9. NTN architecture with regenerative payload for satellite-based access.
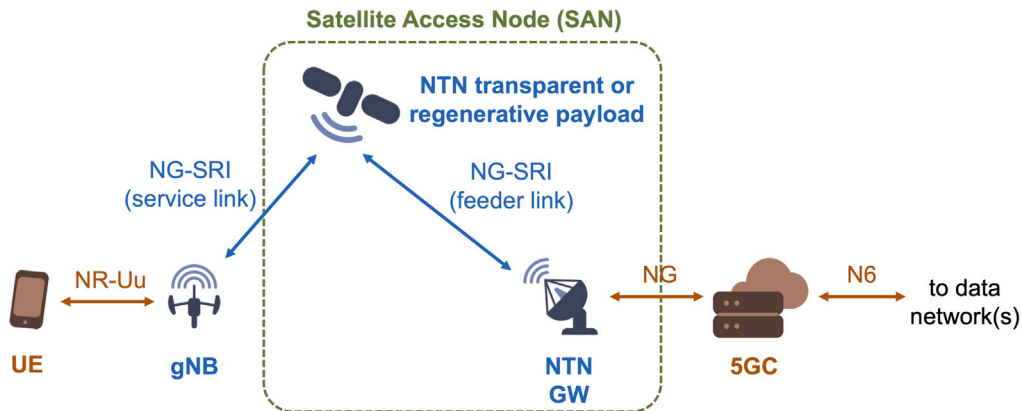

Fig. 10. NTN architecture with regenerative payload for satellite-based backhauling.

remote areas where laying terrestrial cables or establishing direct fiber connections is challenging or cost-prohibitive.

Satellite-based access, as depicted in Figs. 8 and 9 for transparent and regenerative payloads, respectively, refers to the use of satellites to provide direct connectivity to the end-user devices. In the regenerative payload case, a scenario with a full gNB on-board is shown. However, it shall be mentioned that functional split options are possible, with an on-board gNB-Distributed Unit (DU) and an on-ground gNB-Centralized Unit (CU). This scenario is equivalent to the drone-based relay access in terms of Air Interfaces, protocol stack, and signaling. The only difference is related to the user and feeder link channels since the latency and Doppler shifts are larger with space-borne payloads, and also the impact of other impairments (such as atmospheric losses and scintillations) can be more impactful.

Satellite-based backhauling involves satellites as a means to connect remote or underserved ground nodes to the core network infrastructure,

as depicted in Fig. 10. This solution is possible through the exploitation of IAB nodes [15,16].

IAB nodes were introduced in Rel-16 [15] to enable a flexible and scalable multi-hop solution in ultra-dense scenarios, while minimizing the impact on the 5GC [17,18]; the only limitation to the number of hops is given by the network capacity to support the backhaul links. The IAB architecture is based on the CU/DU split of the gNB. An IAB node includes a Mobile Terminal (MT) unit and a DU. The MT unit is connected to the DU of the parent node (i.e., IAB-Donor) as a normal UE [19]. Fig. 11 illustrates the hierarchical RAN structure in the case of IAB-based access. The IAB-Donor is acting as a regular gNB and it is connected via the NG Air Interface to the 5GC; the DU of each IAB-Donor or IAB-node can either provide backhaul connectivity to child IAB-nodes or indirect connectivity to the UEs. This solution allows to exploit a satellite backhaul without requiring adaptations to the UE capabilities, since the serving IAB-node is seen as a normal gNB by
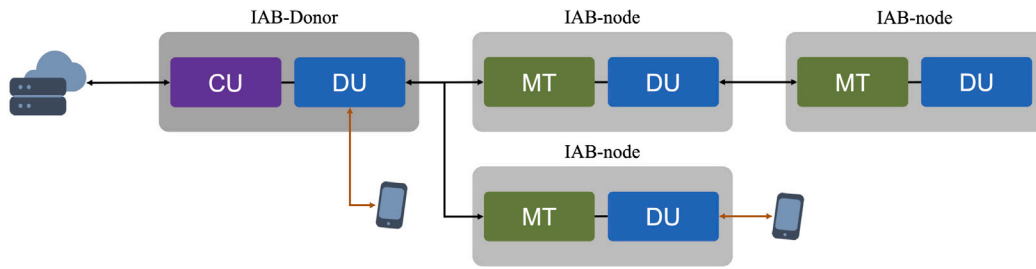
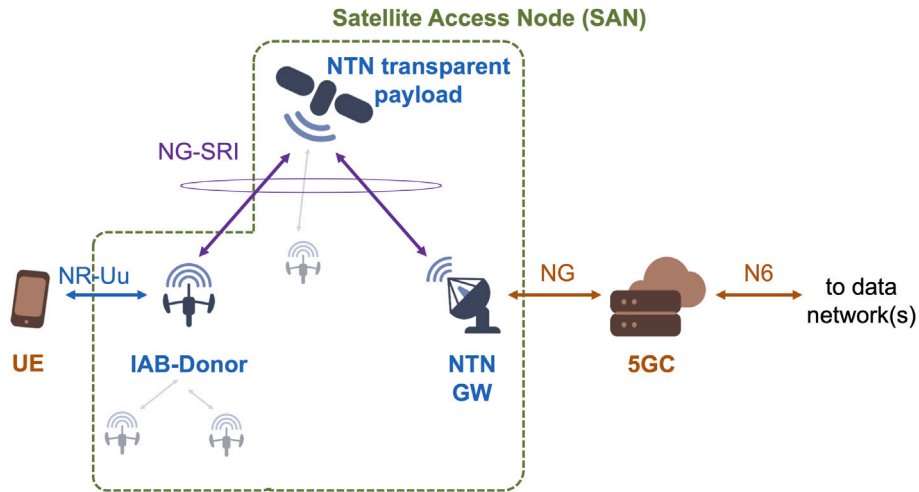**Fig. 11.** Hierarchical RAN structure based on IAB nodes.

