GSMA

White Paper



Implementation Guidelines for NB-NTN 3GPP Devices

Created by the GSMA IoT Community

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1. Introduction

Overview

Cellular IoT crossed a milestone at the end of 2025: one billion active NB-IoT and LTE-M connections worldwide. Mobile IoT now underpins asset tracking, agriculture, utilities, industrial monitoring, environmental sensing, logistics, maritime, and mining, using 3GPP-standardised low power wide area technologies that offer long battery life, deep coverage, and modules costing single digit dollars per unit.[1]

But the industry faces geographic constraints. While 96% of the world's population lives within the footprint of terrestrial mobile broadband, the picture is different for machines. Some high value IoT deployments are beyond the reach of conventional cellular networks: tracking livestock on remote grazing land and containers in the middle of the ocean, sensors along pipelines through deserts, and monitoring stations in mountainous regions. Until recently, connecting these assets meant using bespoke satellite modems costing ten to a hundred times more than a cellular module.[1]

Now, new non-terrestrial networks (NTN) are closing this gap by using satellite constellations, and to a lesser extent, high altitude platforms and unmanned aerial systems, as an extension of the mobile network. 3GPP Release 17 is the turning point: it standardised NB-IoT and LTE-M over NTN so the same air interfaces employed by terrestrial IoT can now operate with satellites. This is what the industry calls IoT-NTN.

As IoT-NTN is based on 3GPP standards, an IoT-NTN device can be built by any chipset vendor, certified once, and deployed globally under normal 3GPP roaming principles. The per unit economics converge on those of a terrestrial NB-IoT module, and the addressable market extends beyond the terrestrial coverage boundary to the whole planet. The first commercial IoT-NTN chipsets, modules, and reference designs are now shipping, satellite operators have live services, and mobile network operators are opening IoT-NTN roaming to their enterprise customers, and consumer devices.

Scope

This white paper is a practical implementation guide for the ecosystem that builds and deploys IoT-NTN devices. It follows the developer journey through the design decisions for a satellite link:

- understanding the 3GPP standards that apply,
- planning for the network behaviour of an intermittent orbital link,
- choosing hardware and antennas,
- deciding SIM and eSIM strategy,
- addressing security specific to satellite access,
- and preparing for deployment and lifecycle operations.

The intended readership includes chipset vendors, module and device manufacturers, mobile network operators and satellite MVNOs, IoT solution providers, system integrators, and regulators.

The primary focus is IoT-NTN (NB-IoT NTN and LTE-M NTN). A small number of NR-NTN topics are included where they inform the direction of the standard. Note, the details of high altitude platform stations (HAPS) and unmanned aerial systems (UAS) are outside the scope of this document.

2. Definitions

Airborne vehicles: Unmanned aerial systems (UAS) encompassing tethered UAS, lighter-than-air UAS and heavier-than-air UAS, all operating in altitudes typically between 8 and 50 km including high altitude platforms (HAPs)

Direct-to-device (D2D): Direct-to-device (D2D) satellite technology enables standard smartphones, wearables, and IoT devices to connect directly to satellites, eliminating the need for specialised hardware. It provides global coverage, filling gaps in terrestrial networks, especially for emergency SOS, messaging, and basic data in remote areas.

Direct-to-cell (D2C): A subset of D2D, direct-to-cell (D2C) services allow mobile phones to connect directly to satellites in orbit.

Feeder link: A feeder link is a high-capacity radio or optical link between a fixed earth station (gateway) and a satellite, used for transmitting data to be relayed to users (uplink) or receiving user data from the satellite (downlink). It connects the satellite network to terrestrial networks, often using large, high-power antennas for reliable communication.

Geostationary Earth orbit (GEO): Circular orbit at 35,786 kilometres above the Earth's equator and following the direction of the Earth's rotation. A GEO object has an orbital period equal to the Earth's rotational period and thus appears motionless, at a fixed position in the sky, to ground observers.

gNB: In 5G networks, gNB is the base station responsible for handling radio communication between user equipment (UE) and the core network.

High altitude platform station (HAPS): airborne vehicle bearing the NTN payload placed at an altitude between 8 and 50 km.

IoT: Internet of Things, a generic term for the network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment. IoT offers functions and services that go beyond the scope of M2M. MIoT is a subset of the far bigger IoT concept. For example, sensors connected via Wi-Fi or Bluetooth are a part of the IoT, but not MIoT.

Low Earth orbit (LEO): Orbit around the Earth at an altitude between 500 kilometres (orbital period of about 88 minutes) and 2,000 kilometres (orbital period of about 127 minutes).

M2M: Machine-to-machine, a general term referring to any network technology allowing devices to communicate with each other. For example, two industrial robots connected to each other via Ethernet in a factory is a part of M2M, but not MIoT.

Medium Earth orbit (MEO): Region of space above low Earth orbit and below geostationary Earth orbit, typically at an altitude between 8,000 to 20,000 km.

MIoT: Mobile Internet of Things, a GSMA term which refers to the 3GPP-standardised LPWA technologies (aka LTE-M, NB-IoT and EC-GSM-IoT) using a licenced band.

NB-IoT NTN or NB-NTN: Narrowband Internet of Things for NTN, with spectrum usage of 180 KHz.

Non-geosynchronous orbit (NGSO): Earth-centred orbit with an orbital period that does not match Earth's rotation on its axis. This includes low and medium Earth orbit (LEO and MEO).

Non-geostationary satellites: Satellites (LEO and MEO) orbiting around the Earth with a period that varies between approximately 1.5 hours and 10 hours. A constellation of several non-geostationary satellites with handover mechanisms is required to ensure service continuity.

Non-regenerative payload (also called "bent pipe payload" or "transparent mode"): A spaceborne/ airborne platform that doesn't process a signal on-board, before transmitting it on the downlink, i.e. the platform corresponds to an analogue RF repeater.

Non-terrestrial networks (NTN): Networks, or segments of networks, using an airborne or space-borne vehicle to carry transmission equipment, such as a relay node or base station.

NR: New Radio is the global standard for the air interface of 5G mobile networks.



NTN Gateway: An earth station located at the surface of the earth, providing connectivity to the NTN satellite payload using a feeder link. An NTN Gateway is a TNL node.

NTN satellite payload: A network node on-board a satellite or high-altitude platform station, which provides connectivity functions between the service link and the feeder link.

Regenerative payload: Payload that processes and amplifies an uplink RF signal before transmitting it on the downlink. The transformation of the signal ijnvolves digital processing that may include demodulation, decoding, re-encoding, re-modulation and/or filtering.

Satellite: A space-borne vehicle carrying a bent pipe payload or a regenerative payload telecommunication transmitter.

Satellite access node (SAN): Node providing user plane and control plane protocol terminations towards NTN satellite-capable UE and connected via the NG interface to the 5GC. It encompasses a transparent NTN payload on board an NTN platform, a gateway and gNB functions.

Space-borne vehicles: Satellites including low Earth orbit (LEO) satellites, medium Earth orbit (MEO) satellites, geostationary Earth orbit (GEO) satellites, as well as highly elliptical orbit (HEO) satellites.

Service link: Wireless link between the NTN payload and UE.

TNL node: A TNL (transport network layer) node is a network element that handles the transport of data within the NTN. Specifically, an NTN gateway is considered a TNL node, acting as the interface between the terrestrial network and the NTN payload (e.g., a satellite) via the feeder link.

3. Abbreviations

Term	Description
3GPP	3rd Generation Partnership Project
5GC	Fifth generation core network
AI	Artificial Intelligence
API	Application Programming Interface
APN	Access point name
BS	Base station
BVLOS	Beyond visual line of sight
CN	Core network
D2D	Direct-to-device
dB	Decibel
DRX	Discontinuous reception
DL	Downlink
eDRX	Extended discontinuous reception
EF	Elementary file
eSIM	Embedded SIM
eUICC	Embedded UICC
FCC	Federal Communications Commission
FDD	Frequency division duplex
FR1	Frequency Range 1
GCF	Global Certification Forum
GEO	Geostationary Earth orbit
GSM	Global System for Mobile Communications
GSMA	GSM Association

Term	Description
GSO	Geosynchronous orbit
HAP	High altitude platform
HEO	Highly elliptical orbit
IoT	Internet of Things
iSIM	Integrated SIM
ISL	Inter-satellite link
Ka band	Frequency band covering the 17.3 - 31GHz frequency range
Ku band	Frequency band covering the 12 – 17.3 GHz frequency range
L band	Frequency band covering the 1-2 GHz frequency range
LEO	Low Earth orbit
LPWA	Low power wide area
LTE	Long-Term Evolution
LTE-M	Long-Term Evolution Machine Type Communications (also called LTE Category M)
M2M	Machine-to-machine.
MEO	Medium Earth orbit
MIoT	Mobile Internet of Things
ML	Machine learning
MNO	Mobile network operator
MTC	Machine Type Communications
NB-IoT	Narrowband IoT
NB-NTN	Narrowband non-terrestrial network
NGSO	Non-geosynchronous orbit
NR	New Radio
NTN	Non-terrestrial network
PLMN	Public land mobile network
PNT	Positioning, navigation, and timing
PSM	Power saving mode
RAN	Radio access network
RedCap	Reduced capability

