Telefónica

TECHNICAL WHITEPAPER

Optimizing IoT Devices for GEO NB-NTN Hybrid Connectivity

TABLE OF CONTENTS

OPTIMIZING IOT DEVICES FOR GEO NB-NTN HYBRID CONNECTIVITY

The introduction of technology innovations is always fraught with lead times, a "learning curve" that the industry needs to understand how best to use and integrate the new capabilities into viable and profitable products or services. This whitepaper introduces the technical aspects involved in designing and optimizing IoT devices for **NarrowBand Non-terrestrial Networks (NB-NTN)**. This is a standardized 5G technology which adapts the terrestrial NarrowBand IoT (NB-IoT) protocol for connecting remote, constrained IoT devices to ground-based cellular networks via orbiting satellites. Specific focus is placed on services intended to communicate over Geostationary Orbit (GEO) satellites and terrestrial networks. Numerous topics will be addressed, including the integration of NB-NTN connectivity providers into classical terrestrial cellular networks, the key benefits of hybrid connectivity, the feature set and configuration differences of terrestrial NB-IoT and NB-NTN networks, as well as the implications that these have on the design and optimization of hybrid IoT devices which can operate on both. This whitepaper collects some of the known potential risks and opportunities that the authors are aware of, with the aim of keeping the productization effort, costs, and time-to-market of device manufacturers, service providers and end-customers to a minimum.

1. INTRODUCING 5G NON-TERRESTRIAL NETWORKS

Satellite IoT refers to the use of non-terrestrial satellite communication systems to provide connectivity to Internet of Things (IoT) solutions. As in the case of the well-established terrestrial cellular standards with high market penetration – ranging from 2G to 5G, for which it has developed technical specifications, the 3rd Generation Partnership Project (3GPP) group began adapting satellite systems to the needs of cellular technology. This process, initiated with a minimum feature set in 3GPP Release 17, provides an initial class of consumer and IoT devices to communicate over orbiting satellites. The industry refers to connectivity provided using these devices as "Direct to Handset" or "Direct to Device." Not only does this breakthrough afford ubiquitous connectivity anywhere on the globe, including underserved areas (consider that 71% of the globe has no terrestrial connectivity), but it also enables the emergence of a more flexible, multi-layered 5G network topology combining ground and space networks, as well as hybrid connectivity services that can reselect between both layers, leveraging the well-established, inter-operator roaming frameworks of the GSMA Association.

NB-NTN, the 3GPP Release 17 standard for space-born cellular networks supports an adapted NarrowBand IoT (NB-IoT) protocol suitable for the massive machine type communication (mMTC) service category of outdoor 5G use cases. Consumer and business IoT devices communicating over this NB-NTN protocol are usually compact, battery-operated devices that run power-optimized, low-bandwidth applications with infrequent, short-burst data transmissions (having a few tens of Bytes per message). Furthermore, the NB-NTN IoT communication module and/or radio baseband chipset may be multimode, additionally supporting terrestrial cellular protocols such NB-IoT, LTE-M, and 2G (E-GPRS). In such cases, NB-NTN is used either as the preferred bearer, or as a fallback technology whenever the device enters areas having no terrestrial coverage. This architecture enables a cost-effective device bill of material (BOM), with a single modem and one compact internal or external antenna that is capable of handling cellular communication over terrestrial and satellite networks, with GNSS reception for positioning and time synchronization.

While specifying the NB-NTN protocol, the 3GPP standardization group formulated modifications to terrestrial NB-IoT that address multiple characteristics of orbiting satellite systems. These include, among others, accommodating a longer delay in packet transmissions due to the larger round-trip time (RTT) of signal propagation between Earth-born devices and the orbiting satellites, as well as adapting several closed-loop Layer 3 procedures, such as the Random-Access (RACH) and the Hybrid Automatic Repeat Request (HARQ) scheduling processes. As satellite beams create cells on the ground that are usually larger than terrestrial cells, procedures to detect NB-NTN cells, enable handovers between these, and the corresponding timers were considered. Whereas the terrestrial radio channel takes advantage of the multi-path environment caused by reflections off obstacles in the path of propagation, satellites enjoy a direct line of sight to the IoT device; the large distance to the satellite causes different propagation paths to be almost parallel, and the angular spread is thus close to zero. Path loss parameters in NB-NTN are influenced instead by the elevation angle of the serving satellite, the attenuation of surrounding objects near the ground-based receivers, atmospheric gas absorption, and ionospheric and tropospheric scintillation losses. The result is a different link budget for communication, something which device manufacturers must consider while minimizing their cable losses and optimizing their antenna performance.

