



UNICO I+D Project

6G-INTEGRATION 02

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6G-INTEGRATION-02-E8

Analysis for strategies for  
combined coverage by NTN + B5G  
version 1

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## Disclaimer

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## Abstract

This deliverable E8 presents a comprehensive and advances analysis of the state of the art in the standardization of integrated terrestrial and non-terrestrial networks (TN–NTN) within the 5G ecosystem and beyond. It reviews 3GPP releases, architectural frameworks, physical layer challenges, and emerging research directions toward 6G. The focus is on achieving seamless global coverage through multi-layer network integration. This document constitutes the seed and starting point of the future final version of this deliverable, D11 that expects to include the emerging research directions toward 6G.

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## List of Acronyms

ACB	Access Class Barring
AMF	Access and Mobility Management Function
GEO	Geostationary Earth Orbit
HAPS	High Altitude Platform System
LEO	Low Earth Orbit
LTE	Long Term Evolution
MEO	Medium Earth Orbit
NTN	Non Terrestrial Networks
TN	Terrestrial Networks
UAC	Unified Access Control

## 1. Introduction

The rapid growth of Internet-of-things (IoT) devices, smart vehicles, and other connected objects is driving demand for ubiquitous connectivity and intensive computing capacity. 5G and upcoming 6G networks are crucial to meeting these demands and the fast-evolving services and applications. However, traditional terrestrial networks face limitations in coverage and capacity. Integrated Terrestrial and Non-Terrestrial Networks (TN and NTN) are emerging to address these challenges. In essence, integration of both network ecosystems combines ground-based infrastructure with aerial, space, and water surface networks to provide seamless connectivity and computing resources anytime, anywhere.

Given the stringent quality-of-service (QoS) of future services, edge computing will be an inseparable component of integrate TN and NTN. Consequently, we analyse in this document the current efforts of integrating cloud/edge computing into NTN layers to facilitate stringent QoS services and address the data processing needs of modern applications. We study the state of the art in this deliverable and we aim to extend the discussion in the next final deliverable E11 by identifying the challenges and future research directions of integrated coverage of TN and NTN.

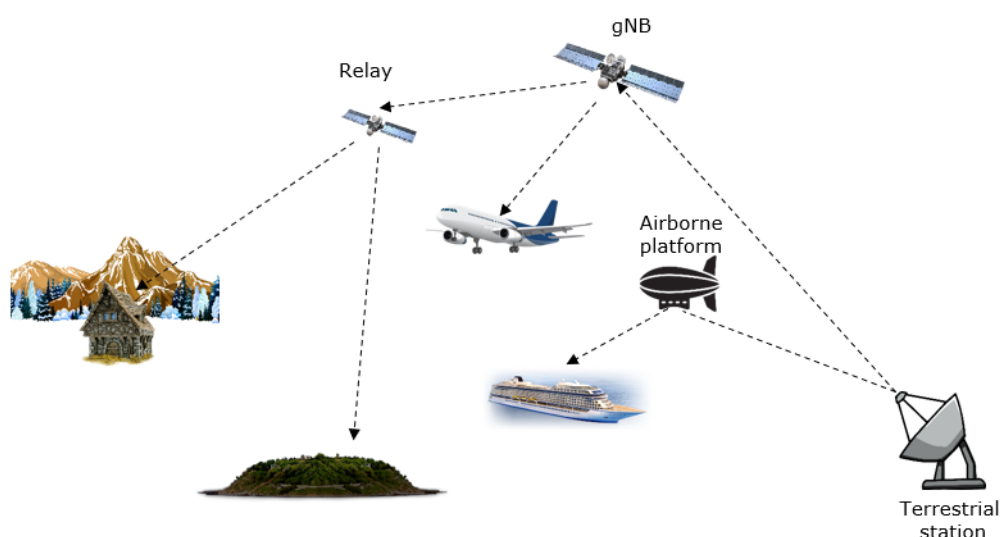


FIGURE 1. GENERAL ILLUSTRATION OF TN AND NTN NETWORKS

NTN has become an umbrella term for any network that involves non-terrestrial flying objects. The NTN family includes satellite communication networks, high altitude platform systems (HAPS), and air-to-ground networks. The integration of terrestrial and non-terrestrial networks (NTN) is a key enabler for ubiquitous connectivity. NTN encompasses satellite systems (GEO, MEO, LEO) and high-altitude platform systems (HAPS). The convergence with terrestrial 5G networks aims to provide service continuity, resilience, and global reach.