Fig. 12. NTN architecture for indirect access with transparent payload: backhaul to the IAB-Donor.
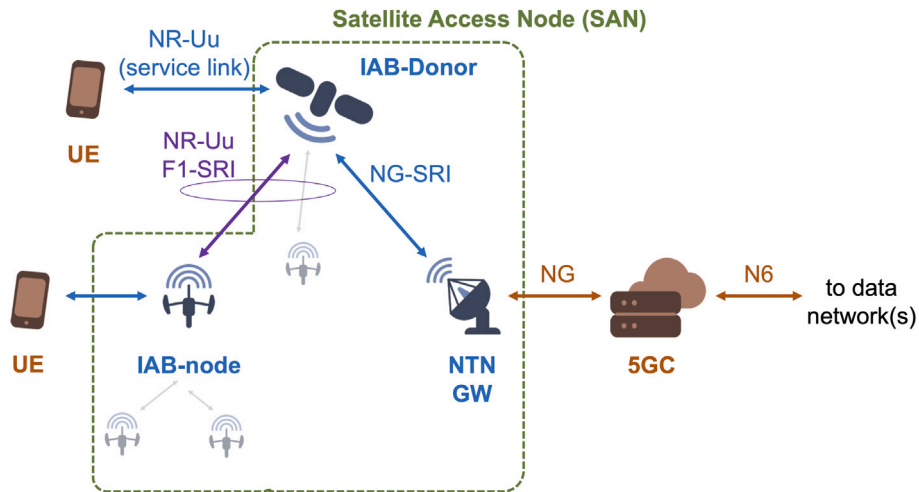

Fig. 13. NTN architecture for indirect access with regenerative payload: full IAB-Donor on-board.

the UE. The F1 interface supports the multi-hop backhaul structure between the IAB-node DUs and the IAB-Donor CUs.

The implementation of IAB nodes in the NTN segment has not yet been addressed by 3GPP and, thus, some considerations and observations based on the above discussions are reported. Fig. 12 shows a scenario for indirect access with a transparent payload that provides a backhaul link between an on-ground IAB-Donor and the 5GC. It can be noticed that the UE is served by a terrestrial IAB-Donor and, thus, through the NR-Uu Air Interface. The connection between the IAB-Donor and the 5GC is based on the NG Air Interface, with similar considerations as those reported above for other scenarios.