1.1. Constellation Characteristics

NB-NTN satellites can be deployed in three different orbital regions, distinguished primarily by their altitude from Earth. This affects satellite characteristics such as coverage footprint (i.e., the number of satellites in the constellation needed to provide for global coverage) and communication capabilities:

- **Low Earth Orbit (LEO)** constellations are non-geostationary orbit (NGSO) satellites having an orbit typically between 160 km and 2,000 km above the surface of the Earth. Their orbiting period (i.e., the time to circle the Earth) can vary between 84-127 minutes. Due to the closer proximity to Earth, LEO satellites can offer a much lower transmission latency (typically 20-50 ms), which is ideal for near-realtime applications like video conferencing. Cellular communication with technologies such as 4G (LTE Cat 1, Cat 1bis, and Cat 4), 3G (UMTS), 2G are possible with these latencies, and many in-cellular devices are implicitly compatible out-of-the-box with this LEO NTN connectivity.

  Because LEO satellites move rapidly over the Earth's surface, they only remain above the horizon relative to the device's location for approximately seven to ten minutes. This results in multiple complexities: short windows for transmitting and receiving data over the individual satellites, performance impacts due to the doppler effect, increased path loss as the satellite approaches the horizon, the potential for significant time delays until the next fly-by of a LEO satellite, increased handovers between satellite beams at any given location, and the need to implement ground-based "Fixed Tracking Areas" to avoid frequent, battery-draining registration updates at the devices. Whereas this protocol complexity is transparent for higher bandwidth cellular protocols, the simplified transceiver architecture and lower bandwidth of terrestrial NB-IoT leads to in-market devices not being automatically compatible with LEO, as their 4G, 3G, and 2G cousins. This results in the need to develop dedicated LEO NB-NTN chipsets and modules, with additional considerations which compensate for several aspects described above. The industry decided to deprioritize LEO NB-NTN in its first generation of baseband chipsets, focusing instead on GEO modems; this is expected to change during 2026, onwards.

- **Medium Earth Orbit (MEO)** satellites with a circular orbit above the equator, typically between 2,000 km and 35,786 km, and remain in fixed positions, with respect to the ground underneath. Performance-wise, they offer a compromise between the performance extremes of LEO and GEO satellites. MEO satellites are suitable for cellular 3G and 2G "Direct to Device" connectivity. Terrestrial 4G and NB-IoT devices are not compatible, for the reasons outlined above.

- **Geostationary Orbit (GEO)** constellations orbit approximately 35,800 km above the equator and their satellites remain at fixed positions in the sky, with rates of revolution matching those of the Earth's rotation. Their continuous, stable coverage over a specific area provides greater reliability and stable path loss for communication, a fixed elevation angle for antenna orientation, and no need for inter-satellite handoffs. The key drawback of GEO is a higher transmission latency, typically around 250 ms, which is not compatible with higher-bandwidth cellular protocols such as 4G and 3G. Both 2G out-of-the-box ("Direct to Device") as well as NB-NTN are supported. Due to the lower transceiver complexity of GEO NB-NTN as compared to its LEO pendant, the GEO ecosystem has experienced a shorter time-to-market, with multiple IoT baseband chipsets and modules commercially available and certified for use with GEO NB-NTN service providers.

1.2. Emerging IoT Use Cases

IoT service providers and Mobile Network Operators (MNOs), such as Telefónica Germany / o2 Business, view NB-NTN networks as a way to address IoT use cases which were previously impossible or uneconomical to serve due to high costs or the impracticality of deploying and maintaining cellular network infrastructure at specific locations, the lack of international roaming agreements, or even regulatory hurdles, such as permanent roaming restrictions. With the advent of NB-NTN, and its first generation of connectivity over GEO satellites, MNOs can start providing adapted NB-IoT connectivity for numerous use cases, as described in *Figure 1* below.