Satellite communication networks utilize space borne platforms which include low Earth orbiting (LEO) satellites, medium Earth orbiting (MEO) satellites, and geosynchronous Earth orbiting (GEO) satellites. Over the past several years, the world has witnessed re-

surging interest in the broadband provisioned by LEO NTNs with large satellite constellations (e.g., Starlink, Kuiper, and OneWeb). To benefit from the economies of scale of the 5G ecosystem [1], the satellite industry has engaged in the 3GPP process to integrate satellite networks into the 5G ecosystem.

HAPS are airborne platforms which can include airplanes, balloons, and airships. In the 3GPP NTN work, the focus is on high altitude platform stations as International Mobile Telecommunications base stations, known as HIBS. A HIBS system provides mobile service in the same frequency bands used by terrestrial mobile networks.

Air-to-ground networks aim to provide in-flight connectivity for airplanes by utilizing ground stations which play a similar role as base stations (BSs) in terrestrial mobile networks. But the antennas of the ground stations in an air-to-ground network are up-tilted towards the sky, and the inter-site distances of the ground stations are much larger than that of terrestrial mobile networks.

The focus of 3GPP NTN work has been on satellite communications networks, with implicit compatibility to support HIBS systems and air-to-ground networks. It is worth noticing that 3GPP has also been working on mobile enabled low-altitude unmanned aerial vehicles (UAVs, aka. drones), which can be considered as part of the NTN family in a wide sense. However, this line of work has been carried out in a separate track in 3GPP. Therefore, here we will mainly focus on the satellite communication networks and keep the treatment of other types of NTNs to a minimum.

5G New Radio (NR) based NTN has been the main focus in 3GPP. NR was designed for forward compatibility, support for low latency, advanced antenna technologies, and spectrum flexibility including operation in low, mid, and high frequency bands. This provides a solid foundation for adapting NR to support NTNs.

There is growing interest in NTN based massive Internet of Things (IoT) use cases using narrowband IoT (NB-IoT) and Long-Term Evolution (LTE) for machine type communication (LTE-M). As a result, 3GPP is studying the feasibility of adapting NB-IoT and LTE-M to support NTN in its Release 17 [2].

An overview of the role of NTNs, application scenarios, and networking challenges is presented in [3]. The work in [4] discusses NTN challenges and opportunities and presents a case study on using millimeter wave frequencies to connect mobile terminals. A comprehensive survey on NTN is provided in [5], but the discussion on 3GPP NTN work therein stays at a high level.

## 2. 3GPP Standardization

The 3rd generation partnership project (3GPP) completed the standardization of the first global 5th generation (5G) wireless technology in its Release 15 in mid-2018 [6]. The first evolution step of the 5G system was finalized in Release 16, and 3GPP is working on further evolution of the 5G system in Release 17. Enabling 5G system to support non-terrestrial networks (NTNs) has been one direction under exploration in 3GPP. The

objective of this document is to provide an overview of the state of the art in 3GPP NTN work.

3GPP has formalized NTN integration starting from Rel-17. Key technical reports include **TR 38.811** (*channel models*), **TR 38.821** (*solutions for NTN*), and **TR 23.737** (*system architecture*). Release 18 enhances NTN under the 5G-Advanced umbrella, addressing mobility, performance, and service continuity. Future Release 19 is expected to introduce regenerative payload and deeper integration.

**3GPP TR 38.811 [7]** is a Technical Report titled "**Study on New Radio (NR) to support non-terrestrial networks.**" It serves as the foundational study from **Release 15** for integrating satellites and aerial platforms into the 5G ecosystem. As key objectives, the report defines how **5G New Radio (NR)** technology can be adapted for Non-Terrestrial Networks (NTN), including: **Satellites**: LEO (Low Earth Orbit), MEO (Medium Earth Orbit), and GEO (Geostationary) and **HAPS**: High Altitude Platform Stations (operating between 8 and 50 km). Regarding the channel models, It establishes propagation characteristics for satellite environments, focusing on path loss, fading, and significant Doppler shifts. As deployment scenarios, it analyses use cases such as direct-to-handheld connectivity and satellite-based backhaul for remote areas. The document identifies as technical challenges the impacts caused by long propagation delays (up to 541 ms for GEO) and the high velocity of non-geostationary satellites. As main impact, this study paved the way for **Release 16** (TR 38.821) and the eventual normative standardization in **Release 17**, which introduced the first functional 5G NTN specifications. Official version history and files can be accessed on the 3GPP portal<sup>1</sup>.

