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Integrating Non-Terrestrial Networks Into 6G: Architectural and Spectrum Challenges From the ITA-NTN Overview

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Abstract

The studies conducted within the ITA-NTN project and their results provide a vision of future 6G networks by integrating Terrestrial Networks (TNs) and Non-Terrestrial Networks (NTNs), offering insights into emerging standardization directions. Specifically, an architectural evolution is envisaged in which NTN elements will increasingly perform complex routing operations, such as those of 5G radio nodes. Higher-performance transmission techniques are also expected, exploiting new frequency bands, with a proposal to shift high-bit-rate transmission to the W (75-110 GHz) region. Also, Free-Space Optics (FSO) is a particularly promising technology for achieving high-capacity links, though some limitations still need to be overcome. Furthermore, specific modulation techniques appear to be very important in NTN environments, especially for mitigating Doppler-related degradation, as in Non-Orthogonal Multiple Access (NOMA). Finally, management and orchestration require solutions due to a whole series of behaviors that NTNs have, unlike TNs, and in this context, the concept of Intent-Based Networking appears promising.

Introduction

There is growing interest in Non-Terrestrial Networks (NTNs) [1], [2], [3]. On the one hand, the continuous and increasing launch of satellites is leading to a progressive densification of space-based infrastructures; on the other hand, the use of Uncrewed Aerial Vehicles (UAVs) is becoming increasingly pervasive. This scenario has also been fueled by evolving geopolitical and conflict situations, which have highlighted the strategic role of satellite networks not only in providing coverage to the most disadvantaged areas but also in ensuring the resilience and operational continuity of national communication infrastructures.

However, the full development of NTNs will depend on how they integrate with Terrestrial Networks (TNs), which requires a careful assessment of their potential and a truly integrated set of NTN and TN technologies. To achieve this objective, a series of standardization processes must be undertaken to enable full TN-NTN integration [2].

In this context, the ITA-NTN project [3] has introduced contributions that may be relevant for the generation of regulations to be defined in the framework of different Standardization bodies.

Some contributions for standardization were already presented in [4], primarily focusing on proposals for novel three-dimensional (3-D) architectures, based on the cooperation of different NTN elements, such as satellites, UAVs, and high-altitude platforms – integrated with TN components [3]. Additional contributions addressed throughput enhancement through the adoption of modular radio waveform designs for NTN physical layers, as well as the integration of Free-Space Optics (FSO) technologies into NTN systems, which can be effectively leveraged considering recent advancements in fiber-optic communications.

Furthermore, Management & Orchestration (M&O) approaches were included to improve resource allocation, traffic steering, and QoS enforcement across heterogeneous domains.

Starting from studies and results obtained up April 2026, this paper adds further proposals for candidate standardization directions on the following aspects. Concerning transmission systems, specific contributions for ITU can be given about performance details for the adoption of the W band, specific information on FSO impairments and possible solutions, intersatellite links, and Non-Orthogonal Multiple Access (NOMA) format [5]. Regarding M&O, we are instead focusing on a new transversal conceptual layer that is still in an embryonic phase, but which involves

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various standardization bodies such as 3GPP, ETSI, O-RAN, ONAP, and concerns Intent-Based Networks (IBN) [6].

After this introduction, a current overview of the standardization of TN-NTN integration is illustrated, followed by a description of the relative spectrum for NTN, and then a description of TN-NTN architecture proposals. The results from the ITA-NTN project dedicated to possible standardizations are described in the transmission system section and the one dedicated to M&O with the IBN proposal. A final section is dedicated to the discussions and conclusions.

Standardization for the Integration of TN and NTN: A Current Overview

NTNs have been introduced within the 3GPP framework as an extension of the 5G New Radio (NR) system, with the objective of complementing terrestrial deployments and enabling service continuity in scenarios where ground infrastructure is unavailable or impractical to deploy. Rather than defining a new radio access technology, 3GPP has adopted an evolutionary approach in which NTN support is incorporated into the existing NR architecture, allowing NTN platforms to operate as part of a unified cellular ecosystem [7], [8]. The initial investigation of NTN integration was conducted in 3GPP Rel-15 through Technical Report (TR) 38.811 [8], which analysed the feasibility of adapting NR to NTN environments and identified key challenges such as large propagation delays, Doppler effects, moving cells, and link budget constraints. Rel-16 subsequently introduced the TR 38.821 [9], which investigated technical solutions enabling NTN operation within the NR system, including enhancements to synchronization procedures, timing advance mechanisms, mobility management, and physical layer adaptations.