Agriculture	**Precision Agriculture** Monitoring soil and crop conditions, irrigation and fertilizers, climate monitoring, livestock monitoring	**Automation & Remote Management** UAV farming, precision farming, connected farm equipment/vehicles, water mgmt., fish farms	**Forestry** Wildlife monitoring, forest fire detection, forest worker safety, cut-to-length harvesting
Construction	**Site Monitoring and Surveillance** Unauthorized access, security and safety, video surveillance, motion sensors, environment sensors	**Asset Management** Monitoring and tracking of equipment, tools, and materials, theft detection	**Environmental Monitoring and Compliance** Environmental parameter monitoring (air quality, noise levels, dust emissions, etc.)
Consumer	**Remote Connectivity** Voice calling, Internet access, and text messaging capabilities, Personal Locator Beacons, SOS	**Asset Tracking** Tracking of pets, purses, suitcases, vehicles, trailers, boats, and personal equipment.	**Internet Routers** Broadband internet access to businesses and homes, for browsing, streaming, telecommuting
Environment & Government	**Critical Communication** Disaster and emergency fallback network for communication and coordination, location services	**Climate Change Monitoring** Monitoring sea surface temperatures, ice extent, greenhouse gas concentrations, land temperatures	**Air and Water Quality Monitoring** Particulate matter, NO_2, O_3, SO_2, chlorophyll-a concentration, turbidity, dissolved oxygen levels
Maritime & Aeronautical	**Tracking and Tracing** Container tracking, container security, cold chain monitoring, luggage tracking	**Safety** Collision avoidance, man overboard detection, offshore platform monitoring, back-up connectivity	**Broadband Connectivity** Take-off to Landing connectivity, in-flight infotainment, airplane telematics
Mining	**Precision Mining** Monitoring sensors, unstable shaft detection, composition sensors	**Remote Equipment Management** Machinery telematics, inventory management, theft detection, predictive maintenance	**Compliance and Safety** Environmental regulation compliance, employee safety, hazard management, emergency response
Oil and Gas	**Pipeline Management** Real-time distribution management, flow rate & mass balance monitoring	**Quality Control** Oil composition monitoring, tank monitoring, carbon emissions control, digital twin	**Automation & Remote Management** Remote site monitoring, refinery automation, workforce & hazard management, inventory
Transportation & Logistics	**Tracking and Tracing** Global tracking, cold chain monitoring, restriction of goods movement, theft detection	**Vehicle to X (V2X)** V2-Network, V2-Infrastructure, V2-Vehicle, V2-Cloud, V2-Pedestrian	**Safety & Customer Services** Collision avoidance, eCall, door unlocking, in-vehicle infotainment, telematics, theft recovery
Utilities & Energy	**Grid Management** Digital grid, real-time distribution, consumption and loads management, short circuit identification	**Security** Critical infrastructure monitoring, workforce safety, video sharing, theft detection	**Utilities** Smart metering, leak detection, consumption monitoring, ESG reporting

Figure 1: NB-NTN verticals and diverse use cases

1.3. Implementation of NB-NTN Networks

Commercial NB-NTN networks consist of one or more satellites which establish and maintain a radio link between IoT devices and regional ground stations, where the NB-NTN Radio Access Network (RAN), i.e., an eNodeB, is located. Each current-generation GEO satellite simply acts as a “bent-pipe transceiver,” receiving the transmitted signal (the transparent payload), filtering and down-converting it to a lower radio frequency, amplifying the signal, and then retransmitting it down to the receiver. Such a communication system passes all traffic through the satellite in a completely transparent manner; (de)modulation happens only at the end-points – the device and the NB-NTN RAN (refer to *Figure 2*).