Term	Description
RF	Radio frequency
RSP	Remote SIM provisioning
S band	Frequency band covering the 2 - 4 GHz frequency range
S&F	Store and forward
SAN	Satellite access node
SIM	Subscriber identity module
SMS	Short Message Service
SoC	System on chip
SRI	Satellite radio interface
TNL	Transport network layer
TS	Technical specification
UAS	Unmanned aerial system
UE	User equipment
UICC	Universal Integrated Circuit Card (sometimes known as the SIM card)
UL	Uplink
VSAT	Very small aperture terminal

4. References

Ref	Doc Number	Title
[1]	GSMA	http://gsma.com/solutions-and-impact/technologies/internet-of-things/billion-lpwan-connections
[2]	3GPP TS 38.101-5	5GNCTF
[3]	3GPP TS 36.102	Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception for satellite access
[4]	GSMA SGP.32	eSIM IoT Technical Specification
[5]	3GPP TR 38.811	Study on New Radio (NR) to support non-terrestrial networks
[6]	3GPP TR 22.822	Study on using Satellite Access in 5G; Stage 1
[7]	3GPP TR 22.926	Guidelines for extraterritorial 5G Systems (5GS)
[8]	GSMA TS.34	IoT Device Connection Efficiency Guidelines
[9]	3GPP TS 31.102	Characteristics of the Universal Subscriber Identity Module (USIM) application
[10]	Antenna Optimization for NTN IoT Devices	https://www.kyocera-avx.com/docs/techinfo/Antennas/Optimizing-IoT-Devices-GEO-NB-NTN-Hybrid-Connectivity.pdf

5. NTN standardisation

3GPP has made significant progress in standardising non-terrestrial networks (NTN), starting with Release 17 and continuing through Releases 18, 19, and the upcoming Release 20. This work defines support for satellite-based 5G NR and IoT technologies, enabling direct-to-device services and expanding coverage to remote or underserved regions.

The role of standards: 3GPP evolution

Industry-wide standards, primarily those developed by the 3rd Generation Partnership Project (3GPP), are the bedrock upon which an interoperable, scalable, and economically-viable NTN ecosystem is being built. The phased evolution of these standards, complemented by collaborative industry initiatives, is shaping the trajectory of NTN technology.

3GPP Release 17, often referred to as "the first wave" for NTN, marked a pivotal moment by formally standardising the integration of non-terrestrial networks with the NB-IoT and 5G system. Release 17 introduced support for both NGSO constellations (including LEO and MEO) and GSO (GEO) satellites. Crucially, it laid the groundwork for two main service categories: 5G New Radio NTN (NR-NTN), enabling direct satellite connectivity for 5G handsets operating in Frequency Range 1 (FR1), and IoT-NTN, supporting low-power wide-area (LPWA) technologies, such as NB-IoT and LTE-M, over satellite for various use cases. IoT-NTN based on the NB-IoT protocol is commonly called NB-NTN.

3GPP Release 18, themed around "enhancing performance", introduced a range of improvements for both LTE-based NTN (primarily IoT NTN) and NR-NTN. It defined frequencies beyond 10 GHz for NTN use, including enabling the Ka-band for NR-NTN services. Additionally, Release 18 defined new frequency bands below 3 GHz, such as an extended L-band (primarily for NB-NTN) and a combination of L and S bands (for both NB-NTN and NR NTN).

3GPP Release 19, was finalised in late 2025, and is focused on increasing capacity. Key improvements include support for regenerative payloads for both IoT-NTN and NR-NTN (which allows for on-satellite processing to improve link budgets and efficiency), enabling NTN connectivity for reduced capability (both RedCap and eRedCap) UE (designed for simpler, lower-cost 5G devices), and the formal definition of Ku-bands for NTN operation. Looking ahead, 3GPP Release 20 studies are ongoing, indicating a continued commitment to the evolution and progression of NTN technology within the 5G Advanced framework and towards 6G; including GNSS resilience in NTN.



Looking ahead, **3GPP Release 20** studies are ongoing, indicating a continued commitment to the evolution and progression of NTN technology within the 5G Advanced framework and towards 6G; including GNSS resilience in NTN.

3GPP Release	Key NTN features & enhancements	Implications for devices & infrastructure	Support for use cases
Rel-17	Initial NTN integration with 5G; support for NGSO (LEO, MEO) & GSO; NR-NTN (FR1) & IoT-NTN (NB-IoT, LTE-M); addressed basic Doppler & delay compensation.	First-generation NTN chipsets/ modems; UE adaptations for satellite links; satellite payload considerations for 3GPP waveforms.	Basic IoT (tracking, sensing); emergency messaging; initial direct-to-device trials.
Rel-18	Performance enhancements for NR-NTN & IoT-NTN; improved uplink coverage (NR); enhanced NTN-TN & NTN-NTN mobility; UE location verification; Ka-band for NR-NTN.	Second-generation chipsets with better performance; advanced antenna systems; ground segment upgrades for new bands & mobility features.	Improved IoT services, more robust mobile broadband extension; early direct-to-device voice/data; public safety applications.
Rel-19	Focus on increased capacity; regenerative payload support (IoT & NR); RedCap UE support; Ku-band definition; Reduced GNSS dependence.	Advanced SoCs for regenerative payloads; Optimised RedCap devices; Multi-band UE RF front-ends; Enhanced satellite processing capabilities.	High-capacity direct-to-device, advanced IoT with store-and-forward; efficient broadcast/ multicast services; more resilient positioning for NTN UEs.
Rel-20 (Outlook)	Continued evolution of NTN; potential for AI/ML in NTN resource management and beamforming.	Next-gen chipsets with AI capabilities; highly-integrated satellite and terrestrial network functions; new spectrum considerations for 6G.	Seamless 5G Advanced services over NTN; AI-optimised network performance; immersive experiences; highly autonomous systems.

Table 1: Evolution of 3GPP Standards for NTN

In summary, there is a collaborative effort to integrate satellite communication with IoT and NR, enabling a more connected and resilient wireless ecosystem.

Benefits of NTN standardisation

- Improved interoperability: NTN standardisation allows for seamless communication between cellular standards-compliant devices and via satellites interfacing cellular network infrastructure.
- Reduced complexity: Standardised technologies and protocols simplify the development and deployment of NTN terminals.
- Economies of scale: A single, global standard allows for the mass production of compatible chipsets and modules. This high-volume manufacturing dramatically drives down costs for devices, making NTN connectivity economically-viable for a much wider range of applications. Standardised NTN devices are much lower cost than non-standardised devices, allowing for lower network subscription costs and overall more cost-effective solutions.
- Global roaming and service portability: Standardisation enables global roaming across different TN and NTN operators, just as between terrestrial networks. This ensures a consistent user experience and allows device manufacturers to build a single product that can be deployed worldwide. If a satellite constellation ceases operation, devices can switch to another—provided it adheres to 3GPP standards and the MNO issuing the SIM maintains the necessary roaming agreements.

NTN frequency bands

The following tables, which are replications of tables 5.2.2-1 & 5.2.3.1 from 3GPP TS 38.101-5[2] and table 5.2.1 in 3GPP TS 36.102[3], specify the frequency bands used for NTN communication between UE and satellites.

NTN satellite operating band[1]	Uplink (UL) operating band Satellite Access Node receive / UE transmit $F_{UL,low}$ – $F_{UL,high}$	Downlink (DL) operating band Satellite Access Node transmit / UE receive $F_{DL,low}$ – $F_{DL,high}$	Duplex mode
n256	1980 MHz – 2010 MHz	2170 MHz – 2200 MHz	FDD
n255	1626.5 MHz – 1660.5 MHz	1525 MHz – 1559 MHz	FDD
n254	1610 – 1626.5 MHz	2483.5 – 2500 MHz	FDD
n253	1668 MHz – 1675 MHz	1518 MHz – 1525 MHz	FDD
n252	2000 – 2020 MHz	2180 – 2200 MHz	FDD
n251	1626.5 MHz – 1660.5 MHz	1518 MHz – 1559 MHz	FDD
n250	1668 MHz – 1675 MHz	1518 MHz – 1559 MHz	FDD
n248	14000 MHz - 14500 MHz	10700 MHz – 12750[2,3] MHz	FDD
n247	13750 MHz - 14000 MHz	10700 MHz – 12750[2,3] MHz	FDD

NOTE 1: NTN satellite bands are numbered in descending order from n256.
NOTE 2: For Region 2, the downlink is limited to 10700 – 12700 MHz.
NOTE 3: For the US, the downlink is limited to 10700 – 12200 MHz for Mobile VSAT.
NOTE 4: Operating band n200 is a reserved value.