The first 3GPP specifications formally incorporating NTN capabilities were finalized in Rel-17, marking the transition from feasibility studies to standardized support of NTN operation within the NR ecosystem [10]. Rel-17 shipped the first NR-NTN standard with the transparent payload [2].

Rel-18 targeted real deployments, still with a transparent payload, adding mobility enhancements, improved performance, and support for transmission in different frequency bands. Furthermore, Rel-18 defined enhancements and functionalities to support space- and air-borne components in 5G-Advanced [2].

Rel-19 is currently underway and introduces a fundamental innovation with the support of regenerative-payload NR-NTN, which allows the flying object to become a real network node for traffic routing [4]. This evolution represents a significant step beyond earlier NTN configurations based on transparent payloads.

One of the most debated topics is the direct connectivity between NTN and User Equipment (UE). Early commercial deployments and ongoing standardization activities have demonstrated the feasibility of direct satellite-to-device communication, particularly for messaging and low-rate services, using adapted terrestrial waveforms. According to Rel-18, the NTN component enables Direct-to-Device (D2D) communications, where UEs are directly connected to their serving satellite. This configuration is often referred to as star connectivity, as a single NTN node simultaneously serves multiple UEs. Despite this progress, current standardization only partially addresses the operational framework required for large-scale direct NTN-to-UE integration within the broader International Mobile Telecommunications (IMT) ecosystem.

Current Radio Spectrum Role for TN-NTN

The TN-NTN integration must also be considered when defining the bands for the new 6G technology. 6G will exploit increasingly higher bands, from mmWave to THz and up to optics, while also seeking new reallocations in the lower frequency bands, where many other systems already transmit. Looking at the IMT, ITU-R WP 5D has finalized the IMT-2030 framework for the next generation of mobile that will require multiple frequency ranges to meet the capacity and coverage requirements of IMT systems from sub-1 GHz up to frequencies above 100 GHz, even though the 1–24 GHz frequency range, commonly referred to as the *mid-band spectrum*, provides a favourable trade-off between coverage and capacity. The current situation is characterized by a high demand for spectrum below 6 GHz, and by an in-depth analysis of strategies for using the upper 6 GHz (6.425-7.125 GHz), which may be assigned or shared among different radio networks (IMT, Radio LAN, etc.).

The emergence of large-scale Low-Earth Orbit (LEO) constellations, together with aerial platforms such as UAVs and High-Amplitude Platform Stations (HAPSs), introduces new characteristics in terms of system density, mobility, and dynamic spectrum usage.

Looking at the lower frequencies, the main bandwidths adopted for NTN are L (1–2 GHz), S (2– 4 GHz), and C (4–8 GHz), which are related to the most consolidated communication techniques. Furthermore, current first-generation constellations primarily operate in the Ku (10.7-14.5 GHz)- and Ka-bands (27-40 GHz, but ITU also includes 17.3–21.2 GHz). Furthermore, the increasing adoption of advanced spatial selectivity techniques in space, such as beam steering [8], will allow an ever-increasing sharing of the assigned frequency portions and greater immunity to attack phenomena such as jamming and spoofing at the physical level [11].

As illustrated in Fig. 1, NTN spectrum usage spans multiple frequency ranges and deployment scenarios, highlighting the complexity of coexistence and regulatory coordination.

Currently, there is much interest in "Sub-THz," defined as frequencies between 100 and 300 GHz, because the attenuation of electromagnetic (EM) signals above 300 GHz is too high to support long-range communications, as in the case of NTN systems. For this reason, the ITA-NTN investigation has been mainly dedicated to frequency bands below 300 GHz, and in particular to the W band (75–110 GHz), where plenty of allocated bandwidth is already available.

Integrated TN-NTN Architectures

The analysis conducted within the ITA-NTN project [3], considering both existing and emerging

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use cases, highlights the need for more complex architectures, such as those proposed in [4] and summarized in Fig. 2: Drone-based Relay, Satellite Access, 3-D Single Connectivity, and 3-D Multi-Connectivity [3], [4].