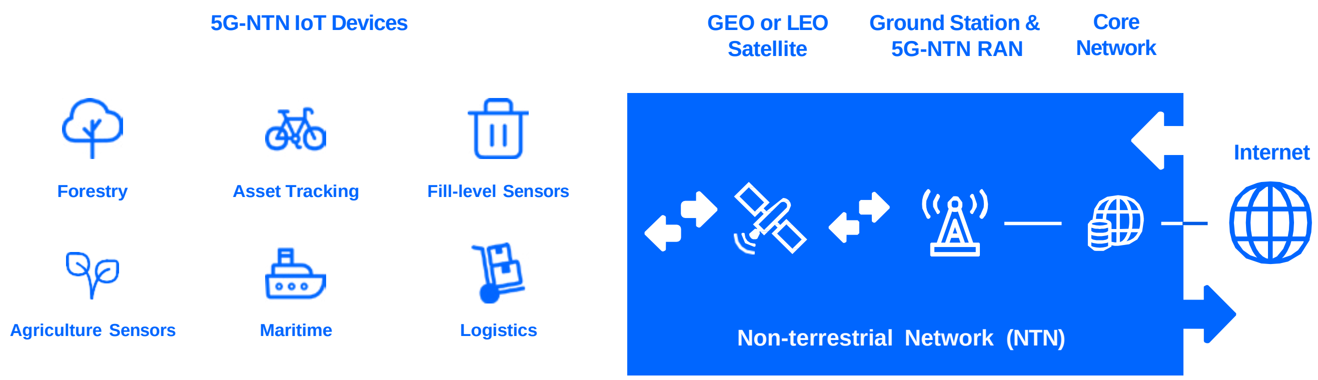


Figure 2: Simplified NB-NTN network architecture

This NB-NTN traffic is sent within discrete NB-IoT carriers, slotted in the allocated spectrum as Physical Resource Blocks (PRB) of 180 kHz, each. Whereas terrestrial networks usually allocate only one PRB per cell to NB-IoT (serving a maximum of twelve NB-IoT devices simultaneously on the Downlink in the coverage footprint of that cell), orbiting satellites will see a far greater number of devices within their beam, resulting in a need to deploy multiple carriers in the NB-NTN connectivity provider’s eNodeB. In this approach, one PRB is configured as an “anchor carrier” for all signaling traffic exchanged with all devices, which remain attached in Idle Mode. When a data transaction occurs, the respective device is temporarily redirected to a “non-anchor carrier” PRB with available capacity for the communication to take place. Once that transaction completes, the device then reverts to the anchor carrier. Another detail of the NB-NTN network implementation is that all carriers operate in standalone mode, as 4G and 2G services are currently not offered in the same spectrum. This differs from terrestrial NB-

IoT networks, where the NB-IoT carrier is typically deployed either in an 4G carrier's guardband or even in-band, replacing a PRB block within the 4G carrier itself. Since NB-IoT signals are modulated in the same manner as 4G, signals from both technologies are orthogonal, preventing any mutual interference, even if deployed side-by-side. The only drawback of in-band terrestrial deployments is experienced by terrestrial MNOs: each in-band NB-IoT carrier steals 180 kHz of capacity from the host 4G carrier.

1.4. Application Payload Sizes in GEO NB-NTN vs. Terrestrial Networks

As is the case with terrestrial NB-IoT, NB-NTN uses the Control Plane Cellular IoT EPS Optimization feature, which allows packetized traffic to piggyback Non-Access Stratum (NAS) signaling messages over the Control Plane (i.e., the S1-MME interface). The ability to forgo use of a User Plane in both technologies is key efficiency factor made possible by using very small payload sizes, where individual packets never exceed a set **Maximum Transport Unit** (MTU) size. GEO networks may be configured to reject any packets that are greater than 1200 Bytes (= 1172 Bytes payload + 28 Bytes of UDP/IPv4 wrapper), as shown in *Figure 3*. The use of dual stack IPv4v6, IPv6, or an optional source port and checksum in the UDP overhead will also reduce the permissible application payload further.