Table 2: NTN satellite bands in FR1-NTN

Satellite operating band	Uplink (UL) operating band SAN receive / UE transmit $F_{UL,low}$ – $F_{UL,high}$	Downlink (DL) operating band SAN transmit / UE receive $F_{DL,low}$ – $F_{DL,high}$	Duplex mode
n512[1]	27500 MHz - 30000 MHz	17300 MHz - 20200 MHz	FDD
n511[2]	28350 MHz - 30000 MHz	17300 MHz - 20200 MHz	FDD
n510[3]	27500 MHz - 28350 MHz	17300 MHz - 20200 MHz	FDD
n509	14000 MHz - 14500 MHz	10700 MHz – 12750[4,5] MHz	FDD
n508	13750 MHz - 14000 MHz	10700 MHz – 12750[4,5] MHz	FDD

NOTE 1: This band is applicable in the countries subject to or referring to CEPT ECC Decision(05)01 and ECC Decision (13)01.
NOTE 2: This band is applicable in the countries subject to or referring to FCC 47 CFR part 25.
NOTE 3: This band is applicable for Earth Station operations in the USA subject to FCC 47 CFR part 25. FCC rules currently do not include ESIM operations in this band (47 CFR 25.202).
NOTE 4: For Region 2, the downlink is limited to 10700 – 12700 MHz.
NOTE 5: For the US, the downlink is limited to 10700 – 12200 MHz for Mobile VSAT.

Table 3: Satellite operating bands in FR2-NTN



E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit $F_{UL,low}$ – $F_{UL,high}$	Downlink (DL) operating band BS transmit UE receive $F_{DL,low}$ – $F_{DL,high}$	Duplex mode
256	1980 MHz – 2010 MHz	2170 MHz – 2200 MHz	FDD
255	1626.5 MHz – 1660.5 MHz	1525 MHz – 1559 MHz	FDD
254	1610 – 1626.5 MHz	2483.5 – 2500 MHz	FDD
253[2]	1668 MHz – 1675 MHz	1518 MHz – 1525 MHz	FDD
252	2000 – 2020 MHz	2180 – 2200 MHz	FDD
249[4]	1616 MHz – 1626.5 MHz	1616 MHz – 1626.5 MHz	TDD
246[3]	N/A	1467 MHz – 1492 MHz	SDO

NOTE 1: Satellite bands are numbered in descending order from 256
NOTE 2: UE assigned to channels and allocated frequency resources in the lower portion of Band 253 may experience blocking or harmful interference from terrestrial networks in adjacent or nearby frequencies when operating in the proximity with terrestrial base stations.
NOTE3: Band 246 only applies for LTE-based 5G Broadcast over Geosynchronous Satellite in region 3.
NOTE 4: Band 249 is defined only for NB-IoT operation.

Table 4: E-UTRA operating bands for satellite access

Region	Band
Europe	256, 255, 254*, 253*
USA	256, 255, 254*
Canada	256, 255
India	256*, 255*
Australia	256*, 255*
Japan	256, 255, 254*
China	254*
Brazil	256*, 255
Africa	256, 255

* – trials/planned/consideration

Table 5: Mobile IoT regional frequency usage across the globe

Transmit power

The UE is required to transmit using Power Class 3 (23 dBm) as default power class, as detailed in table 6.2.1-1 of 3GPP TS 38.101-5[2] for NR NTN and table 6.2A.1-1 of 3GPP TS 36.102[3] for NB-NTN.

6. IoT use cases

NTN technology is set to unlock, or significantly enhance, a wide array of IoT use cases across numerous industries by providing connectivity in environments where terrestrial networks (TN) are absent or not functioning.

- **Maritime:** This sector is a prime beneficiary of NTN. Applications include real-time vessel and cargo monitoring, enhanced navigation and safety systems, optimised fleet management, improved communication capabilities for crew welfare and operational efficiency, streamlined logistics through container tracking, and marine environmental monitoring.
- **Agriculture:** NTN enables smart farming practices in vast rural areas lacking cellular coverage. This includes real-time monitoring of soil moisture, water levels, and overall crop conditions; tracking livestock for health, location, and environmental factors; enabling precision farming techniques to optimise resource use (water, fertilisers); and improving overall farm management.
- **Logistics and asset tracking:** NTN provides the backbone for truly global asset tracking and comprehensive fleet management. This ensures uninterrupted visibility of goods, vehicles, and containers as they traverse remote land regions, cross oceans, or move through areas with patchy terrestrial coverage, thereby enhancing supply chain efficiency and security.
- **Mining and energy:** In the mining and oil and gas sectors, operations often occur in extremely remote or offshore locations. NTN could deliver essential connectivity for autonomous equipment, robust worker safety systems, environmental sensors, and remote monitoring of critical infrastructure, such as drilling platforms and production sensors.
- **Disaster recovery notification systems:** During natural disasters or other crises, terrestrial communication infrastructure is sometimes damaged or overwhelmed. NTN can provide an alternative mode of communication, enabling life-saving coordination for first responders. HAPS and LEO satellite constellations can rapidly deploy temporary NB-NTN coverage for emergency teams and support search-and-rescue IoT devices.
- **Remote monitoring and environmental protection:** NTN facilitates the deployment of IoT sensors for monitoring crucial climate change indicators, tracking wildlife movements in vast, inaccessible habitats, assessing water and air quality, providing early warnings for wildfires, and monitoring critical infrastructure (such as pipelines and bridges) in remote areas.
- **Heavy equipment and industrial IoT:** For manufacturers of construction, mining, and agricultural machinery, NTN provides a vital link to vehicles operating in areas with no cellular service. This enables real-time telematics for tracking engine hours, fuel consumption, and location; supports predictive maintenance by monitoring component health remotely; and allows for remote diagnostics and software updates, significantly reducing the need for costly on-site technician visits.
- **Other emerging areas:** NTN is also finding applications in unmanned aerial vehicle (UAV)-based services requiring beyond-visual-line-of-sight (BVLOS) connectivity, enhancing public safety communications, supporting defence operations, and contributing to smart city initiatives where ubiquitous sensor connectivity is required.

7. Network considerations for IoT-NTN devices

For an application to perform reliably on an NTN-capable device, developers can't make the same assumptions as they do with terrestrial networks. The unique characteristics of satellite connectivity introduce specific challenges and considerations that directly impact application architecture, data handling, power management, and user experience. Developers who understand and design for these factors will create more successful and resilient solutions.

Interworking between NTN and TN

When developing NTN devices, it is important to consider support for TN as well. TN and NTN can complement each other: TN provides primary connectivity, while NTN can extend service to remote or underserved areas beyond the reach of TN, creating a more resilient and ubiquitous connectivity solution.

An IoT-NTN device will typically operate across both terrestrial and satellite coverage over its lifetime. The mobile operator and the satellite operator are responsible for network level interconnection, while the device OEM determines the bands and 3GPP Releases the modem will support. The SIM profile's PLMN and roaming configuration are controlled by the network, and the application logic is developed by the application developer.

Building network-aware application logic

As devices will often operate across both terrestrial networks (TN) and NTN, the application should behave intelligently based on the active network connection.

- **Handling network transitions:** The switch between TN and NTN can cause momentary service loss. The application needs to be resilient to these handovers and reliably provide continuity in data flows. It should also avoid logic that could trigger rapid, repeated switching between networks, a phenomenon known as "bouncing".
- **Context-aware features:** The application should adapt its functionality based on the network type. For example, it could disable non-essential, high-bandwidth features when on a higher-latency NTN connection or change its data synchronisation frequency. Awareness of the active SIM profile (one for TN, one for NTN) could be a mechanism to determine the network context. This prevents a poor user experience and avoids unnecessarily high data usage on the NTN link.



Managing variable latency and intermittent links

Unlike stable terrestrial networks, NTN connectivity is characterised by significant and fluctuating delays. An application must be architected to handle this reality.

- **High and variable delay:** The choice between NGSO and GSO is driven by specific use cases - balancing the need for low latency against high availability - applications must be designed to accommodate the resulting variability in network delay. To ensure a responsive interface across either architecture, developers should employ asynchronous communication while data is in transit.
- **Intermittent connectivity:** A clear line of sight to the satellite is crucial. Obstructions, such as moving into a building or even natural terrain, as well as movement of NGSO satellites, can cause temporary service outages. Applications must implement robust data caching and retry mechanisms with backoff to handle these connection drops gracefully without losing data or draining the battery with constant connection attempts.

Adapting to a "store and forward" paradigm

3GPP Release 19 introduces "store and forward" (S&F) functionality for NTN, enabling satellites to buffer and relay data during feeder link outages. This enhances connectivity and reliability for delay-tolerant IoT applications in intermittent coverage scenarios.

Key aspects of store and forward in Release-19:

- **Addressing intermittent connectivity:** The primary motivation for S&F in Rel-19 is to handle the challenge of maintaining connectivity when the feeder link (satellite-to-ground station) is severed.
- **Enhancing IoT applications:** S&F is particularly beneficial for delay-tolerant IoT applications where data can be temporarily stored on the satellite and forwarded later when a reliable connection is established.
- **Regenerative payload:** S&F is enabled by a regenerative payload architecture where core network functions and a base station (gNB) are placed on the satellite. This allows the satellite to act as a more intelligent intermediary, processing data and potentially even terminating connections directly between user equipment (UE).
- **Impact on the core network:** The introduction of S&F requires adaptations to the core network to support the storage and forwarding of data, as well as potentially new requirements for terminals (UEs) to interact with the S&F enabled network.
- **Implications for applications:** Application developers must shift from a real-time, "always-connected" mindset to one where data packets may be delivered hours later. This impacts everything from data structure (e.g., ensuring packets are self-contained with timestamps) to the design of the end-user platform. To maximise battery life, an application should align its data transmission schedule with the device's wake-up cycles, which is especially critical for IoT devices designed to last years in the field.