Following the initial phase, embarking the full gNB on board the satellite, further architectural evolutions are expected. These include the introduction of functional split solutions as in the Radio Access Network (RAN) and the integration of data analytics and Artificial Intelligence (AI) mechanisms, in line with the approaches already adopted in terrestrial RAN by 3GPP and O-RAN [12]. Furthermore, typical core functions to support local data switching, for instance via an on-board User Plane Function (UPF), were proposed in TR 23.700-27.

The evolution of the NTN architecture also enables additional features for NTN–TN integration, which require dedicated procedures and Operation & Management (O&M) mechanisms. These include D2D via satellite, enabling UE-Satellite-UE communication without traversing the ground network for the user plane [10]. This approach can reduce latency, improve data rates, and alleviate feeder/backhaul resource consumption. However, the evolution toward IMT D2C scenarios still requires extensive studies and experimentation, particularly from an M&O perspective, since coexistence with terrestrial IMT systems must be considered. In fact, some stakeholders aiming to provide satellite D2D services intend to operate in frequency bands identified by ITU-R for Mobile-Satellite Service (MSS), in the 1-3 GHz range, as specified in ITU-R Recommendation M.1184. Other actors propose instead reusing the terrestrial spectrum already allocated to mobile network operators.

A novel aspect also regards the role of the integration with synchronization and positioning networks. In fact, operations without Global Navigation Satellite System (GNSS) capabilities at the UE are under definition. These scenarios are particularly challenging because UEs must precompensate for time and frequency offsets during the initial access procedure [10]. At the same time, removing GNSS dependence improves security, since GNSS signals are vulnerable to spoofing attacks [11]. Related architectural enhancements are documented in 3GPP TR 23.700-29.

Another important issue for the NTN nodes is their role in backhaul solutions, and in Rel-19, newly introduced Wireless Access Backhaul (WAB) approaches have been defined.

Transmission Systems for NTN

The set of transmission systems that can operate within a generic 3-D NTN network is very broad, as it depends on operating frequency, link distance, and the specific functionality required (feeder, inter-satellite link, or user access).

ITA-NTN provided a holistic design approach for different NTN configurations, comparing technologies and accounting for transmitter-receiver solutions and propagation impairments across GHz to optical frequencies to determine how each portion of the spectrum can be best exploited for each type of NTN link. In this article, we focus only on those systems that could bring significant innovation to NTN networks.

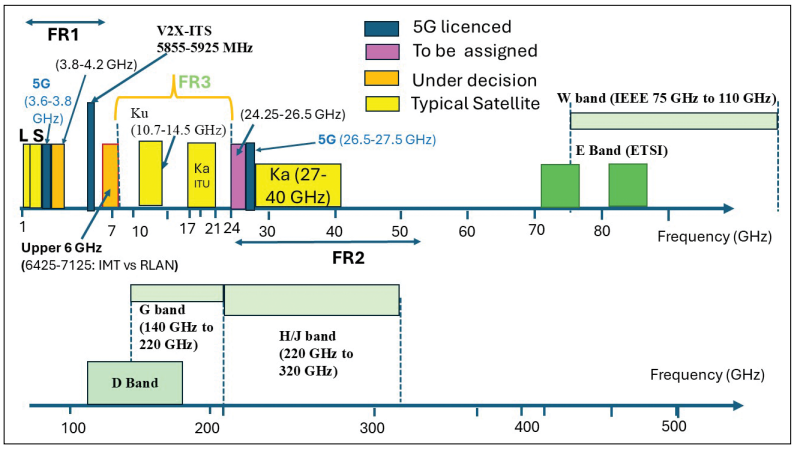


FIGURE 1. Current bands defined for the electromagnetic spectrum according to IEEE, ETSI, and ITU.

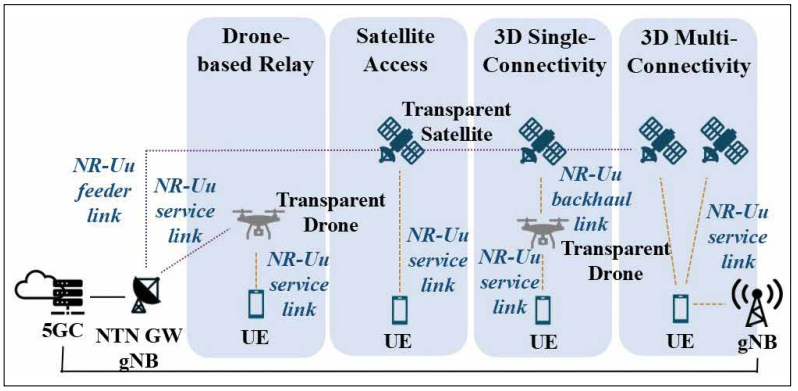


FIGURE 2. ITA-NTN architectures.