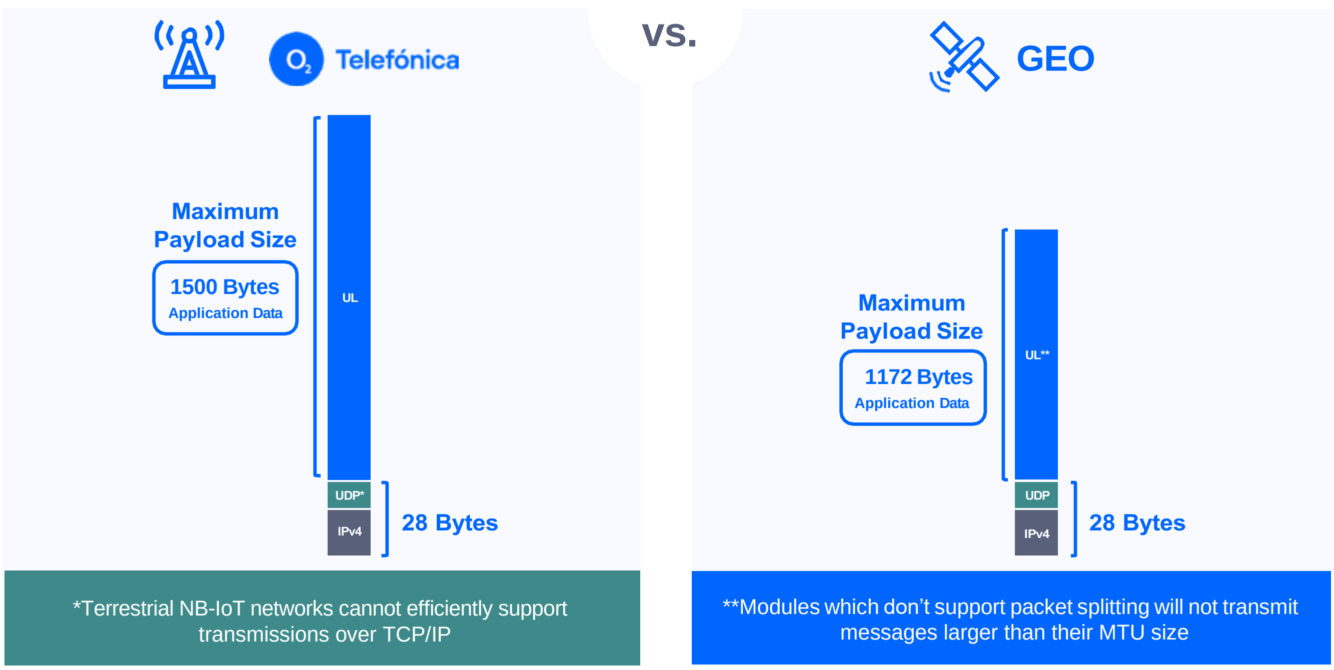


Figure 3: Comparison of Application Payload Sizes - Terrestrial NB-IoT vs. NB-NTN

RECOMMENDATION

Generally, wireless communication modules restrict their MTU on terrestrial NB-IoT networks at around 1500 Bytes, or less, for transmission either over TCP/IP, UDP/IP, or Non-IP. This is slightly reduced on GEO NB-NTN networks to 1172 Bytes, which can be transmitted over UDP/IP. Transmitting data over Non-IP allows for payloads of 1200 Bytes over GEO NB-NTN but would not be able to leverage roaming over multiple terrestrial NB-IoT networks. The MTU is therefore a key aspect that developers designing hybrid devices must consider. Applications may need to reduce the maximum size of their payloads when switching between the terrestrial NB-IoT and the NB-NTN bearer.

1.5. Integration of NB-NTN and Terrestrial Networks

Now that the NB-NTN connectivity provider's satellite(s) and RAN have been addressed, how is the application data forwarded to the MNO customer and how can the customer use their MNO SIM card with non-terrestrial connectivity? The solution to both is straightforward, since NB-NTN plugs into the well-established and streamlined IT frameworks and business models of cellular connectivity, whereby satellite networks and MNOs integrate as roaming partners.

When enabled on an MNO SIM card, NB-NTN devices can roam from terrestrial networks onto GEO or LEO constellations, which serve as Visited Public Land Mobile Networks (PLMN). To illustrate this, consider the detailed network architecture diagram shown in *Figure 4*, where Telefónica Germany is the terrestrial Home PLMN (HPLMN) and a NB-NTN service provider is a non-terrestrial Visited PLMN (VPLMN). Both networks transmit a unique identifier (PLMN ID) in their SIB1 messages (as seen in Table 1). If the NB-NTN PLMN ID is included in the connectivity tariff which Telefónica Germany applies in Kite (Telefónica's IoT connectivity management platform) to the customer's SIM card, the device using that IMSI will be authorized by the Telefónica Home Subscription Server (HSS) to consume services on that NTN network. Traffic passing through the NB-NTN service provider's core network simply gets "home-routed" to/from the Telefónica Germany core network, passing from the NB-NTN network's Serving Gateway (SGW) to the Telefónica Germany PDN Gateway (PGW); this path is designated the S8-C interface. All routing is done in a secure manner through one or more Internet Protocol Exchanges (IPX) – private networks used primarily by MNOs, Internet service providers (ISPs), and enterprises to facilitate high-performance, reliable, and secure data transfers between IP-networks. A customer using Telefónica Germany's IoT SIM card can therefore communicate with their IoT devices – regardless of whether they are on their home network in Germany, outbound on another terrestrial roaming network around the world that is authorized by their tariff, or if they are outbound on the NB-NTN satellite network. The Telefónica Germany PGW serves as the unique endpoint, where their public or private Access Point Name (APN) connection and VPN from the customer's own IT infrastructure terminate. As a final note, the customer has the possibility to monitor their data consumption by logging into the Kite account, where they can set alarms or rules to cap data traffic whenever thresholds are met. This is possible, as Kite implements a "valve tap" at the PGW, which meters and monitors data flow though this key control point. This is directly analogous to when a cellular subscriber roams internationally today – the user is still able to connect using their Home SIM without having to make changes.