Fig. 13 shows the NTN architecture for indirect access with a regenerative payload, which allows to implement the IAB-Donor on-board. In this case, the feeder link still requires the support of the glsng Air Interface to connect the Donor and the 5GC. As for the user link towards the child IAB-nodes, there is the need to implement both the NR-Uu interface for lower layers and the open F1 Air Interface for upper layers, as requested by the IAB specifications in the above-mentioned 3GPP documents. One of the most interesting benefits to the system flexibility brought by the implementation of IAB-based access via NTN is that the NTN payload can both provide connectivity to the UEs and provide backhaul connectivity between the IAB-Donor and the IAB-nodes.
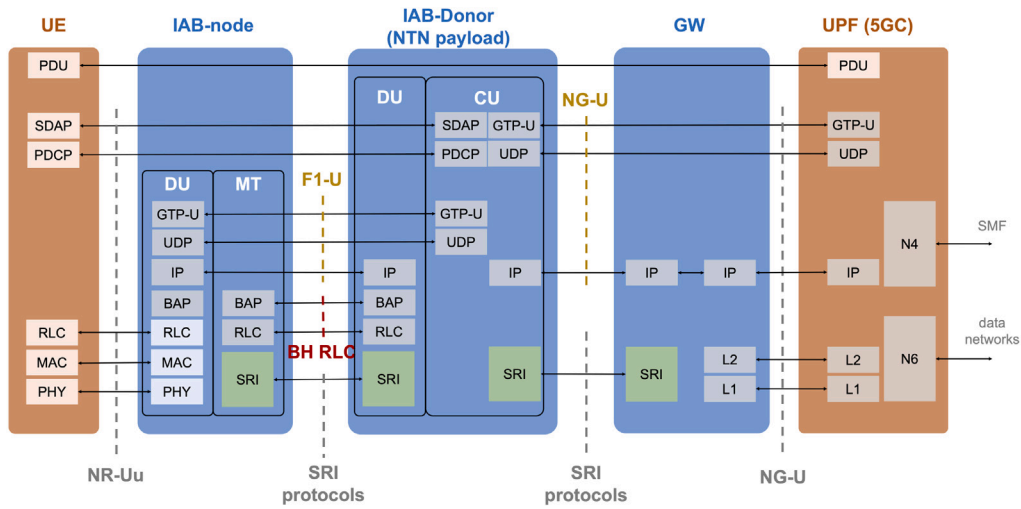
Fig. 14. UP protocol stack of the NTN architecture for indirect access with transparent payload: backhaul to the IAB-Donor.
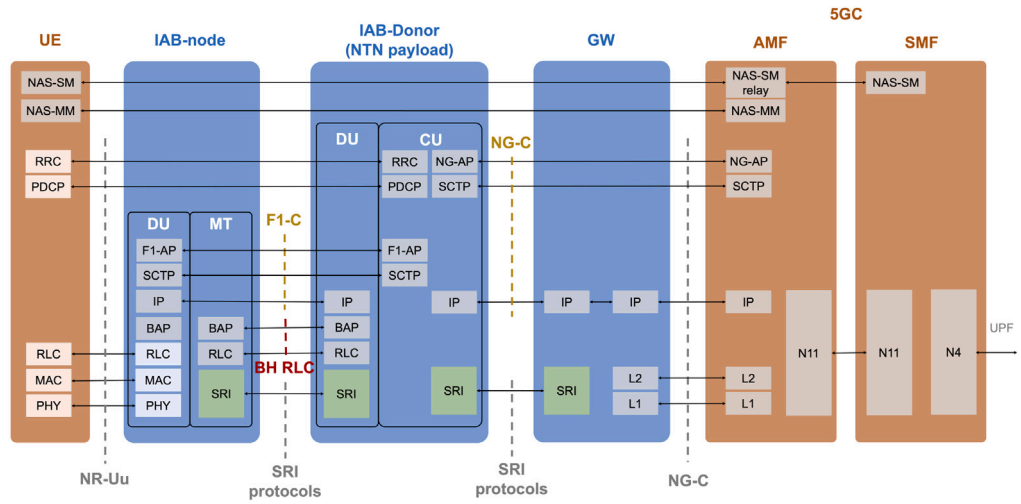

Fig. 15. CP protocol stack of the NTN architecture for indirect access with transparent payload: backhaul to the IAB-Donor.

5.2.1. Protocol stack for satellite-based architecture

Figs. 14 and 15 show the UP and CP protocol stacks for indirect access with a transparent payload, respectively. The case with transparent payload does not pose significant modifications compared to previous considerations, as it implies that the NG Air Interface shall be supported through SRI on the feeder link. When the IAB-Donor is fully implemented on-board, the NR-Uu Air Interface on the user link shall transport the backhaul (BH) Radio Link Control (RLC), which supports the RLC functionalities of the IAB structure. In particular, such a channel carries the Backhaul Adaptation Protocol (BAP) that enables efficient IP forwarding across the multi-hop topology. The BAP supports the F1 Air Interface and the related protocols on both the CP and the UP. When the NTN component is present, the SRIs shall support both the BAP and RLC communications between the IAB-Donor and the IAB-nodes on the user link and the NG interface on the feeder link. All of the layers and interfaces carried over SRI shall not be impacted by the NTN links. The only adjustments might be related to extending the timers in the procedures to accommodate the larger propagation delays.

5.3. 3D single-connectivity architecture

The 3D single-connectivity architecture combines all the entities of the previously described schemes, as depicted in Figs. 16, 17, 18, and 19.

Indeed, the UE can communicate with a low-altitude intermediary node, i.e., drone or HAP, which routes the traffic toward a satellite and hence the 5GC. As for the already discussed architectures, also in this case the Non-Terrestrial nodes can adopt a transparent or regenerative approach. This kind of architecture is particularly useful in emergency situations in which UEs do not have the necessary technology or capabilities to communicate directly with the satellite or the gNB. However, it comes with challenges related to technology integration, further complexity, and communication latency. Indeed, working with diverse technologies, such as classical cellular networks with NTNs, makes seamless interoperability an important challenge that requires standardized protocols across different systems. Additionally, single-connectivity architecture may be more susceptible to disruptions. If the single network experiences outages or congestion, it can lead to service interruptions for users.