Platform	UAV	HAPS	LEO	MEO	GEO
Target Capacity [Gb/s]	10	40	40	10	10
Required BW [GHz]	1.02	4.08	4.08	1.02	1.02
Required C/N_0 [dBHz]	110.08	116.1	116.1	110.08	110.08
C/N0 margin [dB]	19.6	25.5	8.8	11.9	4.8
Max Capacity [Gb/s]	49.1	49.1	49.1	49.1	29.4

TABLE 1. Feeder-link design for NTN platforms at W band (71-76 GHz).

Performance in W Band

In Table 1, we report a feeder-link design for several NTN platforms in the W-band frequency range 71-76 GHz. The following distances between the Earth and the NTN node are assumed: UAV=10 km, HAPS=20 km, LEO=500 km, MEO=1000 km, GEO=36000 km. We hypothesized a dual-polarization link with the 64-APSK modulation, the rate-9/10 DVB-S2 LDPC code of maximum length, and a roll-off factor of 0.1.

Given a target capacity of 10-40 Gb/s, we derived a required bandwidth of 1.02-4.08 GHz. We assume quasi-error-free conditions if the signal-to-noise ratio (SNR) at the decoder input is at least 20 dB, from which we derive the minimum carrier-to-noise density ratio (C/N0) in dBHz, as shown in the table. We also performed a link budget (not shown here for lack of space) in clear-sky conditions, using commercially available

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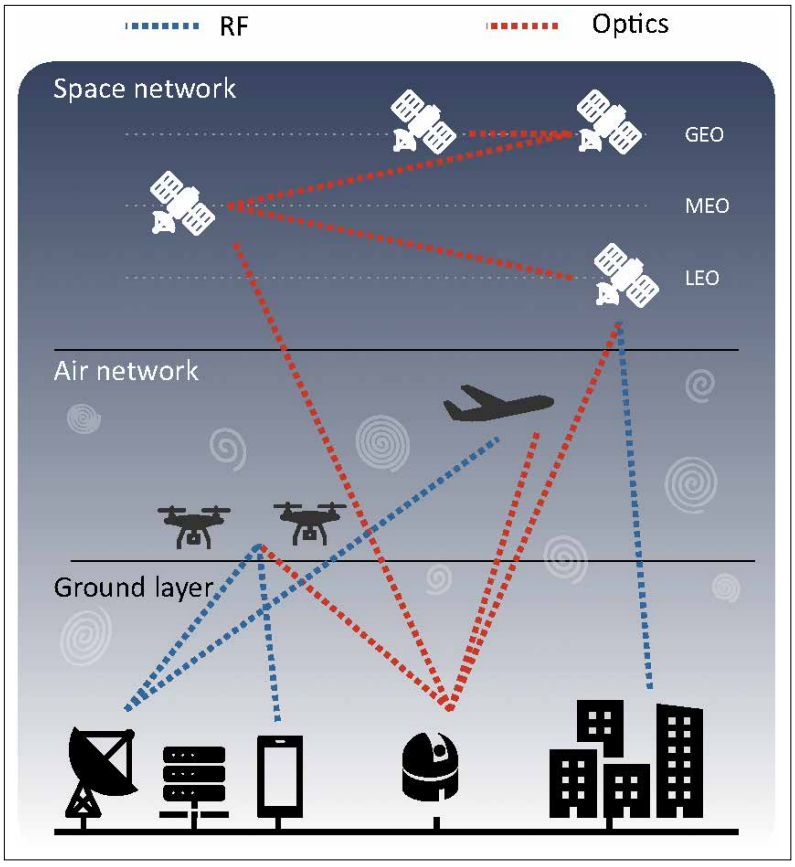


FIGURE 3. Conceptual representation of an integrated multi-layer TN-NTN architecture, showing space, air, and ground network segments interconnected through RF and optical links.

components, yielding a positive C/N0 margin for all platforms. This can be used to downsize components or to ensure link reliability in case of rain. Finally, the last row of Table 1 shows the maximum achievable capacity in the considered band. For all platforms, this capacity is obtained by using the entire available 5-GHz bandwidth, except for the GEO platform, for which the maximum available bandwidth is used (about 3 GHz), yielding an SNR at the decoder input of at least 20 dB. These results suggest that we should aim to define transmission standards in the W band to be used by a wide range of NTN systems.