**TR 38.821 [8]** is a 3GPP Technical Report titled "**Solutions for NR to support Non-Terrestrial Networks (NTN)**". Originally part of **Release 16**, it provides the foundational technical analysis for integrating satellites and high-altitude platforms into 5G networks. The key technical pillars are: **Architecture Scenarios**: Evaluates both **Low Earth Orbit (LEO)** (600–1200 km) and **Geostationary (GEO)** (35,786 km) satellite deployments. **Payload Types**: Primarily focuses on **transparent payloads**, where the satellite acts as a radio frequency relay between the ground gateway and User Equipment (UE) and **Frequency Bands**: Discusses operation in the **S-band** (~2 GHz) for handheld devices and the **Ka-band** (~20/30 GHz) for high-throughput fixed terminals. Regarding technical adaptations: **Timing & Sync**: Solutions for extreme propagation delays (over 540ms round-trip for GEO); **Doppler Compensation**: Handling frequency shifts caused by LEO satellites moving at high velocities and **Mobility Management**: Strategies for tracking area updates and paging when satellite beams move independently of the Earth's surface.

<sup>1</sup> <https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3234>

The report serves as a baseline for the later Release 17 work on **NB-IoT** and **LTE-M** over satellite for IoT integration. It enabled the "direct-to-cell" capabilities now being commercialized, allowing standard 5G devices to connect to satellite constellations with minimal hardware changes.

**3GPP TR 23.737 Error! Reference source not found.** is a Technical Report titled "**Study on architecture aspects for using satellite access in 5G**". The document is a cornerstone for the integration of **Non-Terrestrial Networks (NTN)**—such as satellites and high-altitude platforms—into the 5G ecosystem. Its primary goal is to ensure that satellite connectivity is not a separate silo but a fully integrated part of the 3GPP standard. The report identifies and analyses several critical technical aspect. There are two **Architectural Models** that defines how satellites interface with the 5G Core (5GC). One is the **Transparent Mode**: The satellite acts as a radio frequency (RF) repeater, simply reflecting signals between the ground station (gateway) and the user device and the other one is a **Regenerative Mode**: The satellite carries onboard processing power, effectively acting as part of the base station (gNB). Another critical aspect is the **Latency Challenges** because satellites (especially GEO) are far from Earth, the report studies how to adapt 5G protocols to handle significant propagation delays. Regarding **Mobility & Registration**, it outlines procedures for how a device (UE) registers with the network when its "cell" is a moving satellite and how to handle handovers between terrestrial and satellite coverage. In the case of **Spectrum Coexistence**, the study explores how 5G satellite services can coexist with existing terrestrial networks on adjacent channels. The findings in TR 23.737 paved the way for **Release 17**, which introduced the first official normative requirements for NTN. This enables standardized global connectivity for: **IoT Devices** in remote or maritime areas, **backhaul services** for moving platforms like planes and trains and **critical Communications** and disaster recovery when terrestrial towers are down.

Technical Specification Group	Release	Study Item/Work Item	Responsible Groups	Technical Report
<b>RAN (Radio Access Network)</b>	Rel-15	RP-171450: Study on NR to support non-terrestrial networks  Objective: study channel model, deployment scenarios, and potential key impact areas	RAN plenary, RAN1	TR 38.811 [7]
	Rel.16	RP-190710: Study on solutions for NR to support non-terrestrial networks	RAN1, RAN2, RAN3	TR 38.821 [8]

		Objective: study a set of necessary features enabling NR support for NTN.		
	Rel-17	RP-201256: Solutions for NR to support non-terrestrial networks Objective: specify the enhancements identified for NR NTN with a focus on LEO and GEO and implicit compatibility to support high altitude platform station and air-to-ground scenarios.	RAN1, RAN2, RAN3, RAN4	n/a
	Rel-17	RP-193235: Study on NB-IoT/eMTC support for NTN Objective: identify scenarios and study necessary changes to support NB-IoT and eMTC over satellite.	RAN1, RAN2	TR 36.763 [9]
<b>SA (Service &amp; System Aspects)</b>	Rel-16	SP-170702: Study on using satellite access in 5G Objective: identify use cases and the associated requirements	SA1	TR 22.822 [10]
	Rel-17	SP-180326: Integration of satellite access in 5G Objective: specify stage 1 requirements.	SA1	n/a
	Rel.17	SP-181253: Study on architecture aspects for using satellite access in 5G Objective: identify key issues of satellite integration in 5G system architecture and provide solutions for direct satellite access and satellite backhaul.	SA2	TR 23.737 [12]
	Rel-17	SP-191335: Integration of satellite systems in the 5G architecture Objective: produce normative specifications based on the conclusions identified in TR	SA2	n/a