5.3.1. Protocol stack 3D single-connectivity architecture

The CP/UP protocol stacks for the 3D Single-Connectivity scenarios can be easily inferred from the previous architectures. In particular:

- the fully transparent scenario is equivalent to the protocol stacks of the NTN architecture with transparent payload and direct access, shown in Figs. 4 and 5. The only difference is related to the presence of an intermediate transparent node between the
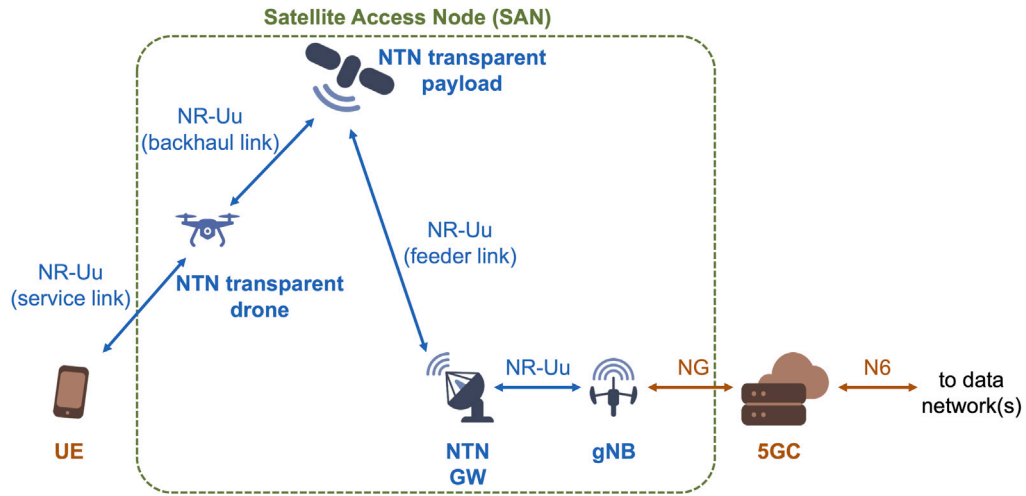
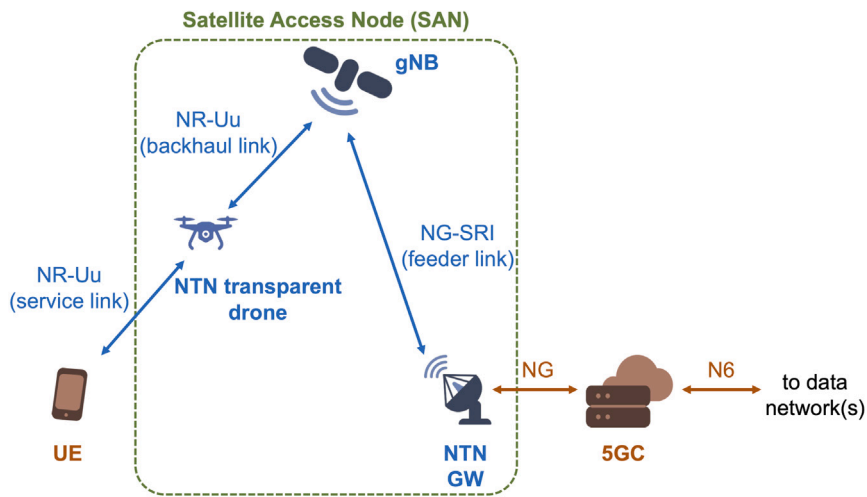**Fig. 16.** 3D single-connectivity: fully transparent option.

Fig. 17. 3D single-connectivity: regenerative satellite (full gNB) and transparent drone.
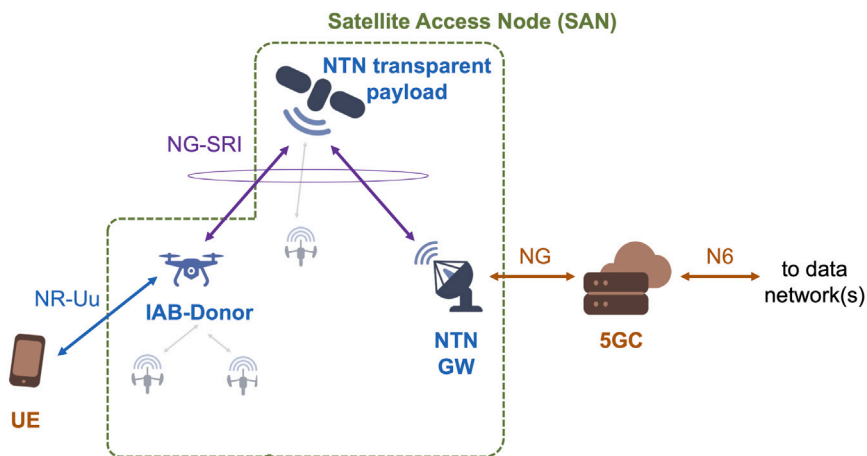