Free Space Optics for NTN

Recently, FSO emerged as a fundamental technology for satellite communications and fronthaul/backhaul connectivity, particularly within 6G NTN scenarios. The use of optical beams offers several advantages, such as high-speed transmission (potentially exceeding 100 Gb/s), extended link ranges (due to the high directivity), and a significant reduction of the required space, weight, and power (SWaP) compared to conventional systems. These attributes make FSO a suitable solution for NTN architectures - specifically those involving the space layer (Fig. 3) – where long-range propagation and high-capacity links are required. Leveraging significant technological developments in optical fiber communications, very high capacity can be achieved using the well-known wavelength-division multiplexing (WDM) technique. More recently, 2x100 Gb/s was demonstrated from a LEO satellite to an optical ground station [13]. However, to fully exploit this potential, critical innovations are still required. These involve the development of new telescopes, efficient interfacing between free-space and fiber-based transceivers, and the space qualification of existing photonic subsystems.

One of the most challenging aspects of FSO links in NTN is related to the atmospheric channel for Earth-space links (see Fig. 3), either in uplink or downlink. As optical signals travel through various atmospheric layers, their intensity can be attenuated and, mostly, their wavefront distorted. These effects produce high loss, which also randomly changes on millisecond timescales and can result in unpredictable fading events that can severely degrade link reliability. To balance the high loss, high-power optical amplifiers are being investigated.

To mitigate the random fading events, several strategies were proposed at both physical and network levels. In the data plane, the solutions focus on adaptive optics systems and interleaving techniques. At the network level, there are different options, such as dynamic re-routing, Automatic Repeat Request (ARQ), and assuming different classes of services: they can be employed to enhance overall network robustness.

Furthermore, an effective control system should be capable of predicting or promptly detecting outages caused by atmospheric fading, enabling timely countermeasures. Understanding and managing these fading events is crucial for the design and development of reliable NTN FSO.

Regarding standardization, the USA Space Development Agency (SDA) in the "Optical Communications Terminal (OCT) Standard"[1] and, more recently, the European Space Agency in the ESA Specifications for Terabit/sec Optical Links[2] are defining specifications of optical terminals to achieve interoperability in FSO communications for a satellite constellation, including transmission rates (2.5, 10, 100, 200, and 400 Gb/s), standard FEC, acquisition pointing and tracking procedure (to align telescopes and lens), wavelength-division-multiplexing (WDM) grid, and framing encapsulation.

Inter-Satellite Links as Enablers of Scalable and Resilient NTN Architectures

Inter-Satellite Links (ISLs) are a key enabler for scalable and resilient NTN, particularly in large LEO constellations envisioned for 6G systems. By enabling direct communication among satellites, ISLs reduce reliance on ground gateways, mitigate backhaul bottlenecks, and support low-latency forwarding paths that are beneficial for delay-sensitive and mission-critical services. From a system perspective, ISLs enable advanced NTN operating modes such as UE–satellite–UE communication and store-and-forward services, improving service continuity in scenarios with limited terrestrial infrastructure.

ISLs are often treated as internal transport mechanisms and implemented through vendor-specific solutions. Consistent with this view, 3GPP does not specify ISLs in detail and generally assumes them as transparent transport links in NTN architectures.

[1] https://www.sda.mil/wp-content/uploads/2025/04/SDA-OCT-Standard-v3.2.0_FINAL.pdf

[2] https://connectivity.esa.int/wp-content/uploads/2025/07/ESTOL_air_interface_v2.2.pdf

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While this abstraction simplifies architectural modeling, it also limits the ability to jointly and predictably optimize access, backhaul, and core network functions across the NTN segment.

In this context, ISL standardization is not about enabling physical interconnection or cooperation across operators, but about defining common architectural assumptions, abstractions, and performance models. Harmonized characterization of ISL capabilities, such as latency bounds, capacity variability, and availability patterns, would allow terrestrial control and orchestration entities to reason coherently about the NTN segment within 3GPP-defined frameworks. Coordination between 3GPP, ITU-R, and Consultative Committee for Space Data Systems (CCSDS) is therefore essential to ensure predictability, scalability, and effective end-to-end integration of NTN components within future 6G systems. To address such limitations, we propose a standardized ISL Capability Abstraction Model enabling NTN-aware orchestration while preserving implementation flexibility for satellite operators.