		23.737.		
	Rel-17	SP-190138: Management and orchestration aspects with integrated satellite components in a 5G network  Objective: identify key issues associated with business roles, service and network management, and orchestration of a 5G network with integrated satellite component(s) and study the associated solutions.	SA5	TR 28.808 [12]
	Rel-18	SP-191042: Guidelines for extra-territorial 5G systems  Objective: study use cases of extra-territoriality, identify relevant features, technical aspects, and applicable types of regulations.	SA1	TR 22.926 [13]
<b>CT (Core networks &amp; Terminals)</b>	Rel-17	CP-202244: CT aspects of 5GC architecture for satellite networks Objective of study phase: study the issues related to PLMN selection and propose solutions.  Objective of normative phase: support the stage 2 requirements, and the requirements and solutions for PLMN selection for satellite access.	CT1, CT3, CT4	TR 24.821 [14]

FIGURE 2. TABLE WITH A SUMMARY OF 3GPP NTN WORK

### 3. NTN Architectural Models

Three main architectures are defined: (i) **transparent payload (bent-pipe)**, (ii) **regenerative payload (on board processing)**, and (iii) **hybrid architectures**, ensuring direct-to-device connectivity and enhanced network flexibility.

Transparent payload architectures rely on ground-based processing, while regenerative payloads move processing on board satellites, enabling reduced latency and improved scalability. The key aspects on each NTN Architectural Models lies in how the payload is processed in space:

- **Transparent Payload (Bent-pipe):** The satellite acts as a repeater. It amplifies the signal received from the user terminal (UE) and redirects it to the ground station (gateway), or vice versa, without changing the waveform.
- **Regenerative Payload (Onboard Processing):** The satellite performs base station (gNB) functionalities, such as demodulation and decoding. This model can improve efficiency and reduce latency by handling data onboard before sending it to the core network.
- **Hybrid (Integrated Terrestrial-NTN):** Combines satellite/aerial networks with traditional terrestrial networks, allowing devices to switch seamlessly between cell tower and satellite coverage.
- **Multi-Tier Architectures:** Integrates different types of non-terrestrial elements, such as LEO constellations for low-latency communication and GEO satellites for wide-spread coverage.

The key components of the NTN Architecture are:

- **User Equipment (UE):** Standard 5G smartphones, IoT devices, or dedicated VSAT terminals.
- **NTN Payload/Platform:** Space borne (LEO, MEO, GEO satellites) or Airborne (HAPs, UAVs) systems.
- **Gateway:** Ground stations that connect the satellite to the 5G Core Network.
- **Service Link:** The wireless link between the UE and the satellite/aerial platform.
- **Feeder Link:** The link between the satellite/aerial platform and the gateway.

NTN architecture is visualized as **3D layered Network**:

- **Space Segment:** LEO (Low Earth Orbit), MEO (Medium), and GEO (Geostationary) satellites.
- **Aerial Segment:** High Altitude Platform Stations (**HAPS**) like balloons or gliders (approx. 20km altitude).
- **Ground Segment:** The **UE (User Equipment)**, the **NTN Gateway** (Earth Station), and the **5G Core Network**.

## 4. Physical Layer and Channel Modeling

In Non-Terrestrial Networks (NTN), the **Physical Layer (PHY)** and **Channel Modeling** are redefined to handle extreme distances, massive Doppler shifts, and atmospheric interference. NTN channels are characterized by long propagation delays, high Doppler shifts, and link asymmetry. GEO systems introduce delays up to 250 ms RTT, while LEO systems exhibit fast time-varying Doppler. 3GPP defines NTN-specific adaptations including extended timing advance, Doppler pre-compensation, and flexible numerology.

Models NTN-TDL-A to NTN-TDL-D are defined in TR 38.811. Adaptations include extended timing advance, HARQ process optimization, and Doppler pre-compensation.

### Channel Modeling (3GPP TR 38.811)

Unlike terrestrial networks, NTN channels are dominated by Line-of-Sight (LOS) conditions but suffer from massive path loss.