8. Antennas for IoT-NTN

Antennas determine how efficiently devices can establish and maintain satellite links - especially under the constraints of low power, compact size, and cost efficiency that IoT devices demand. As NTN moves from 3GPP Release 17 into mainstream deployment, antenna design will become a key enabler of reliable connectivity.

Key considerations for antennas in IoT-NTN

Satellite communication brings unique challenges for antennas. The received signal is inherently weak, and IoT devices are designed to minimise power consumption. If the antenna fails to capture enough signal, devices may require multiple retransmissions, wasting energy and reducing battery life.

Key antenna parameters for satellite communication:

- **Gain:** sufficient to close the link budget without requiring higher transmit power.
- **Polarisation:** matching satellite polarisation improves reception; circular (RHCP/LHCP) signals lose ~3 dB if received with linear antennas.
- **Bandwidth:** must cover transmit and receive frequencies across L- and S-bands.
- **Radiation pattern:** gain at low elevation angles is essential, especially for LEO satellites not always overhead.

The link budget highlights this dependency:

$G_{rx} = P_{req} - EIRP + L_{FreeSpace} + L_{at} + L_{other}$

Preq = required received power (dBm) = receiver sensitivity (TIS) + margin

EIRP = satellite effective isotropic radiated power (dBm)

$L_{FreeSpace}$ = $20\log10(d)+20\log10(f)+20\log10(4\pi/c0)$ (d being the distance between the LEO satellite and the ground, and f the carrier frequency) = free-space path loss (dB) = $20\log10\ (4\pi/\lambda)$

L_{at} = Atmospheric losses[10]

Typical free space losses + atmospheric losses for a satellite at 600 km altitude is:

- 152 dB for L-Band 1.6GHz
- 154 dB for S-Band 2GHz

L_{other} = sum of other additional losses in dB (satellite misalignment, polarization mismatch, etc.)

These additional losses are much more pronounced in satellite links than in terrestrial networks.

Beyond technical metrics, size and cost matter: traditional satellite antennas are too large and expensive for IoT. To scale NTN adoption, antennas must balance performance, integration, and affordability.

Antenna requirements in NTN

3GPP Release 17 defined initial device classes for NTN

Typical antenna specifications relate to the device performance TRP (total radiated power) and TIS (total isotropic sensitivity):

TRP *(total radiated power)*

TRP_{dBm} = Conducted PowerdBm + Antenna Total $Gain_{dB}$

TIS *(total isotropic sensitivity)*

TIS_{dBm} = Conducted $Sensitivity_{dBm}$ + Antenna Total $Gain_{dB}$ (ideally)

While TRP can be estimated from conducted power and antenna efficiency, TIS is more vulnerable to real-world noise and losses, making the antenna design and integration critical to close the link budget.

Antenna options for IoT-NTN devices

Hybrid devices (Terrestrial + NTN)

Hybrid IoT devices must support terrestrial LTE bands alongside NTN bands. While many LTE antennas already overlap with the S-band, coverage of the L-band is less common.

- **Single antenna:** lower cost and footprint, but typically linear polarisation and suboptimal for NTN.
- **Dedicated NTN antenna:** enables circular polarisation and better gain patterns, but increases complexity and cost, as the NTN bands must be extracted from the single output of the module. The orientation of the antenna must be defined towards the sky to take advantage of the circular polarisation.

When linear polarisation is used for both transmission and reception, the angle between the receive and corresponding transmit polarisation planes shall not deviate by more than 1° from the nominal value declared by the manufacturer. Linear polarisation can experience a significant signal penalty if the orientation is misaligned with the satellite signal.

Circular polarisation (LHCP (left hand circular polarisation) or RHCP (right hand circular polarisation)) can offer better performance in satellite communications because it is less susceptible to polarisation mismatch caused by the user equipment's orientation and the varying look angles to the satellite, especially for non-geostationary orbits (NGSO).

The choice between linear and circular polarisation for the actual product implementation ultimately depends on the use case, device vendor, balancing performance requirements with cost and design complexity.

Satellite-only devices

For satellite-only devices, orientation drives antenna design.

- **Static use cases:** can be oriented toward the sky, making circularly polarised antennas attractive due to their improved robustness.
- **Non-static use cases:** can also benefit from circular polarisation if the antenna maintains sky-facing orientation; otherwise, omnidirectional coverage becomes critical.

Traditional patch or helix antennas provide circular polarisation, but often suffer from limited bandwidth (not covering both Tx and Rx in L- and S-bands) or are too bulky for IoT form factors. Emerging laser direct structuring (LDS) techniques enable compact, circularly-polarised antennas with wide bandwidth and improved azimuth gain, offering a path to more practical IoT integration.

Towards multi-band and multi-constellation antennas

The next generation of NTN-IoT devices will require antennas that:

- Operate across both L- and S-bands
- Support multiple orbital constellations (NGSO, GSO)
- Seamlessly switch between terrestrial and satellite connectivity
- Remain compact and affordable for mass deployment

Innovations, such as designs in laser direct structuring (LDS), are opening paths to create multi-band, circularly polarised antennas in compact form factors. These technologies can provide consistent gain from zenith to near the horizon, improving link reliability for IoT devices even at low satellite elevations.

Another approach is the use of active antennas. One type can dynamically switch between radiation patterns—providing high gain toward the sky for satellite connectivity and enhanced azimuth gain for terrestrial base stations. A second type integrates a low-noise amplifier (LNA) at the receiver side, improving sensitivity and helping to close the link budget.



9. eSIM and eUICC considerations for NTN

As NTN deployments become more widespread, device identity management and profile flexibility grow increasingly critical. Embedded SIMs (eSIMs) or integrated SIMs (iSIMs) offer the adaptability and scalability necessary for managing connectivity in a dynamic NTN environment. Their use in NTN-capable devices presents both new opportunities and unique operational considerations.

Profile management in multi-domain connectivity

NTN-capable devices often need to function across both terrestrial (TN) and non-terrestrial (NTN) domains. eSIMs allow multiple subscription profiles to coexist securely within the same device, enabling operational flexibility:

- **Single profile, multi-domain roaming:** A profile can be provisioned to enable roaming across both TN and NTN infrastructures. This approach simplifies device management and reduces provisioning complexity. However, it depends heavily on the profile being pre-configured with appropriate access point names (APNs), PLMN identifiers, and frequency support aligned with both terrestrial and satellite networks.
- **Dual profiles, domain-specific operation:** Alternatively, distinct available profiles may be assigned for terrestrial and non-terrestrial networks. Devices then dynamically switch profiles based on coverage and signal strength. This model is particularly beneficial where satellite coverage is intermittent or governed by different operators. Implementation requires:
  - Smart profile switching logic in the device firmware
  - Coordinated provisioning between MNOs and satellite operators
  - Careful consideration of regulatory and spectrum constraints

GSMA SGP.32 for IoT and NTN scalability

The GSMA SGP.32[4] specification introduces optimisations tailored for IoT and constrained devices, which align well with the satellite IoT use cases detailed in this document. Key enhancements include:

- **Lightweight architecture:** Reduces protocol overhead, ideal for narrowband NTN links and LPWA technologies, such as NB-IoT over satellite.
- **Remote SIM Provisioning** (RSP) download and profile enable/disable commands via low-bandwidth interfaces. It is important however to note that profile downloads can introduce challenges for power- and battery-constrained devices, especially those operating on a single-charge battery over several years (e.g., asset trackers or remote sensors). The profile download process often requires tens of kilobytes of data and a sustained radio session, which increases both battery drain and data usage. These factors must be carefully balanced against operational constraints in ultra-low-power NTN deployments and therefore it is recommended to pre-install the necessary operator profiles at production time or download profile when a TN is available.
- **Support for profile switch triggers** from the network or device firmware.
- **Increased provisioning autonomy**, critical for NTN where continuous connectivity cannot be assumed.

Similar to TN devices, using SGP.32-compliant eUICCs in NTN-capable devices ensures long-term manageability, especially in logistics, agriculture, and maritime applications where devices may move in and out of coverage frequently.

3GPP Release 18 and eUICC interoperability

3GPP Release 18 introduces improved NTN-TN handover mechanisms, frequency support expansion, and location verification enhancements, all of which can be further leveraged by eUICC-based device architectures:

- The eSIM profile must be provisioned with NTN-specific frequency bands (e.g., n254–n256 for NR NTN, B254–B256 for LTE NTN).
- Location-aware capabilities (used for beam steering and mobility optimisation) can be augmented by eUICC-local storage of geographic preferences and access rules.
- Regulatory compliance (e.g., in extraterritorial scenarios) may rely on operator-defined rules embedded in eUICC Access Rule Reference (EFARR) files.