The proposed abstraction is defined as a standardized information model consisting of:

- deterministic descriptors (maximum latency, minimum guaranteed capacity, expected path persistence);
- statistical descriptors (latency distribution, availability probability, congestion probability);
- predictive descriptors (validity interval, confidence level, predicted degradation horizon).

The model deliberately excludes satellite topology, routing policies, and link scheduling, thereby preserving operator autonomy while providing sufficient information for terrestrial orchestration.

Such descriptors would allow 3GPP network functions to incorporate orbital transport conditions into mobility management, QoS enforcement, and traffic steering decisions without requiring disclosure of proprietary satellite routing implementations. From a standardization perspective, the proposed framework requires coordinated extensions across multiple standardization bodies.

Within the 3GPP, the existing NTN Assistance Information framework could be extended to include predictive ISL transport descriptors, such as expected latency, available capacity, and link persistence. These descriptors could be utilized by the Access and Mobility Management Function (AMF) to support mobility management, the Session Management Function (SMF) for path selection and Quality of Service (QoS) enforcement, and Radio Access Network (RAN) optimization functions for resource allocation and handover management. In parallel, the CCSDS could define interoperable telemetry information models for exposing ISL status and performance metrics across heterogeneous satellite platforms, while the ITU-R could develop standardized statistical models for ISL latency, availability, and capacity variations under different orbital configurations.

Non-Orthogonal Multiple Access (NOMA)

In NTN domains, the stringent bandwidth requirements and the location of the users make the NOMA technique [5] a promising candidate for combining versatility and robustness. In particular, the grant-free power-domain NOMA (PD-NOMA) scheme has been proved to deal with the significant link quality variations and the task-driven heterogeneous traffic scenarios. This scheme exploits Interference Cancellation (IC) to decode multiple users hosted in the same time slot without additional overhead, with packets diversified by statistical power fluctuations rather than by signature codes [3] (i.e., no additional signaling required). This capability of providing high capacity in harsh scenarios makes PD-NOMA specifically suitable for the air layer, where UAVs with irregular trajectories may have to exchange critical information with anchored Networked Tethered Flying Platforms (NTFPs) or orbiting satellites. The combination of low-order modulations and, differently from the 5G context, prevailing Line-of-Sight (LoS) conditions has provided significant robustness against different impairments, such as small-scale fading, airframe shadowing, antenna pointing errors, polarization losses, and imperfect IC [5], thus leading to benefits not only in terms of throughput and fairness, but also in terms of computational burden. Fig. 4 illustrates the throughput gain achieved in a space environment, comparing the typically adopted slotted Aloha (SA) scheme with the PD-NOMA one without IC, with perfect IC, and with imperfect IC (an ε=10% residual interference is usually considered a threshold for the adequate operation of an IC receiver). These encouraging results obtained during the ITA-NTN project suggest the inclusion in forthcoming 6G amendments and standards of PD-NOMA for robust massive low-rate access in aerial/space scenarios.

Orchestration and Management

One of the fundamental aspects of 6G will be the M&O of the integrated TN-NTN. Standards Development Organizations (SDOs) such as ITU-T, ETSI, 3GPP, Internet Research Task Force (IRTF), and O-RAN [12] have proposed different approaches