- **Propagation Models:** 3GPP uses **Clustered Delay Line (CDL)** and **Tapped Delay Line (TDL)** models (e.g., TDL-D and TDL-E for LOS) specifically tuned for satellite altitudes.
- **Path Loss:** Beyond Free Space Path Loss (FSPL), models must account for **clutter loss** (buildings/trees), **ionospheric scintillation**, and **tropospheric absorption** (gas/rain), especially in Ka-band.
- **Doppler Shift:** LEO satellites travel at  $\sim 7.5$  km/s, causing frequency shifts far beyond 5G terrestrial limits. Modeling must include both **common Doppler** (satellite-to-beam center) and **differential Doppler** (across the beam footprint).

### Physical Layer Adaptations

Standard 5G NR is "hardened" to survive the satellite environment:

- **Numerology (SCS):** Higher Subcarrier Spacing (e.g., **30, 60, or 120 kHz**) is used to combat Phase Noise and Doppler spread.
- **Timing & Synchronization:** Because the Round Trip Time (RTT) can be up to 541ms (GEO), the PHY layer introduces **timing advances (TA)** and frequency offsets that are pre-compensated by the UE based on GNSS data.
- **Reference Signals:** DMRS (Demodulation Reference Signal) patterns are often made more **dense** to track rapidly changing channels in LEO orbits.
- **Hybrid ARQ (HARQ):** Due to long delays, standard HARQ stop-and-wait processes are often disabled or extended (up to 32 processes) to prevent link stalling.

### Payload Architectures

- **Transparent (Bent-pipe):** The satellite acts as a radio frequency (RF) repeater. The PHY layer processing happens entirely on the ground (Gateway).
- **Regenerative (On-board processing):** The satellite carries a full or partial **gNB**. This allows for signal demodulation and decoding in space, significantly reducing latency for signaling loops.

### Link Budget (Power vs. Performance)

In NTN, the budget is usually "downlink limited" (satellite to phone) due to the extreme distances.

- **Path Loss:** For a LEO satellite at 600km, the **Free Space Path Loss (FSPL)** at 2 GHz is  $\sim 154$  dB. For a GEO satellite, it jumps to  $\sim 210$  dB.

- **G/T Ratio:** This is the key metric for receiver sensitivity (Gain-to-Noise Temperature). Satellites need massive antenna arrays to maintain a positive **Signal-to-Noise Ratio (SNR)**.
- **EIRP:** Satellites must blast high Effective Isotropic Radiated Power to reach standard handheld devices, often requiring specialized **spot beams** to concentrate energy.

### Synchronization (Timing & Doppler)

Because the "cell" is moving at 27,000 km/h (LEO), the phone cannot just "listen" like it does for a cell tower.

- **Pre-compensation:** The UE (User Equipment) uses its own **GNSS (GPS)** coordinates and the satellite's **Ephemeris data** (orbital path) to calculate and "pre-shift" its frequency. This cancels out the Doppler effect before the signal even leaves the phone.
- **Timing Advance (TA):** In terrestrial 5G, TA is measured in microseconds. In NTN, the delay can be hundreds of milliseconds. 3GPP Rel-17 introduced **Common TA** (delay to the beam center) and **UE-specific TA** (additional delay based on the user's position) to ensure the signal hits the satellite's "uplink window" perfectly.
- **Random Access (RACH):** The initial handshake is modified. The UE sends a "pre-compensated" preamble so the satellite perceives the signal as if it came from a stationary source at a fixed distance.

Feature	Terrestrial (TN)	LEO NTN	GEO NTN
Propagation Delay	< 1 ms	10 – 40 ms	~541 ms
Doppler Shift	Negligible	Up to 500+ kHz	Minimal
Cell Radius	1 – 5 km	100 – 1000 km	200 – 3500 km
Handover	UE-controlled	Satellite-controlled	Rare

FIGURE 3. TERRESTRIAL VS NTN

## 5. Mobility Management and Service Continuity

In NTN, **Mobility Management** is inverted compared to terrestrial networks: instead of a user moving between stationary towers, the "towers" (satellites) are moving at 27,000 km/h over stationary or moving users.

Mobility in NTN requires predictive handover mechanisms based on satellite trajectories. Multi-connectivity enables simultaneous TN and NTN links, ensuring seamless service continuity. Interworking between access networks is a critical standardization focus.

This creates a high-frequency handover environment where **Service Continuity** is the top priority.

### The Two Types of NTN Mobility

- **Earth-Moving Cells (LEO):** The satellite beams move across the ground. A user stays in one spot but must switch beams every 1–2 minutes as the satellite passes overhead.
- **Earth-Fixed Cells:** The satellite uses steerable antennas to keep a beam pointed at a specific geographic area (e.g., a city) until it reaches the edge of its visibility, then "hands off" the entire area to the next satellite.