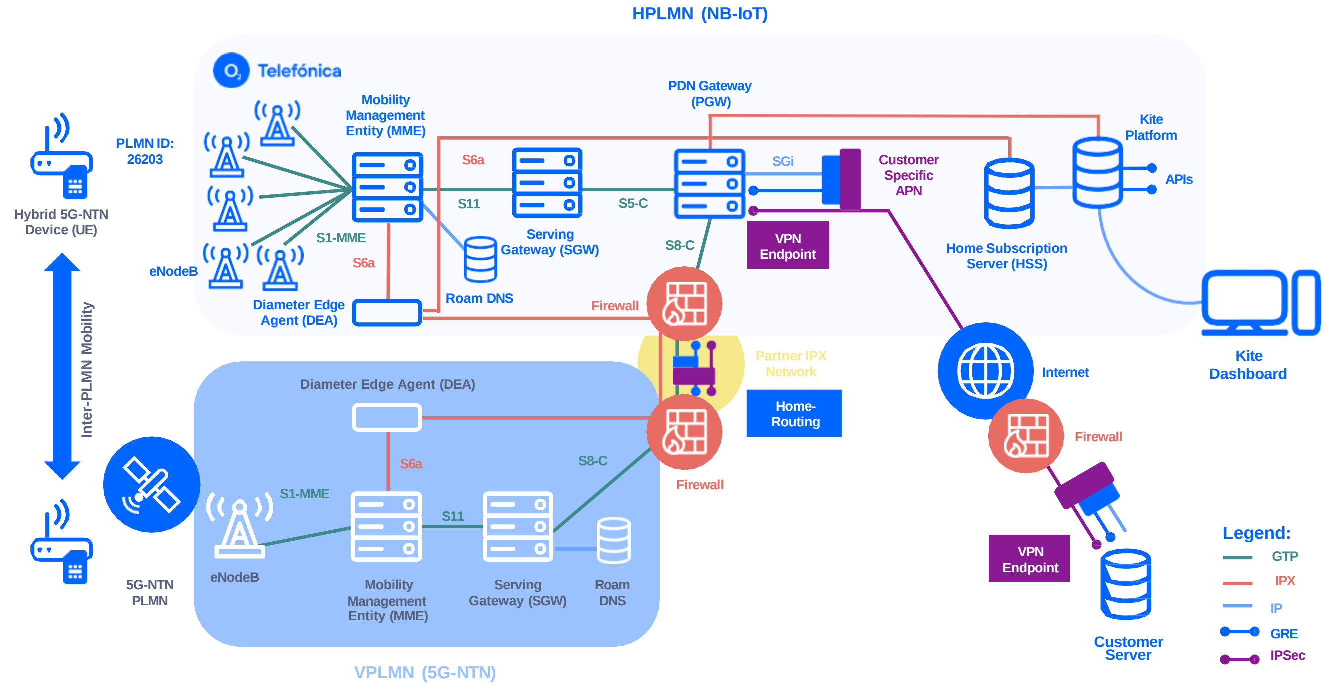


Figure 4: Detailed architecture of home-routing

SUMMARY

Satellite IoT leverages non-terrestrial satellite communication systems to provide global connectivity for IoT solutions, enabling communication for devices where terrestrial networks are unavailable. The 3GPP standardization group adapted satellite networks to cellular technology in recent specification releases, introducing 5G Non-Terrestrial Networks (NB-NTN), which implements NarrowBand IoT (NB-IoT) over satellite for connecting low-bandwidth, battery-efficient IoT devices. NB-NTN networks are typically deployed via Low Earth Orbit (LEO) or Geostationary Orbit (GEO) satellites, each offering different performance characteristics, with an ecosystem of GEO-centric NB-NTN modules, chipsets, and devices currently being the most established for NB-NTN connectivity.