Design recommendations

- Use SGP.32-compliant eUICCs to future-proof NTN device provisioning, particularly for constrained IoT form factors.
- Design devices to handle on-device logic for profile switching, especially where NTN roaming agreements are still evolving. For devices with stringent power constraints, such as those using primary cells (non-rechargeable), the overhead introduced by RSP download operations should be minimised. Consider toggling between preloaded profiles to avoid unnecessary provisioning cycles.
- Collaborate with MNOs and satellite operators to define flexible provisioning templates that accommodate evolving NTN spectrum and roaming configurations.
- Validate interoperability with 3GPP TS 31.102[9], which defines key USIM file structures and protocols used by NTN-enabled UEs

10. NTN device security in 3GPP

The security stack for NTN devices is still evolving in 3GPP. It integrates satellite access, including LEO access, into the 5G system and then adds NTN-specific security work where satellite operation creates new risks, especially around discontinuous coverage. The same architectural logic spans both NR satellite access and IoT NTN, such as NB-IoT over satellite. A key consideration is the extra trust problems that appear when 5G security runs over long-delay, moving, and intermittently-available satellite links.

The baseline is still identity privacy, authentication, and protected signalling.

An NTN device has to implement the normal 5G security chain. 3GPP protects the subscriber's identity over-the-air with SUCI instead of exposing the SUPI, derives keys through 5G AKA or EAP-AKA', and then protects NAS, RRC, and, when configured, user-plane traffic with integrity, ciphering, and replay protection. 3GPP allows SUCI to stay inside the USIM and requires the home-network public key used for SUCI protection to be securely provisioned under home-operator control. In NTN, this foundation matters and the credential root in the USIM/UICC cannot be treated as optional.

NTN-specific requirement: Secure operation through discontinuous coverage

NTN devices often disappear from the network for planned periods because coverage itself can be discontinuous. To handle unavailability, 3GPP allows the UE to store mobility management (MM) and session management (SM) context in the USIM for later reuse. That creates a device security requirement that is highly relevant to NTN. Security context is no longer only a live radio state; it can become a persisted state that must survive long sleep, power cycling, and delayed return to coverage without becoming stale or corrupted. Here, an NTN device needs protected storage, context-age checks, conservative resume rules, and a fallback to re-registration whenever integrity or freshness is uncertain.

NTN-specific requirement: Trust in satellite assistance data and switchover procedures

NTN access depends on satellite-specific operating data that terrestrial UE does not use. SIB19 and NTN-configuration carry assistance, such as ephemeris, timing advance, offset values, validity duration, and epoch time, while the network must also manage service-link and feeder-link switchovers. The SA3 security study stipulated that satellite coverage availability information used by the AMF should come from trusted operations and maintenance (O&M), not from external sources[2]. Secure NTN design must validate the freshness and validity of satellite assistance data and add strong protection on every non-3GPP segment between payload, gateway, and gNB implementation.

What a secure NTN device looks like

A secure NTN device is more than an IoT endpoint with secure boot, a secure element, and encrypted transport. It is a UE that preserves 5G identity privacy, authenticates into the 5GS, stores suspended security state safely across long unavailability periods, report's location only through secured procedures, and does not blindly trust satellite assistance or network-selection inputs just because they arrived over a satellite path. The hardware root of trust (RoT) remains a foundation of device security, but the device must maintain its security despite NTN-specific challenges, including longer and varying communication delays, intermittent coverage, and satellite mobility.

11. Guidance for devices development

If not addressed properly, the increase in growth of IoT devices and associated IoT device applications could create major challenges for mobile network operators. When deployed on a mass scale without appropriate measures, IoT devices can cause network signalling traffic to increase to a level that impacts network services for all users of the mobile network.

Connection efficiency framework (TS.34)

Users are advised to follow GSMA TS.34[8], which provides various IoT device connection efficiency guidelines[8];

- IoT device requirements,
- IoT device application requirements,
- Communication module requirements,
- IoT service provider requirements,
- Policy based connection efficiency requirements,
- Radio policy manager (RPM) requirements,
- RPM (U)SIM requirements and
- various 3GPP connection efficiency features, such as
  - Extended access barring (EAB),
  - Power saving mode (PSM),
  - etc.

Use case specifics

The specifics of IoT use cases play a vital role when designing the characteristics of NTN devices.

For example, a use case for tracking mobile assets will have different mobility and latency requirements than one for monitoring static environmental sensors. Solution architects and system engineers should define the optimal technical requirements for IoT devices to ensure high service quality and performance upon commercial rollout.

A fast and smooth switching mechanism needs to be in place for the transition between the TN and NTN. This is important so devices can quickly acquire a satellite connection when losing TN coverage and switching to NTN and then move back to the TN, when coverage is available again, to avoid higher latency or service outages. The software application itself must be resilient to these handovers, managing data buffers and session state gracefully. Software client application features on the device, such as connection watchdog and connectivity retry mechanisms, should be finetuned to make optimal use of the underlying NTN-TN switching mechanisms of the hardware platform (chip/module vendor/NTN service providers).

Furthermore, the usage of lightweight communication protocols can minimise the volume of data being transmitted and positively impact overall device performance. The algorithms used should also consider the volume deployment of devices and avoid situations where the loss of either TN or NTN coverage sees thousands of devices switching across to the other access networks in unison[8]. This "thundering herd" problem can be mitigated by implementing randomised reconnection timers (jitter) in the device application logic.



GSO versus NGSO selection

During the system design, the selection of GSO or NGSO technologies must also consider IoT device deployment specifics.

A NTN IoT device will typically send monitoring data in a time-driven (i.e. periodically) or event-driven way to an application server, and it may receive some data from the application server (e.g. configuration, commands, firmware updates). In most of the cases, the messages exchanged are delay tolerant (e.g. monitoring application reporting a few messages per day and for which delivery time between the device and the application server could be in the range of hours).

In other cases, delivery time between the device and the application server can be more critical (i.e. delay sensitive) and in the range of several seconds (e.g. alarms reporting). Device can latch on to NGSO satellites in case of delay-tolerant applications and on to GSO satellites in case of delay-sensitive applications.

Tracking satellite motion (SGP4, SIB31, SIB32)

IoT devices need to continuously monitor satellite motion, especially in NGSO mode. Various prediction models, such as SGP4, can be used to track satellites. These models are discussed below:

Satellite prediction models:

SGP4 is a widely-used mathematical model for predicting the position and velocity of Earth-orbiting objects, such as satellites. It is an orbital propagation model that quickly and reliably calculates an object's path by accounting for various gravitational and atmospheric perturbations. SGP4 is frequently used with two-line element sets (TLEs), a common data format for providing satellite orbital data.

SIB31/SIB-31-NB includes satellite assistance information consisting namely of Ephemeris data (orbital parameters that is, the semi-major axis, eccentricity, periapsis, longitude, inclination, and anomaly of the satellite), NTA common parameters, UL Sync Validity and K-Offset.

SIB31/SIB31-NB also includes t-ModeSwitching-r19 indicating the time information on when an NTN cell is going to switch from the store and forward satellite operation mode to the normal mode or vice versa depending on operation mode of the cell.

SIB32/SIB 32-NB contains satellite assistance information for prediction of discontinuous coverage which helps a UE predict when it will be in-coverage and out-of-coverage – this in turn will help a UE turn off its radio/modem when it is predicted to be out-of-coverage.

It is the responsibility of the UE to calculate the next satellite to connect to, based on the input received in SIB31 and SIB32 and the GNSS location of the UE.

The calculation works as follows:
Inputs: TLE (e.g. received in SIB32) and time.
Output: Orbital state vector, which includes the position and velocity of the object, for the given time.

12. NTN device design considerations

The choice of using TN or NTN will be governed by the commercial terms and use cases. But OEMs should prioritise dual-mode (TN plus NTN) hardware where feasible, as this enhances service availability, and flexibility. By building NTN readiness into devices from the early design stages, manufacturers can future-proof products and accelerate time-to-market in a growing NTN ecosystem.

To enable optimal device performance upon rollout, ensure the IoT deployment and use case specifics are evaluated during design stage.Other key considerations include:

- **Propagation delay and Doppler effects:** Satellite orbits introduce high latency and frequency shifts. Modules should be NTN ready and include Doppler compensation and robust timing correction.
- **Link budget:** Longer transmission paths demand improved power amplification and high-gain antenna systems. In handheld devices, trade-offs between size, power, and performance must be carefully balanced.
- **Atmospheric effects:** The signal must traverse the ionosphere and troposphere, which can cause scintillation (fading) and Faraday rotation (polarisation shift). The receiver design should be robust enough to handle these variable channel conditions.
- **Multi-RAT and frequency support:** Devices should support multi-band RF front ends covering NTN bands (e.g., n254, n255, n256) alongside terrestrial frequencies.
- **GNSS integration:** Location and timing information is vital for satellite beam management and regulatory compliance.
- **Component selection:** Choose chipsets and modules with a proven roadmap for supporting 3GPP NTN features across multiple releases (e.g., Rel-17, Rel-18 enhancements). This ensures long-term viability and reduces redesign risk. Where possible, use modules certified by certification bodies, such as GCF/PTCRB and respective NTN operator-level standard certification programs.
- **Power efficiency:** Power-saving features (e.g., PSM, eDRX) should be optimised for the intermittent connectivity typical in NGSO satellite coverage. For example, align device wake-up cycles with predictable satellite passes in LEO deployments.
- **Application-level logic:** The on-device application must be "NTN-aware." Features, such as connection watchdogs, data transmission retry logic, and session management, should have longer timeouts and more patient backoff algorithms to accommodate satellite latency, preventing the application from giving up on a connection prematurely.
- **Lightweight communication protocols** minimise data payload size, which reduces transmission costs and improves overall device performance over constraint links.
- **Tailor the hardware:** Align the device's hardware design, especially the antenna system and RF front-end, with the specific characteristics of the target satellite constellation (GSO or NGSO) to ensure optimal link performance.
- **Implement robust security** measures to protect data and devices from unauthorised access and cyber threats.