### Handover Mechanisms (Rel-17/18)

To prevent dropped calls or data sessions during these fast transitions, 3GPP introduced specific enhancements:

- **Time-Based Triggering:** Since satellite orbits are deterministic (predictable via **Ephemeris data**), the network doesn't just wait for the signal to get weak. It can trigger a handover based on a **timer** or a specific **location** before the satellite disappears over the horizon.
- **Conditional Handover (CHO):** The network sends the "target cell" information to the phone in advance. The phone then executes the switch automatically when a specific condition is met (e.g., a time threshold or GPS coordinate), reducing the risk of signaling failure during the critical switch moment.

### Service Continuity Challenges

- **Propagation Delay:** In GEO, the 541ms delay makes standard terrestrial handovers too slow. NTN uses **RACH-less handovers** where the target cell already knows the UE's timing/power parameters, skipping the "handshake" to save time.
- **Feeder Link Switchover:** Service continuity isn't just about the User-to-Satellite link. If the satellite moves out of range of its **Ground Gateway**, it must switch to a new gateway. This can cause a brief "micro-interruption" unless **Inter-Satellite Links (ISL)** are used to route data through the vacuum of space.
- **Ephemeris Assistance:** The UE uses orbital data to predict which satellite will be available next. This allows the device to stay in "sleep mode" (DRX) longer and wake up exactly when the next beam is overhead, saving battery.

### Tracking Area Management

In terrestrial 5G, Tracking Areas (TA) are small. In NTN, a single satellite beam can cover hundreds of kilometers.

- **Fixed TAs:** TAs are mapped to geographic coordinates on Earth. Even as satellites fly by, the "Tracking Area ID" for a city remains the same, reducing the amount of signaling the phone has to do as it "changes" satellites.

Challenge	Terrestrial Solution	NTN Solution
Trigger	Measurement-based (RSRP)	Time & Location-based
Execution	Immediate command	Conditional Handover (CHO)
Delay	~10-50 ms	Up to 600 ms (GEO)
Visibility	Random	Predictable (Ephemeris)

FIGURE 4. CHALLENGE TERRESTRIAL VS NTN

## 6. Integrated Coverage Mechanisms

To achieve **Integrated Coverage**, the goal is to make the transition between Terrestrial Networks (TN) and Non-Terrestrial Networks (NTN) invisible to the user. This is often called **Service Continuity** across a 3D network. Integrated coverage is achieved through multi-layer networking, beamforming, beam hopping, and dynamic resource allocation. The objective is seamless user experience across heterogeneous infrastructures, including rural, maritime, and aerial domains.

Here are the core mechanisms enabling this integration:

### Unified Core Network (5G Core)

Both the cell tower (gNB) and the satellite (NTN Gateway) connect to the same **5G Core (5GC)**.

- **AMF (Access and Mobility Management Function):** It treats the satellite as just another "cell," allowing the user to keep the same IP address and session while moving from a 5G tower to a satellite beam.
- **PLMN Selection:** The phone is programmed to prioritize TN (cheaper, lower latency). It only scans for NTN signals when the terrestrial signal drops below a specific **RSRP (Power)** threshold.

### Steering of Roaming & Access Control

Since satellite bandwidth is expensive and limited, integration uses **Access Class Barring (ACB)**:

- **Unified Access Control (UAC):** The network can "block" certain types of traffic (like video streaming) on the satellite link while allowing emergency calls or SMS, ensuring the integrated coverage doesn't collapse under high load.
- **Steering:** The network can force a device back to a terrestrial cell the millisecond it detects one, even if the satellite signal is technically "stronger."

### Conditional Handover (CHO) for Integration

This is the "bridge" between the two worlds.

- In a TN-to-NTN transition, the phone receives **CHO configurations** for both types of cells.
- **Execution:** If you drive into a tunnel or a remote "dead zone," the phone doesn't wait for a command from the dying TN tower. It uses a **local trigger** (e.g., TN signal < -110 dBm) to instantly execute the switch to the pre-configured satellite beam.

### System Information Blocks (SIB19)

A key mechanism for integration is **SIB19**, a new broadcast message introduced by 3GPP.

- **NTN Assistance Data:** It provides the satellite's **Ephemeris** (where it is in space) and **Common TA** (timing delay).
- **TN-NTN Neighbors:** Terrestrial towers now include satellite cells in their "Neighbor List." This tells your phone exactly which frequency to scan to find a satellite, preventing a battery-draining "blind search" of the entire sky.