Fig. 18. 3D single-connectivity: transparent satellite and regenerative drone (full IAB-Donor).
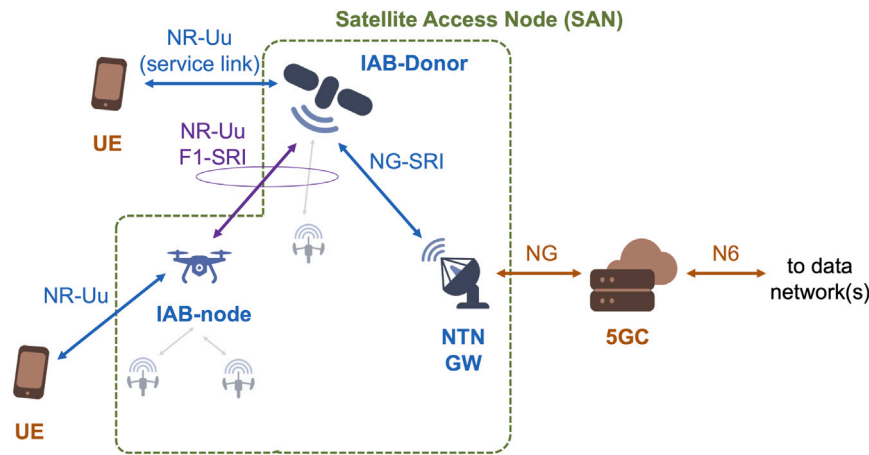
Fig. 19. 3D single-connectivity: regenerative satellite (full IAB-Donor) and regenerative drone (IAB-node).
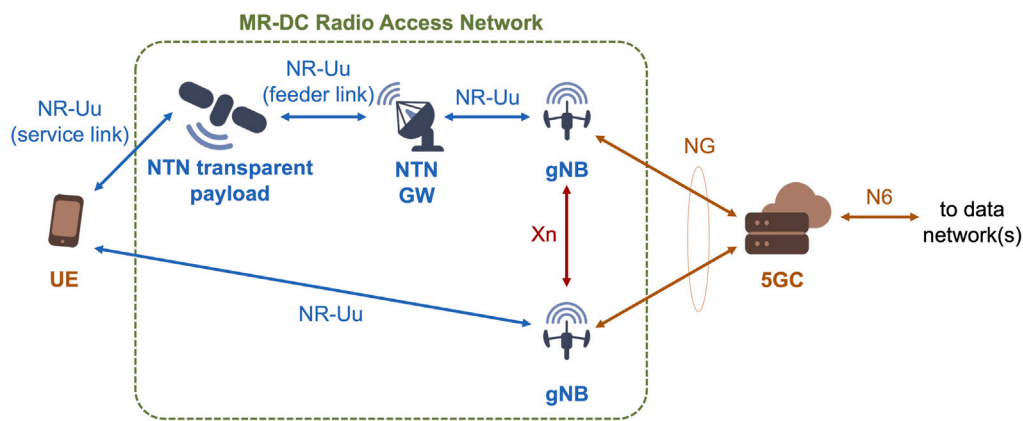

Fig. 20. MR-DC architecture between TN and NTN with transparent payload.

satellite and the UE. However, since the node is transparent, no modification is needed on the Air Interfaces or protocol stacks already discussed above;

- similarly, the architecture option with the gNB on-board the satellite and a transparent drone has protocol stacks equivalent to those in Figs. 6 and 7, related to the NTN architecture with regenerative payload (full gNB) and direct access, again with the addition of a transparent drone between the satellite and the UE;
- the architectures of the 3D Single-Connectivity scenarios in Figs. 18 and 19 are completely equivalent to those in Figs. 12 and 13 referring to the NTN architecture for indirect access with transparent payload, i.e., backhaul to the IAB-Donor, and regenerative payload, i.e., full IAB-Donor on-board, respectively. The only difference is the presence of the IAB-Donor or IAB-node on-board a drone and not on-ground.

5.4. 3D multi-connectivity architecture

The 3D Multi-Connectivity (MC) architecture is a variant of the 3D Single-Connectivity type. This scheme offers several benefits. Firstly, 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 improved coverage in various environments with respect to 5G existing technologies. Secondly, the architecture improves network reliability and resilience. If one layer of connectivity encounters issues or disruptions, other layers can provide backup or alternative routes, ensuring continuous communications. Additionally, 3D MC enables seamless handover

between different networks, enhancing user experience and maintaining uninterrupted connectivity. However, in addition to significant advantages, the 3D MC architecture also has some drawbacks. One notable challenge is related to different latency times characterizing the involved links, which can be mitigated by choosing nodes at similar altitudes. Moreover, also the increased complexity of network management and coordination could represent an important issue. Integrating and synchronizing different layers of connectivity requires sophisticated algorithms and protocols to optimize resource allocation and ensure seamless handovers. Furthermore, the deployment and maintenance of multiple network layers can be costly and require substantial infrastructure investments. Additionally, interoperability and standardization across different network layers may pose challenges, as each layer may have different protocols and technologies. Within 3GPP, MC, and in particular DC, was analyzed to simultaneously transmit PDU sessions to the same UE over multiple SAN/RAN nodes. However, it was not included in Rel-17 and more analyses are being performed in Rel-18. As of today, it can be expected that the technology shall be defined in Rel-19 at the latest.