13. IoT application development for NTN

The true value of NTN will be realised through the innovative applications it enables, particularly in the IoT domain. IoT application development for NTN involves creating software solutions that enable IoT devices to communicate, interact, and exchange data through NTN. This includes leveraging satellite and aerial platforms to enhance IoT connectivity in remote areas or where traditional terrestrial networks are limited.

NTN-IoT solutions aim to extend the reach and reliability of IoT deployments, enabling use cases, such as precision farming and smart city solutions, in areas with challenging connectivity. The design of the IoT application goes hand-in-hand with the IoT device design.

Steps in developing IoT applications for NTN:

- **Define use case:** Clearly define the specific needs and goals of the IoT application, considering factors, such as data types, connectivity requirements, and data processing needs.
- **Select technology stack:** Choose the appropriate hardware, software, and network technologies for the application, considering factors, such as device capabilities, connectivity options, and cloud platforms.
- **Design architecture:** Design the IoT application architecture, including device communication, data processing, storage, and analytics.
- **Develop an application:** Develop software applications, including front-end and back-end components, and ensure seamless integration with the chosen technology stack.
- **Implement security:** Implement robust security measures to protect data and devices from unauthorised access and cyber threats.
- **Test, deploy and monitor:** Test IoT devices before deploying the IoT application and monitor its performance, ensuring optimal connectivity and data transmission.

Recommendations for accelerating NTN-centric IoT application development

To accelerate the development and deployment of NTN-centric IoT applications:

- **Expand and simplify access to developer resources:** Satellite operators and chip vendors should continue to expand their NTN developer programmes, providing affordable and easy-to-use development kits, comprehensive SDKs, clear documentation, and access to certified NTN modules and chipsets. Lowering the technical and financial barriers to entry will encourage a broader range of developers and companies to explore NTN IoT solutions.



- **Promote cross-industry collaboration and co-creation:** Fostering partnerships between satellite operators, MNOs, IoT platform providers, application developers, and experts from specific vertical industries (e.g., agriculture, maritime, logistics) is key. Co-creation workshops, hackathons, and joint pilot projects can help identify unmet needs and develop tailored NTN IoT solutions that address real-world problems effectively.
- **Develop clear go-to-market strategies addressing cost and complexity:** While NTN offers unique benefits, concerns about cost and complexity can hinder adoption. Service providers need to develop clear and transparent pricing models for NTN IoT connectivity, potentially offering tiered services based on data volume, criticality, and performance requirements. Highlighting the return on investment (RoI) through case studies and demonstrable efficiency gains is crucial for convincing enterprises to invest in NTN solutions.

Designing applications for resource-constrained networks, such as NB-NTN and NR-NTN, requires a disciplined approach to avoid overwhelming the networks, especially during peak times. As well as failing to perform its own function, a poorly-designed application can degrade the service for all other users in the same cell. Developers should harness the network settings required to best utilise the resources, while ensuring their applications appropriately respond/act on network messages/errors.

Every byte transmitted consumes significant power and network resources. Therefore, design considerations, such as the usage of lightweight data formats, sending data deltas (not full states), implementation of payload compression, and choosing efficient protocols (e.g. UDP), are key.

How and when an application transmits data is just as important as what it transmits. This is the primary cause of network overload from rogue applications. Therefore, design considerations, such as spreading out network access (to avoid access storms), intelligent retry logic, and avoidance of unnecessary status updates/overheads should be evaluated. Due to high NTN latency, every round-trip is costly. Therefore, application designers should consider minimising network "chatter" and prioritising asynchronous communication.

NB-IoT provides network-level features to save power, and the application must be designed to work with them, not against them. Design considerations include respecting PSM and eDRX cycles, and aggregating data (instead of waking up to send every small piece of data).

Cybersecurity considerations for NTN

Security must be robust and based on a secure by design approach. Avoid the principle of safety through obscurity. In addition to the 3GPP-related security measures discussed above, IoT devices should adhere to the GSMA IoT cybersecurity recommendations, ETSI EN 303 645, RED DA, CTIA security, etc and follow GSMA security guidelines.

Recommendations to harden IoT security for NTN

Protecting the hardware

Using a certified secure element (SE) is a great first step, but only if implemented correctly. It is crucial to:

- **Disable debug interfaces:** It is imperative to disable or password-protect **JTAG/SWD** interfaces in production. If an attacker can read the RAM, the secure element's protection is effectively bypassed.
- **Implement unique per-device authentication:** The SE access "Password" must not be global for the entire fleet. Each satellite or device should have unique credentials derived from a hardware unique ID (UID).
- **Ensure secret isolation:** Never store the SE password in cleartext in the RAM. Use "key wrapping" mechanisms or load the secret into a buffer only at the exact moment of the transfer, "zeroing" the memory immediately afterward.
- **Use credential lifecycle management:** for unique per-device secrets, define secure provisioning, rotation, revocation, and replacement of device credentials over the lifecycle, using attestation based on a hardware root of trust (RoT).
- **Implement internal hardware communication security:** In NTN devices, the physical links between the host MCU, the satellite modem, and the secure element are primary targets for local tampering. Physical access to the PCB must not result in a total system compromise.
  - **Hardening the host-modem interface** The UART/USB bus between the MCU and the modem is the most exposed path.
  - **Command integrity:** Implement message authentication codes (MAC) for every packet to prevent "man-in-the-middle" command injection via logic analysers.
  - **Anti-sniffing layout:** Route TX/RX lines on internal PCB layers. Avoid placing test points (TP) for these signals on the bottom or top silkscreen where they can be easily probed.
  - **Restricted authenticated service:** Expose only the minimum required command or services on internal buses. Provisioning or debug commands should be disabled in production or enabled only through authenticated debug service mode.
- **Secure element and connectivity:** The link to the identity module (where NTN credentials are stored) must be isolated.
  - **Protocol:** Use SCP03 for all MCU-to-SE communications. This ensures that even if an attacker probes the I2C/ISO7816 bus, they can only see an encrypted blob.
  - **Dedicated power rails:** Use independent LDOs for the secure element to prevent power analysis attacks (monitoring power consumption to guess cryptographic keys).

Advanced cryptographic management

The error of using the same data block for the SE password and the AES key is a critical point of failure.

- **Key derivation functions (KDF):** Utilise KDFs (like HKDF) to derive different keys for different purposes, one for authentication, one for data encryption, and one for integrity.
- **Session key rotation:** Do not rely on a static “master key” for the device’s lifetime. Implement key exchange protocols (like Elliptic Curve Diffie-Hellman – ECDH) to generate ephemeral session keys.
- **Key length:** For critical NTN communications, the minimum standard should be AES-256 or Elliptic Curves of at least 256 bits.
- **PQC readiness:** NTN systems have long lifecycles, so design the stack to support algorithm replacement and migration (certificates, key-establishment methods), including a path toward post-quantum readiness where needed with crypto-agility.

Communication security (transport layer)

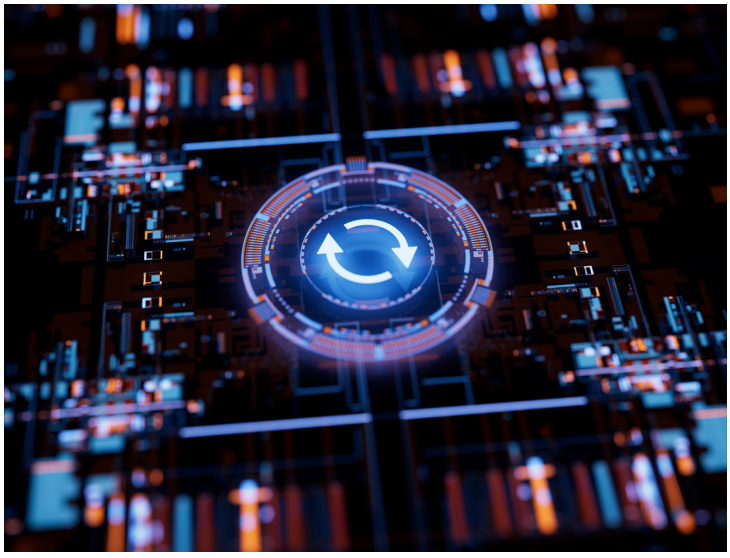
NTN signals cover massive geographic areas, making interception trivial for an attacker with a high-gain antenna. Therefore, it is important to implement the following:

- **Message authentication (MAC):** Every radio packet must include a message authentication code (HMAC or CMAC) to prevent command injection or spoofing attacks.
- **Replay protection:** Include encrypted timestamps or sequence numbers (nonces) in every APDU or radio packet so an attacker cannot capture a legitimate command and "replay" it later.
- **End-to-end encryption (E2EE):** Encryption should occur within the secure element and only be decrypted at the final destination (Earth), ensuring that intermediate ground stations or nodes cannot access the data.