### Multi-Connectivity (Dual Connectivity)

In advanced scenarios (Rel-18+), a device can maintain **simultaneous links**:

- **User Plane:** High-speed data (YouTube/Web) goes over the **TN** link.
- **Control Plane:** Critical signaling or backup data goes over the **NTN** link.
- If the TN link fails, the NTN link is already "warm" and takes over the traffic immediately with **0ms interruption**.

Mechanism	Purpose	Key Feature
<b>SIB19</b>	Discovery	Tells the phone where the satellites are.
<b>CHO</b>	Reliability	Moves the "decision" to the phone for faster switching.
<b>Ephemeris</b>	Precision	Syncs timing and frequency across space and ground.
<b>UAC</b>	Management	Prevents satellite congestion in integrated areas.

FIGURE 5. MULTICONNECTIVITY MECHANISMS

## 7. Spectrum Management and Coexistence

Efficient spectrum sharing between TN and NTN is a major challenge. Techniques include dynamic spectrum allocation, interference coordination, and cognitive radio. Regulatory frameworks from ITU complement 3GPP specifications. Managing spectrum in an integrated **TN-NTN** environment is one of the most complex regulatory and technical hurdles. The goal is to maximize capacity without causing the satellite to "blind" the ground towers or vice versa.

### Spectrum Allocation Strategies

There are two main ways to divide the airwaves:

- **Orthogonal (Fragmented) Allocation:** TN and NTN use different frequency bands. For example, 5G towers use **Band n78** (3.5 GHz), while the satellite uses **Band n256** (S-band). This is the safest way to avoid interference but is less efficient.
- **Co-Channel (Shared) Spectrum:** Both networks use the **exact same frequency**. This is the "holy grail" of integrated coverage but requires sophisticated coordination to prevent the satellite signal from drowning out local cell towers.

### Interference Scenarios

When sharing spectrum, two main types of interference occur:

- **Satellite-to-TN (Downlink):** A satellite's massive beam can cover a whole city, creating "noise" for ground users trying to talk to a local tower.
- **UE-to-Satellite (Uplink):** Thousands of ground phones talking to towers can create a "noise floor" that prevents the satellite from hearing its own users in space.

### Coexistence Mechanisms

To make sharing possible, the 3GPP and ITU (International Telecommunication Union) use these tools:

- **Geofencing & Beam Nulling:** The satellite uses **Digital Beamforming** to "turn off" or "dim" its signal over areas where terrestrial 5G is highly active (like downtown Manhattan).
- **Power Control (TPC):** The network tells the phone to use the absolute minimum power needed to reach the satellite, reducing the "leakage" into nearby ground towers.
- **Guard Bands:** Placing a small "buffer" of unused frequency between the TN and NTN channels to prevent signal bleeding.
- **Frequency Reuse:** Using different "colors" (frequencies) for adjacent satellite beams to minimize self-interference, similar to how cellular hexagonal cells work.

## Key Frequency Bands for NTN

- **S-Band (2 GHz):** Best for **direct-to-handheld** (smartphones). It penetrates clouds and trees well but has limited bandwidth.
- **Ka-Band (20/30 GHz):** Massive bandwidth for **backhaul** (connecting a remote tower to the internet) or specialized terminals, but it is very sensitive to rain and oxygen absorption.
- **L-Band (1-2 GHz):** Highly reliable, used for legacy satellite IoT and emergency messaging.

## Regulatory Challenges (The "Radio Regulations")

- **Cross-Border Interference:** A satellite beam might cross from a country using S-band for satellites into a country using S-band for 5G towers. This requires international coordination via the **ITU-R**.
- **Priority:** Generally, terrestrial networks have "primary" status in many bands, meaning the satellite must prove it won't cause interference before it is allowed to transmit

## 8. Performance Metrics and KPIs

Key performance indicators include latency, throughput, spectral efficiency, reliability, and availability. NTN systems must balance coverage extension with performance degradation due to propagation constraints. Latency varies by orbit: GEO (~600 ms RTT), MEO (~150 ms), LEO (~30–50 ms). Throughput depends on bandwidth and link budget. Availability can exceed 99% with constellation diversity. In terms of coverage, GEO and LEO orbits has a global coverage and MEO a regional one.