In principle, MC including a Non-Terrestrial node can be implemented between TN and NTN or between two NTN nodes. In the latter case, the NTN nodes can be either transparent or regenerative. In Figs. 20, 21, 22, 23, 24, and 25, some MR MC, and in particular DC, architectures that are possible with MC in 5G TN-NTN systems are reported. It is worthwhile noticing that:

- with TN-NTN MC, both the NTN and the TN gNBs (or gNB-CUs) can be elected as Master Node and the other acts as Secondary Node (SN);
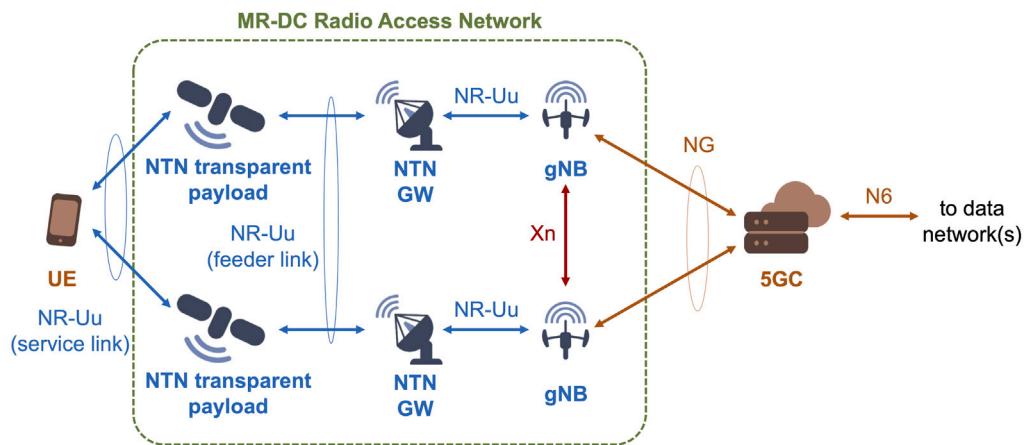
Fig. 21. MR-DC architecture between NTN and NTN with transparent payload.

Fig. 22. MR-DC architecture between TN and NTN with regenerative payload: full gNB on-board.

Fig. 23. MR-DC architecture between NTN and NTN with regenerative payload: full gNB on-board.

- with NTN-NTN MC, the two nodes can also belong to different orbits, e.g., a drone and a satellite or a drone and a terrestrial gNB;

- with TN-NTN MC, the scenario with a full gNB on-board is quite challenging and, for the moment being, not considered in 3GPP, due to the need to transport Xn protocols (see the

Table 1
Mapping of UCs, architectures, and the adopted links.

UCs	Architecture	ISL/inter-layer links
Offloading of traffic in event scenarios	LEO/GEO satellite based access, 3D Single/Multi-Connectivity (with HAP intermediate layer and HAP-satellite interlayer links)	Both ISLs and interlayer links
Coverage of non-connected areas	LEO/GEO satellite based access, 3D Single/Multi Connectivity (with HAP intermediate layer and HAP-satellite interlayer links)	Both ISLs and interlayer links
Ordinary and extraordinary firefighters operation management	3D Single/Multi Connectivity (either terminal to UAV and then UAV and HAP/satellite, or directly terminal to HAP/satellite)	Yes (ISLs)
Interactive Aerial Telepresence	Ground-drone direct communication	No
Drones for delivery	3D Single Connectivity (either to satellite or to HAP)	No
IoRT	Direct-to-satellite links	No
Maritime Broadband (for work and leisure)	Satellite-based access and backhauling, 3D Multi-Connectivity	No
Maritime autonomous vessels	Drone-based relaying	No
Maritime Search&Rescue	LEO satellite-based access	No
Automotive	3D Multi-Connectivity	No

protocol section) over the feeder link. In addition, TN-NTN MC usually requires smart adjustments of the F1 and/or NG timers, so as to compensate for the significantly different latencies on the different Radio Access Technologies.

5.4.1. Protocol stack for 3D multi-connectivity architecture

For the protocol stacks in the 3D MC architecture, the radio protocol architecture of a UE for the Master Cell Group (MCG), Secondary Cell Group (SCG), and split bearers and network side protocol termination options for MCG, SCG, and split bearers in NR-MC are considered [11, 20]. In general:

- with MSG (SCG) bearers, the RLC bearers are located only in the MSC (SCG), while from the SCG (MCG) the Xn interface allows to interact with the other group RLC protocols;
- with split bearers, the RLC bearer for the UE is both in the MN and SN.