NB-NTN connectivity providers are fully integrated into the proven 3GPP architecture used for international roaming on terrestrial networks. The secure home routing of data packets ensures that all customer data arrives at the very same APN, dramatically simplifying the integration of Satellite IoT into the business processes of enterprises and allowing operators like Telefónica Germany to offer its customers a single service level agreement that includes terrestrial and non-terrestrial connectivity. The key value proposition of NB-NTN hybrid connectivity is that it solves the issues of data fragmentation, multiple platform integrations, risk of data loss, and high costs seen earlier with legacy satellite connectivity solutions of the past. For instance, Telefónica's connectivity management platform "Kite" offers APIs and a dashboard serving as a single pane of glass, enabling customer IoT platforms to manage SIMs and data traffic for devices, no matter where in the world they are located – on land or out at sea.

2. AVAILABILITY OF NB-NTN SERVICE

NB-NTN networks are generally deployed in Non-terrestrial Frequency Range 1, using spectrum allocated for satellite use on a primary basis, or repurposing spectrum made available for terrestrial wireless use on a primary basis (i.e, "conventional MNO" spectrum). There are multiple hurdles to accessing the latter category of spectrum for satellite use, from the regulated processes that grant regional spectrum at auctions, to the risk of causing interference to/from terrestrial networks—including due to frequency and time shifts experienced by signals that propagate over much larger distances. To address NB-NTN's need for spectrum, the ITU and 3GPP defined different 4G bands, which the non-terrestrial connectivity providers can operate their networks on. For example, the GEO NB-NTN service providers use the frequencies listed in Table 1 for their global deployments. Along with the 4G frequency bands used by terrestrial NB-IoT networks, IoT modules and chipsets must also support these NB-NTN frequency bands in order to communicate over said NB-NTN networks.

Connectivity Provider	PLMN ID	Band	Region	Uplink (MHz)	Downlink (MHz)
Telefónica Germany	26203	B20	Germany	832 – 842	791 – 801
Viasat	90111	B24 / n255 (L-Band)	Global	1626.5 – 1660.5	1525 – 1559
Skylo Technologies	90198	B24 / n255 (L-Band)	Global	1626.5 – 1660.5	1525 – 1559
		n256 (S-Band)	Europe	1980 – 2010	2170 – 2200
		B23 (S-Band)	North America	2000 – 2020	2180 – 2200

Table 1: Frequency bands of Telefónica Germany NB-IoT and GEO NB-NTN constellations

The availability of spectrum in a given market does not automatically imply that a satellite connectivity provider can offer commercial services in that market. IoT service providers and customers interested in integrating satellite connectivity in their products should first consult with their MNOs and/or satellite operators to ensure there is proper authorization to use NB-NTN service in a specific country. NB-NTN connectivity providers also must ensure that they have appropriate authorizations in place before they can legally provide services within a given country's jurisdiction. Such authorizations are granted by the individual national governments, allowing satellite networks to transmit signals or data to or from terminals located within the relevant jurisdiction. Authorization policies and procedures can be used to ensure that the satellite networks serving a given country do so in a manner that is consistent with national policy objectives (e.g., with respect to competition, space safety and sustainability, and interference management). Importantly, such authorizations are separate from International Telecommunication Union (ITU) filing procedures, meaning that even if a satellite network is registered with the ITU, territorial landing rights and/or other national authorizations may need to be obtained. The process can vary significantly depending on the market. In many cases, the national regulatory body requires that the application be submitted by an entity formed under local law. The process for expanding the areas in which a given satellite network is authorized to provide service therefore becomes complex, entailing numerous legal, regulatory, and corporate obligations in dozens of markets. Due to the continuously evolving requirements and political situation across the globe, permissions are also subject to change, so it is crucial for IoT service providers and customers to stay informed of any updates that may affect their service availability or legality in any given region. For example, refer to *Figure 5A* which illustrates Viasat's global satellite coverage and *Figure 5B*, which illustrates the service areas where Viasat and Skylo may deploy NB-NTN connectivity services. The current list of countries is expected to expand over the coming quarters to include additional regions for GEO NB-NTN operations.