Firmware integrity and lifecycle

Before joining the NTN service, the device should be able to prove its firmware and boot state to the network using hardware RoT. Also, the device should be able to reject older firmware versions, even if they are correctly signed, to prevent attackers from reinstalling a previously vulnerable image.

- **Secure boot:** The microcontroller on IoT devices must verify the digital signature of the firmware before execution. This prevents an attacker with physical access from loading a modified firmware that leaks secure element secrets.
- **Secure OTA updates:** Over-the-air updates must be encrypted and signed. The update process should never expose current communication keys.
- **Memory sanitisation:** Implement routines that "sanitise" (clear) CPU registers and stack buffers after every sensitive cryptographic operation to prevent residues in CPU registers or the stack pointer (SP).



14. Ecosystem collaboration

Non-terrestrial networks (NTN) are rapidly transitioning from conceptual technology to a pivotal component of the global telecommunications infrastructure. This section explores the multifaceted NTN ecosystem, focusing on three critical pillars: chip vendor collaboration and hardware development; Internet of Things (IoT) application development; and ecosystem education and knowledge sharing. This involves chip manufacturers, such as Qualcomm, MediaTek, Sony, Samsung and Nordic Semiconductor, developing chipsets with built-in satellite connectivity, often working with NTN service providers, such as Sateliot and Viasat (Skylo), to ensure seamless integration and compatibility. Test and measurement companies, such as Keysight, Anritsu and R&S, provide testing solutions to verify the reliability and performance of these devices.

Recommendations for optimising chip vendor collaboration

The development of robust and efficient NTN hardware is a cornerstone of the entire NTN value proposition. The following strategies can help ensure a continued pipeline of innovative and market-aligned chipsets:

- **Deep, early-stage partnerships for specialised hardware:** The development of highly specialised NTN hardware, such as components for regenerative payloads or radiation-hardened systems for space deployment, demands more than standard OEM-vendor relationships. Ecosystem players, including satellite operators and system integrators, should proactively engage with chip designers at the earliest stages of development. This involves establishing joint R&D initiatives, sharing detailed mission requirements and environmental specifications, and potentially co-investing in the development of critical silicon. Deep collaborations are essential for tackling the unique challenges of space-grade NTN components.
- **Establish clear industry roadmaps and demand signals:** As chip vendors invest significantly in R&D, clear signals regarding market needs and future feature requirements can help direct these investments effectively. Industry consortia, standards bodies, and major service providers should work towards creating and communicating clear roadmaps for desired NTN capabilities (e.g., specific performance targets for different use cases, timelines for support of new 3GPP features, demand for specific form factors or power consumption profiles).

Chip Vendor	Key NTN Chipsets/Solutions	Core Technologies/Specialisations	Target 3GPP Releases
MediaTek	MT6825, Dimensity series (e.g., with M90 modem), Filogic, Genio	SoCs, modems, IoT-NTN (GEO), NR-NTN (GEO/LEO), Ku-band, power efficiency, automotive NTN	Rel-17(NTN) and later
Nordic Semiconductor	nRF9151	IoT-NTN NB-IoT (LEO/GEO)	Rel-14(TN), Rel-17(NTN) and later
Qualcomm Technologies	Snapdragon Satellite, 212S Modem, 9205S Modem, X80/X85 Modems, Snapdragon Auto Gen 2 SA522M and SA525M	Integrated SoCs, modems, IoT-NTN (GSO), NR-NTN, terrestrial & non-terrestrial integration	Rel-14(TN) and later, Rel-17(NTN) and later
Sony Semiconductor (Altair)	ALT1350, ALT1250	Highly-integrated SoCs, (GSO) LTE-M/ NB-IoT + NB-NTN, low power, AI engine, security (iSIM)	Rel-14(TN) and later, Rel-17(NTN) and later
Samsung LSI	S5400, E2500	SoC	Rel-17(NTN) and later

Table 5: Sample NTN Chip Vendors (in alphabetical order)



This reduces uncertainty for chip vendors and aligns their product development with tangible market opportunities.

— **Support joint testing, validation, and certification initiatives:** The complexity of NTN requires rigorous testing under realistic conditions. Supporting and expanding access to shared testing platforms, interoperability events, and facilities emulating NTN channel characteristics (including Doppler, delay, and atmospheric effects) are crucial. Furthermore, streamlined and globally recognised certification processes for NTN chipsets and devices can accelerate time-to-market and build confidence among adopters. Collaboration with test and measurement solution providers, such as Anritsu, Keysight, and Rohde & Schwarz, is vital here. The work of test equipment vendors (TEVs) is crucial for moving new NTN technologies from the lab to mass-market adoption. By providing the necessary tools and platforms, TEVs are directly tackling the complex challenges of NTN and accelerating device development and certification.

15. Future evolution of NTN

The NTN landscape is evolving rapidly, with several key trends poised to shape its future trajectory:

- **Advanced application support,** such as voice services, rich media, and low-latency applications as network capabilities evolves.
- **Continued integration into mainstream cellular devices:** The trend of integrating NTN capabilities directly into mainstream cellular SoCs and modems is likely to continue. This should lead to an increase in the number of direct-to-device (D2D) services with flow on economies of scale for both smartphones and IoT devices.
- G**rowth of advanced regenerative LEO constellations:** The development and deployment of LEO satellite constellations featuring regenerative payloads will accelerate. These advanced satellites, capable of on-board processing, will offer enhanced performance, improved link budgets, lower end-to-end latency for certain services, and greater network flexibility, enabling more sophisticated NTN services.
- **Increased adoption in key IoT verticals:** As device hardware becomes more standardised and affordable, the return on investment will become clearer. Adoption of NTN in key IoT verticals such as agriculture, maritime, logistics, and environmental monitoring should increase significantly.
- **AI/ML for network optimisation and management:** The use of artificial intelligence and machine learning will become critical for managing the complexity of NTN. AI will be used to dynamically optimise network resources, manage complex beam switching, predict coverage, route traffic efficiently across satellite and ground links, and enable predictive maintenance of space and ground assets.
- **Precise positioning, navigation, and timing** (PNT) services will be integrated into NTN to support autonomous systems and critical infrastructure.
- **Multi-orbit constellations and inter-satellite links** (ISLs) will enable direct satellite-to-satellite communication, reducing dependency on ground earth stations.

The theoretical understanding and laboratory testing of NTN technologies are essential, but invaluable insights are gleaned from real-world deployments and trials. These practical experiences provide crucial data on actual network performance, device behaviour under dynamic NTN conditions (such as varying Doppler shifts, propagation delays, and fluctuating signal strengths), and the end-user experience.



16. Conclusion

Non-terrestrial networks represent a paradigm shift in global connectivity, transitioning from a specialised niche to an increasingly integral component of the mainstream telecommunications ecosystem. The collaborative efforts of chip vendors, satellite operators, MNOs, application developers, and standards bodies are driving this transformation. The development of sophisticated, standards-compliant NTN chipsets is overcoming significant technical hurdles, enabling a new generation of devices capable of seamless satellite communication. This hardware foundation is, in turn, fostering a burgeoning ecosystem of NTN-optimised IoT applications across a multitude of industries, promising unprecedented levels of operational efficiency, safety, and data-driven insights by extending connectivity to the most remote corners of the globe.

However, the path to realising NTNs' full potential is not without its challenges. Addressing issues of cost, technical complexity, and the need for broader ecosystem awareness remains paramount. Strategic imperatives include deepening collaborations for hardware innovation, simplifying and democratising access to NTN development tools for IoT applications, and implementing comprehensive educational initiatives to ensure all stakeholders are equipped to participate in and benefit from this evolving landscape. The continued evolution of 3GPP standards, coupled with proactive industry forums and learning from real-world deployments, will be crucial in navigating these challenges and ensuring a harmonised, interoperable, and scalable NTN future.

The trajectory of NTN points towards a future of ubiquitous connectivity. By empowering data-rich industrial IoT solutions in remote environments, NTN is set to bridge the digital divide and unlock new frontiers of innovation. As NTN technologies mature and integrate more deeply with terrestrial networks, particularly within the framework of 5G Advanced and the emerging concepts of 6G, their transformative impact on society and industry will continue to grow, forging a new era of global connectivity



Appendix A – Technical Aspects of NTN

Satellite orbits

Low Earth orbit (LEO): Circular orbit at altitudes of 500-2,000km (lower delay and better link budget, but a larger number of satellites are needed for coverage).