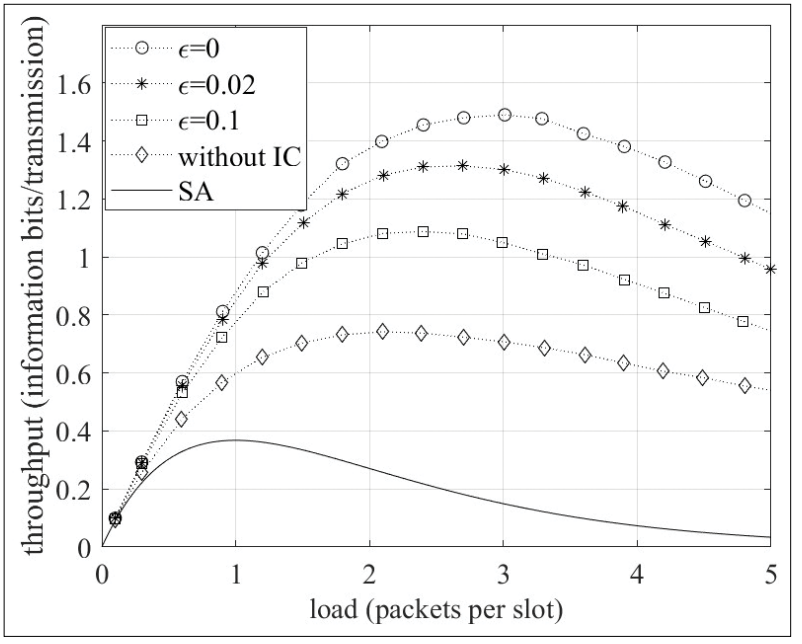


FIGURE 4. Throughput as a function of the offered load for a QPSK modulation with code rate 1/2 in space environment.

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to address various challenges associated with unified management and control for both TN and NTN. However, no definitive solutions have yet emerged, and convergence and interoperability remain a critical gap to be further investigated. To achieve effective orchestration and management in this context, advanced analytics capabilities are essential. These capabilities empower control loops and automation, enabling the system to adapt and respond efficiently to changing conditions. An example of M&O for an entire TN-NTN domain was described in [4]. It takes into account the cooperation among the elements dedicated to data analytics, with coordination based on the Management Data Analytics Function (MDAF) to address these needs in a cross-domain scenario, gathering data from various sources such as Operations, Administration and Maintenance (OAM) systems, intelligent elements within the 5G core network (Network Data Analytics Function, NWDAF), and access networks based on O-RAN with non-Real Time RAN Intelligent Controller (non-RT RIC) and Near RT RIC [12]. However, the detailed design of each functional component, interface, protocol, algorithm, and pipeline must be further studied and discussed within the different standardization organizations, towards the scenario envisaged in ETSI Zero Touch Service Management (ZTSM) [14]. This entails developing intelligent algorithms and protocols capable of efficiently balancing traffic loads, mitigating interference, and adapting to changing network conditions, while accounting for the additional complexities introduced by NTN's varying propagation characteristics, latency issues, and orbital dynamics for satellite constellations.

However, within this evolving landscape, the limitations of conventional analytics-driven automation become increasingly evident. While frameworks such as MDAF, NWDAF, and O-RAN RIC introduce powerful data collection and inference capabilities, they largely operate as *reactive* components within predefined control loops. Their functionality is often constrained to isolated optimization tasks, with limited autonomy, coordination, or reasoning across domains. As 6G systems move toward highly dynamic, multi-domain environments that tightly couple TNs with NTNs, a more radical paradigm shift is required, and the role of Intent-Based Networking (IBN) [6] appears particularly useful. In this context, the integration between TN and NTN is assured by an upper layer, the intent layer, which automatically translates high-level goals into operational configurations, continuously verifying and adapting its behavior to meet them. In practice, a set of intents is defined for the whole network, and the network automatically translates them into each domain. We assume an O-RAN architecture for RAN domains, including the NTN, which is linked to the 5G Core as described in [4].

This shift is encapsulated by the concept of *Agentification* [15]. Agentification refers to the transformation of network management and control functions into *agentic AI entities*—autonomous, goal-driven components capable of perception, reasoning, decision-making, and action within their operational context. Unlike traditional analytics functions that deliver insights to external controllers, agentic components internalize control logic, allowing them to directly act upon the network while continuously adapting their behavior through learning and interaction. This paradigm aligns naturally with the intrinsic complexity of integrated TN–NTN systems, where centralized orchestration struggles to cope with scale, latency, and heterogeneity. In an *agentified* 6G architecture, intelligence is distributed across multiple network layers. At the lowest level, agents embedded in radio access elements—such as terrestrial gNBs, satellite payloads, or UAV-based access points—monitor local radio conditions, traffic demands, and energy constraints. These agents can autonomously tune transmission parameters, manage spectrum usage, or adapt scheduling policies in response to rapidly changing environments. Crucially, they operate under high-level objectives rather than static rules, enabling flexible behavior even under unforeseen conditions. At higher layers, agentic control extends to core network functions, transport networks, and M&O systems. Here, agents reason over aggregated, cross-domain information derived from sources such as MDAF, NWDAF, and O-RAN RICs [4], but go beyond passive analytics. They negotiate resources across TN and NTN segments, coordinate end-to-end service delivery, and dynamically align network behavior with operator intents and service-level agreements. This approach supports *intent-based networking* in its full sense: intents are not merely translated into configurations but continuously interpreted and enforced by collaborating agents. The relevance of Agentification becomes particularly evident in NTN scenarios. Satellite constellations and aerial platforms introduce time-varying topology, intermittent connectivity, and non-negligible propagation delays. In such environments, reliance on centralized decision-making can lead to outdated or suboptimal actions. Agentic AI mitigates this issue by enabling local autonomy combined with cooperative behavior. Agents can anticipate orbital dynamics, predict link availability, and proactively reconfigure routing and resource allocation, while coordinating with terrestrial agents to maintain end-to-end service continuity. From a standardization perspective, Agentification does not replace existing frameworks such as MDAF or ETSI ZTSM [14], but rather builds upon them. These architectures provide essential data pipelines, interfaces, and abstraction layers that agentic components can exploit. The open challenge lies in defining how agents are instantiated, how they interact across administrative and technological domains, and how their learning and decision processes can be made trustworthy, explainable, and interoperable. This calls for new specifications addressing agent lifecycle management, inter-agent communication models, and AI governance mechanisms within SDOs.