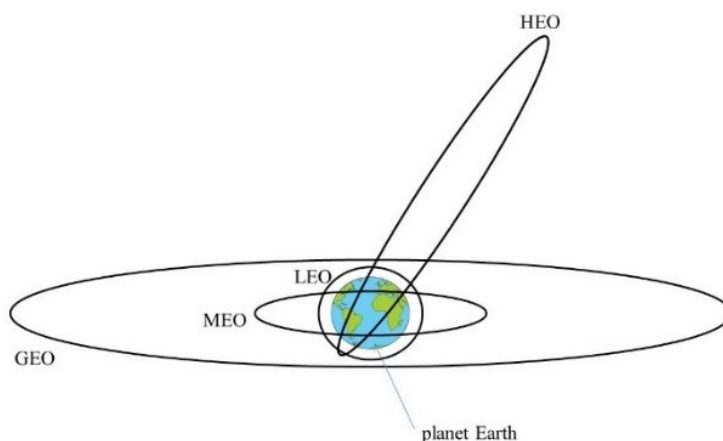


FIGURE 6. ILLUSTRATION OF THE CLASSES OF ORBITS OF SATELITTES  
[SOURCE: TR 22.822]

## 9. Advanced Use Cases

Emerging use cases include direct-to-device satellite communication, global IoT, aviation connectivity, maritime broadband, and disaster recovery. NTN is also a key enabler for mission-critical communications. The main use case for GEO is broadcast, and backhaul in the case of MEO. LEO uses cases are centred on IoT/D2D communications.

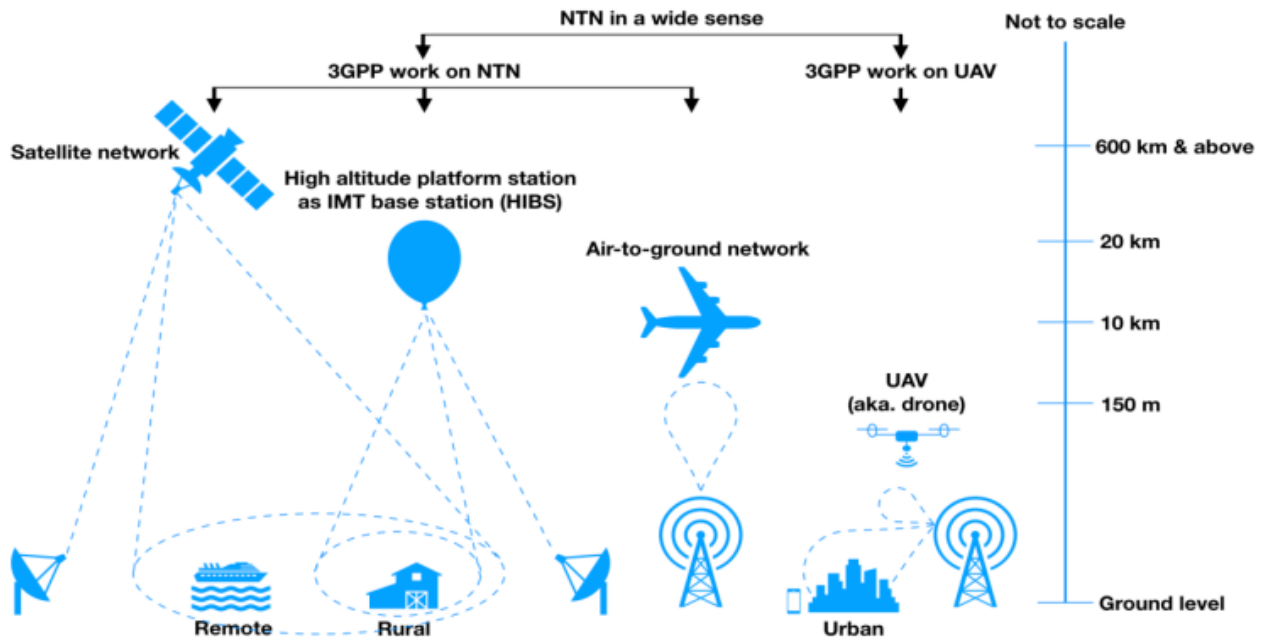


FIGURE 7. USE CASE SCENARIOS

## 12. Conclusion

The integration of TN and NTN is a cornerstone of future communication systems. Ongoing standardization and research efforts are shaping a unified, resilient, and globally accessible network infrastructure. 3GPP introduced NTN support in Release 17, enabling satellite-based connectivity in GEO, MEO, and LEO orbits.. Rel-18 focuses on optimization, Rel-19 on integration, and 6G on AI-native NTN. The main impact is that support EU digital sovereignty, sustainability, and global connectivity. Future roadmap to 6G for NTN includes AI-native control, ISL (inter-satellite links), and integrated sensing.

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