From a network perspective, the bearers terminated by the MN (SN) refer to implementations in which the UP protocols are terminated in the MN (SN). The split option indicates which resources are involved to carry the UP data over the NR-Uu interface; as for the CP, the connection with the 5GC is only implemented on the node acting as MN, while the SN only provides additional radio resources to the UE via the SCG. It shall also be mentioned that the MN and SN are logical network nodes; as such, they can be located either in different network elements or in the same one, as long as the Xn Air Interface is used to exchange information.

6. Preliminary considerations

The preliminary considerations on the mapping of UCs, architectures, and the adopted links are summarized in Table 1.

6.1. Orchestration, resource management, and security issues

Orchestrating and managing the integration of TN and NTN is a multifaceted endeavor essential for achieving seamless connectivity across diverse communication infrastructures. This integration involves coordinating the operation, configuration, and optimization of both Terrestrial and Non-Terrestrial elements to ensure efficient data transmission and reliable network performance.

One of the primary challenges in integrating these networks is managing the heterogeneity of technologies, protocols, and interfaces inherent in Terrestrial and Non-Terrestrial environments [21]. This requires the development of interoperable standards and protocols that facilitate seamless communication between different network elements, regardless of their physical location or underlying technology. Orchestration and management of integrated architecture can leverage advanced SDN, NFV and cloud native technologies to dynamically allocate resources, adapt to changing network conditions, and optimize traffic routing across Terrestrial and Non-Terrestrial segments. Furthermore, effective orchestration and management demand real-time monitoring and analytics capabilities to assess network performance, identify potential bottlenecks or failures, and implement timely remedial actions. This entails deploying network monitoring tools and Artificial Intelligence (AI)-driven analytics platforms to proactively manage network resources and handovers and ensure optimal service delivery. In fact, the integration of NTNs into existing TNs towards 6G introduces various challenges, including task offloading, network routing, network slicing, satellite handover, resource allocation. In this context, the AI-native design of 6G, in conjunction with SDN and NFV paradigms, represents a promising solution to capture intricate correlations among diverse network parameters and to manage and prevent unexpected situations in advance [5,21]. Additionally, security emerges as a critical concern in integrated terrestrial and non-terrestrial networks. With data traversing multiple network domains, stringent security measures, including encryption, authentication, and access control mechanisms, must be implemented to safeguard sensitive information and mitigate cybersecurity threats.

Ultimately, successful orchestration and management of integrated TN and NTN require close collaboration between network operators, service providers, equipment vendors, and regulatory authorities. By leveraging cutting-edge technologies, standardized protocols, and robust security measures, organizations can harness the full potential of these interconnected networks to deliver seamless connectivity and unlock new opportunities for innovation and growth in the digital era.

The themes of Management, Orchestration, and Security require also a specific comparison with the existing solution for RAN and core segment. Therefore, these topics will be included in a specific contribution that will be issued in the next months in the framework of ITA-NTN activities.