Alongside these SDO-driven architectural efforts, the broader AI ecosystem is also converging on open, agent-centric interoperability technologies. In particular, the Model Context Protocol (MCP) standardizes how Large Language Model (LLM) applications can connect to external data sources and executable tools [15]. As another relevant example, the Agent2Agent (A2A) protocol targets inter-agent communication and collaboration across

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heterogeneous implementations and administrative domains, such as the ones described for TN-NTN. A2A is designed to let agents discover each other's capabilities, coordinate task-oriented interactions (including long-running tasks), and exchange information security [15]. Regarding these technologies, the Network Management Research Group (NMRG) of the IRTF is working on how these agent technologies could be useful for networking-specific problems and requirements. Recent NMRG activities include preliminary Draft documents outlining the fundamental issues with existing agentic technologies that should be addressed to fully automate network operations and discussing how protocols like MCP and A2A could be applied in network management environments.

Discussion and Conclusion

The integration of NTNs into future 6G systems cannot be interpreted as a mere extension of 5G NR capabilities. While 3GPP Rel-17 and Rel-18 have successfully introduced NTN support through adaptations of terrestrial procedures, and Rel-19 is progressing toward regenerative payload architectures, these steps represent only the initial phase of a deeper architectural transformation. Future 6G systems will require a truly 3-D-native design, where terrestrial, aerial, and space components operate as coordinated and intelligent network entities rather than hierarchical extensions of ground infrastructure.

From a spectrum perspective, the rapid densification of LEO constellations and the diffusion of UAVs are intensifying the need for robust sharing frameworks and harmonized regulatory conditions. Current allocations in FR1 and traditional Ku/Ka bands are unlikely to sustain long-term capacity demands, and exploring higher-frequency bands, including Q/V and W, emerges as a strategic direction.

Transmission technologies will play a decisive enabling role in this evolution. High-capacity feeder links in the W-band, advanced modulation schemes such as high-order APSK, and the integration of FSO for feeder and ISLs offer concrete pathways toward multi-Gb/s and even Tb/s NTN segments. At the same time, access-layer scalability, particularly in aerial and highly dynamic environments, can benefit from flexible multiple-access paradigms such as power-domain NOMA, which demonstrate robustness under heterogeneous link conditions and massive access scenarios. ISLs further highlight the need for a shift in standardization perspective.

However, the most transformative implication concerns M&O. Existing analytics-driven frameworks, including MDAF, NWDAF, and O-RAN RIC, offer valuable data-processing capabilities but remain largely reactive and domain-specific. The concept of Agentification, whereby network functions evolve into agentic AI entities capable of perception, reasoning, and action under high-level intents, represents a promising direction for 6G. Standardization bodies will need to address agent lifecycle management, inter-agent communication models, explainability, and AI governance to ensure trustworthy and interoperable deployments.

In summary, the evolution toward integrated TN-NTN 6G systems requires coordinated progress across architecture, spectrum, transmission technologies, and intelligent control frameworks. Incremental adaptations of terrestrial-centric designs will not suffice. A cross-effort involving different standardization organizations, such as 3GPP, ITU-R, ETSI, IETF, and O-RAN, is essential to define harmonized abstractions, scalable spectrum strategies, and AI-native orchestration models.

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