Medium Earth orbit (MEO): Circular orbit in altitudes of 8,000-20,000km

Geostationary Earth orbit (GEO): Circular orbit 35,786 km above the Earth's equator.

Highly elliptical orbit (HEO): Elliptical orbit around the earth.

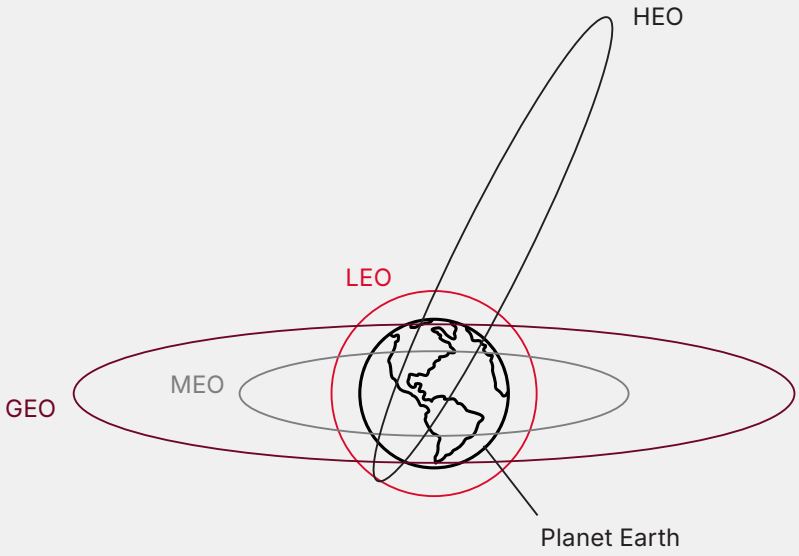


Figure 1: Illustration of the classes of orbits of satellites[5]

NTN payload architectures

The two types of modes or "payload" are shown in Figure 2

— **Non-regenerative payload** - also called "bent pipe payload" (considering the path from the gateway via spaceborne/airborne platform to the UE) or "transparent mode": A spaceborne/airborne platform with no on-board processing capabilities that changes the frequency carrier of the received uplink RF signal, filters and amplifies it before transmitting it on the downlink, i.e. the platform corresponds to an analogue RF repeater.

— **Regenerative payload** (or non-transparent mode): a spaceborne/airborne platform that supports RF filtering, frequency conversion and amplification, as well as on-board processing capabilities (for demodulation/decoding, switching and/or routing, coding/modulation). This spaceborne/airborne platform has base station functions on board.

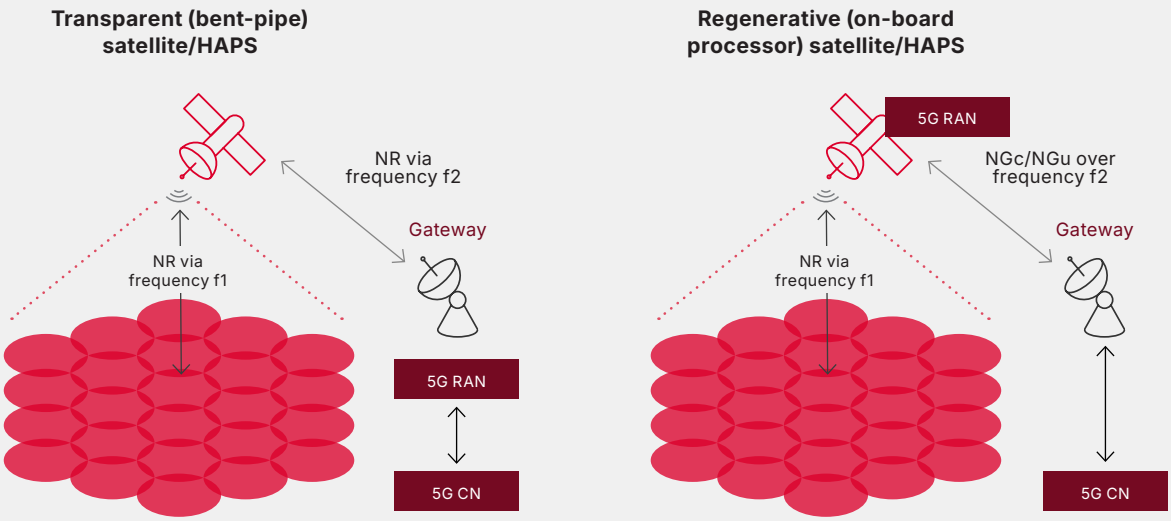


Figure 2: Non regenerative versus regenerative payload and elliptic beam patterns[5]

Summary of key differences:

Feature	Transparent Payload	Regenerative Payload
Signal processing	Relays signals without modification	Demodulates, decodes, and remodulates signals
Complexity	Simpler	More complex
Cost	Generally lower	Generally higher
Flexibility	Limited	Greater
Signal quality	Can degrade over distance	Can be improved
Network support	Suitable for basic communication	Suitable for advanced network architectures

Propagation delay and Doppler Shift:

Propagation delay is the time it takes a signal to travel from one point to another.

GSO (geostationary orbit):

- **High and constant delay:** GSO satellites orbit at a very high altitude (around 35,786 km), resulting in a large, fixed distance between the satellite and the user on Earth.
- **Impact:** This large, constant distance causes a substantial propagation delay, making GSO less suitable for latency-critical applications, such as real-time video conferencing.

NGSO (non-geostationary orbit):

- **Low and varying delay:** NGSO systems, especially those in low Earth orbit (LEO), orbit much closer to Earth.
- **Impact:** The shorter distance leads to a significantly lower propagation delay. However, the delay varies dynamically as satellites in a constellation move in and out of a ground user's view, requiring complex network management to maintain continuous service.

Doppler Shift is the change in a signal's frequency caused by relative motion.

GSO:

- **Negligible shift:** Because GSO satellites remain in a fixed position relative to a point on Earth, there is virtually no relative motion.
- **Impact:** This lack of relative motion means the Doppler Shift is essentially zero, simplifying signal processing.

NGSO:

- **Significant and dynamic shift:** NGSO satellites, particularly LEO systems, are in constant motion relative to ground users.

Challenges in NTNs

Challenges in NTNs include increased latency and Doppler Shift due to satellite distance and motion, creating variable channel conditions and difficulties in handover management. Other significant challenges involve the high cost of deployment and operations, the harsh and inaccessible space environment, the need for more NTN-compatible radios and terminals, and complex regulatory hurdles for deployment and international operation. Additionally, managing the large number of satellites in a constellation, ensuring scalability, and developing effective on-board processing capabilities for each satellite are also major hurdles.

Technical challenges

- **Latency and Doppler Shift:** As discussed above, the long distances from satellites to devices cause significant propagation delays, and the Doppler shift requires devices to compensate for frequency changes.
- **Channel conditions:** NTNs face highly dynamic and variable radio channels due to factors, such as satellite movement, weather, and atmospheric irregularities, requiring sophisticated radio channel emulation for testing and deployment.
- **Handover management:** Ensuring seamless mobility and continuous service continuity when devices move between satellites and terrestrial networks is complex and requires extensive simulation tools.
- **Synchronisation and timing:** Accurate time and frequency synchronisation are critical for NTN operations and require enhanced physical layer procedures to manage the long delays and dynamic channels.
- **Power control:** Efficient and dynamic power control mechanisms are needed to manage communication links and ensure reliable connectivity.

Deployment and operational challenges

- **Harsh space environment:** NTN equipment must operate in extreme temperatures and radiation, and once deployed, it becomes inaccessible for maintenance or repairs, posing a significant risk.
- **Scalability:** NTN systems must be designed to scale from hundreds to potentially thousands of satellites, which presents major challenges for network management and on-board processing.
- **Cost:** The high costs associated with satellite deployment, constellation management, launch, and user terminal manufacturing create significant economic hurdles and affect the viability of the business case.
- **Regulatory hurdles:** Obtaining regulatory approval for launching large constellations and ensuring seamless operation across numerous countries can be a complex and time-consuming process.
- **Lack of infrastructure:** The limited availability of radios and user terminals that support the specific 3GPP NTN frequency bands complicate real-world testing and adoption.

Integration and testing challenges

- **Network integration:** Integrating NTN services seamlessly with existing terrestrial cellular networks requires significant enhancements to the current 5G standards and architectures.
- **Testing complexity:** Emulating the complex NTN environment for testing is difficult, requiring advanced simulation tools to model dynamic Doppler shifts, delays, and variable channel conditions accurately.
- **Root cause analysis:** Identifying and diagnosing issues in NTN networks is complex due to the intricate nature of the satellite-based infrastructure, requiring sophisticated tools for effective debugging.

Technical and architectural aspects

- **5G/6G integration:** A key focus is the seamless integration of NTN with existing 5G and future 6G network cores and architectures for interoperability and unified service delivery.
- **Mobility management:** Efficient management of user mobility as they move between terrestrial, LEO, MEO, and GEO satellites is vital for maintaining continuous connectivity.
- **Network optimisation:** Technologies are being developed to optimise NTN performance, manage network resources, and offload traffic from terrestrial networks when needed.

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