7. Conclusions

The ITA-NTN project aims to significantly contribute to the development and examination of forthcoming integrated Terrestrial/Non-Terrestrial Networks for 6G, ensuring uninterrupted connectivity, bolstering network resilience, fostering reliable connections for mobile users, and enhancing throughput in challenging propagation conditions. Furthermore, the utilization of an integrated Terrestrial/Non-Terrestrial system is poised to expand connectivity in regions lacking terrestrial network coverage or facing capacity constraints, thus addressing the digital divide and facilitating digital transition. This view is expected to contribute to a future characterized by digitalization, environmental sustainability, and resilience. To this end, the paper reviews the main Use Cases of interest for the ITA-NTN project and the possible multi-layer architectures.
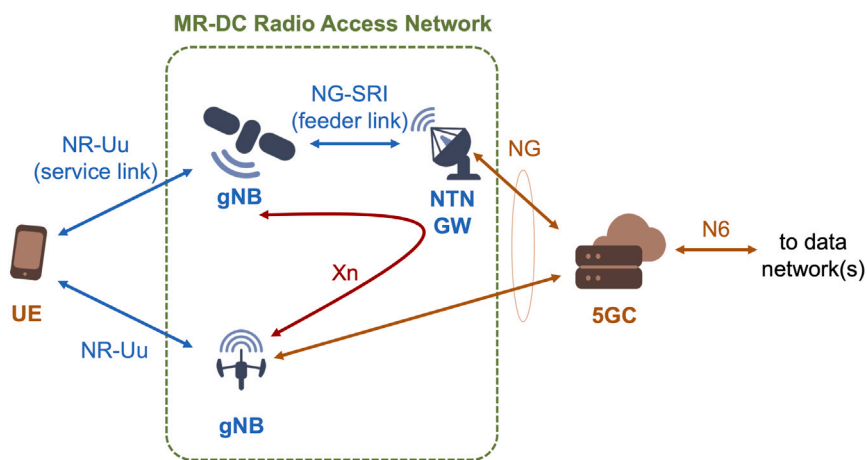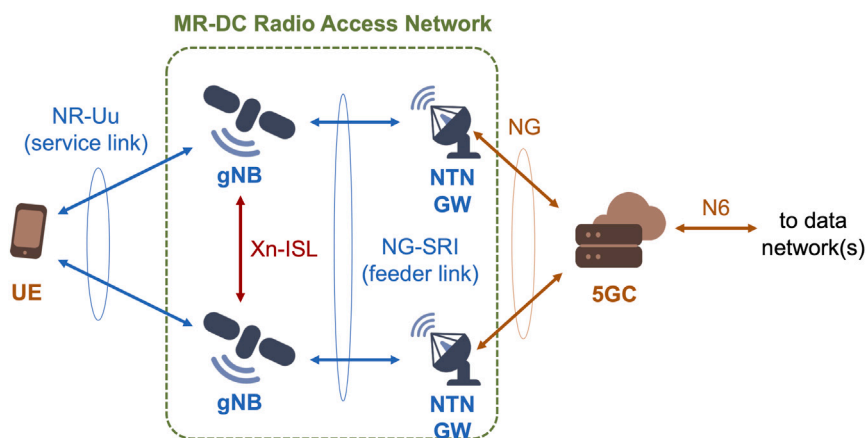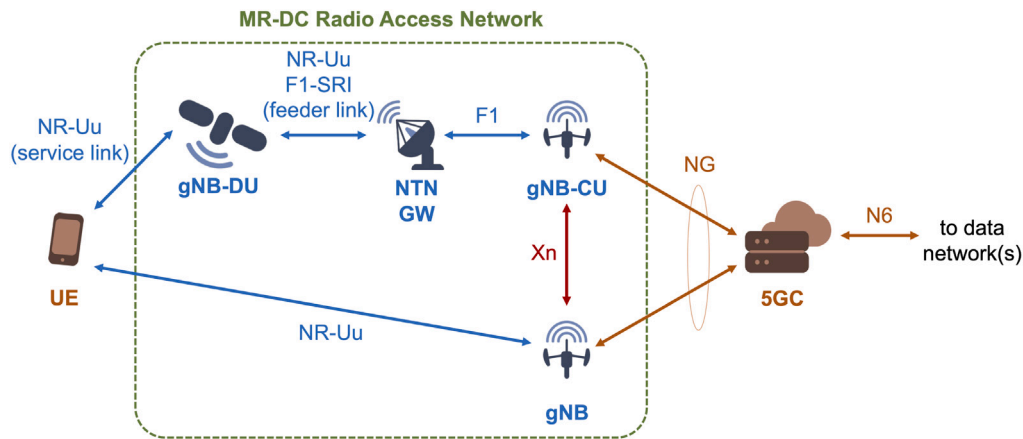
Fig. 24. MR-DC architecture between TN and NTN with regenerative payload: gNB-DU on-board.
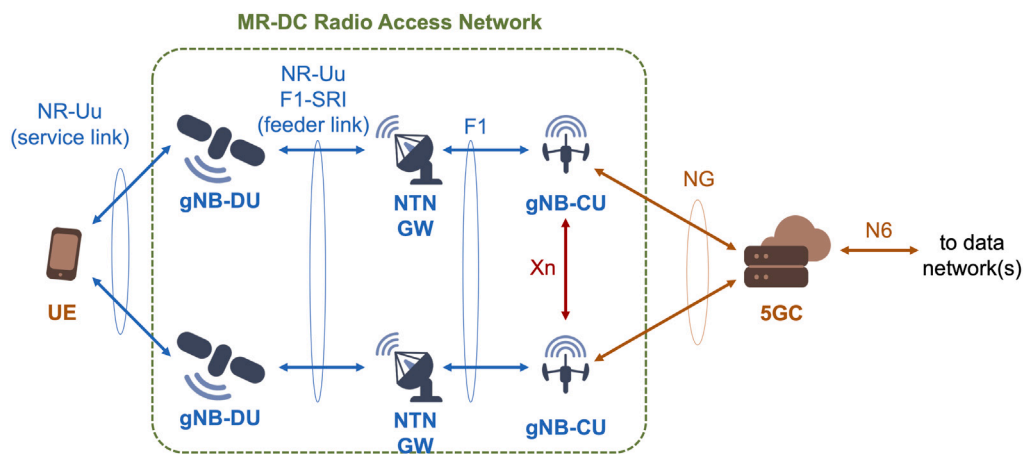

Fig. 25. MR-DC architecture between NTN and NTN with regenerative payload: gNB-DU on-board.

CRediT authorship contribution statement

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Declaration of competing interest

Data availability

No data was used for the research described in the article.

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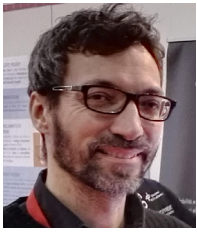
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