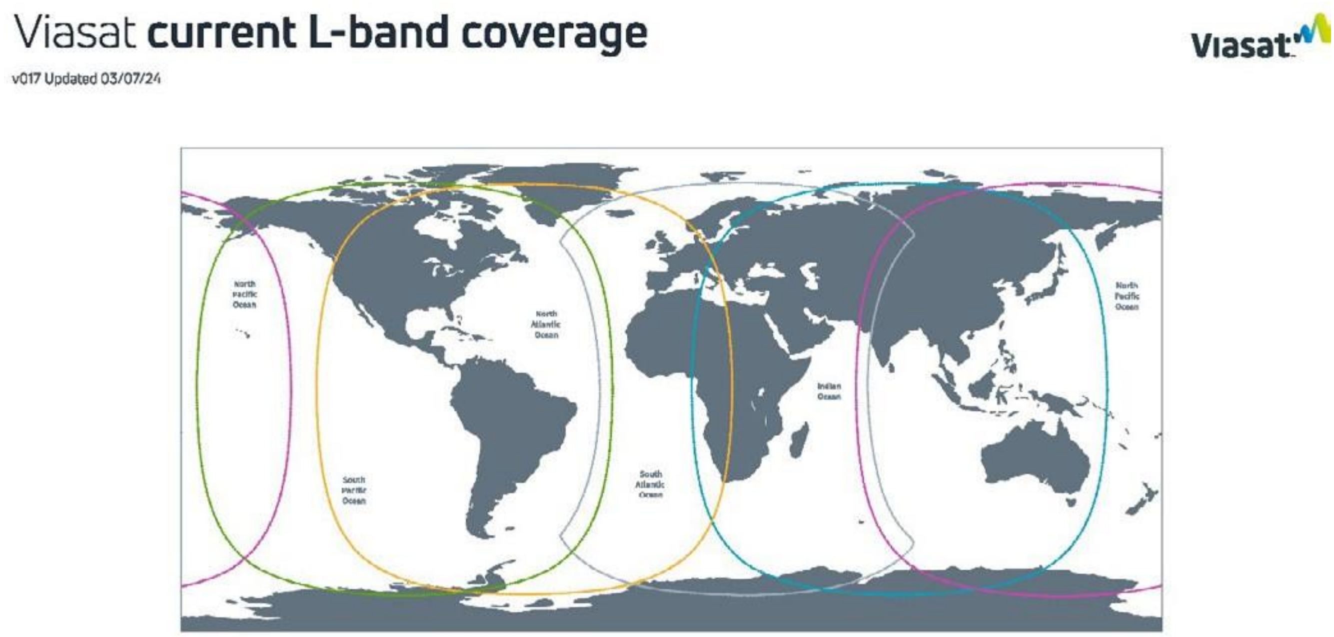


Figure 5A: Viasat GEO NB-NTN regional beams1 (Source: Viasat)

Figure 5B: Skylo GEO NB-NTN regional beams[1] (Source: Skylo)

1 Coverage areas are subject to change. For more information, please consult your O_2 Business sales representative, or contact us online: https://o2business.de/produkte/iot/technology/satellite-iot.

Please note that the national borders of countries do not align precisely with the coverage footprints of GEO service providers. Coverage may be unavailable at high latitudes above the Arctic Circle, as GEO satellites are less effective at providing coverage in these areas due to the curvature of the Earth. The satellites appear too low on the horizon for the link budget to remain within the maximum allowable path loss threshold. Additional remote areas between the polar regions can be covered, however, by GEO satellites when the business demand justifies the deployment of new beams. GEO satellites are able to provide global coverage with just a small number of satellites – for example, Viasat's GEO constellation of four satellites provides global coverage and redundancy. It is also important to note that GEO satellite capacity is shared with non-NB-NTN services.

GEO satellites provide a consistent and stable coverage at locations with high demand, while still allowing capacity to be dynamically reallocated to different locations through the use of steerable beams. LEO satellites fly quickly over regions and therefore must dynamically adapt their beams to the coverage and capacity needs of specific geographies on an ongoing basis. LEO constellations may even provide temporary coverage over remote oceanic areas having few users, in situations where the overall business case does not justify a GEO NB-NTN beam to be deployed (refer to *Figure 6*).

RECOMMENDATION

The choice of satellite network architecture is often determined by the location and communication cadence of the IoT use case, pricing, and time to market considerations. For example, agricultural sensors operating at lower latitudes and transmitting data multiple times per hour are best suited for GEO connectivity. In contrast, companies looking to track containers in transcontinental shipping or connect sensors on vessels far from shore and with infrequent messages may need to implement devices with LEO connectivity if their business case, monthly generated traffic, or device volumes are small. Applications requiring time-sensitive communication will likely rely on continuously available GEO service, though.

SUMMARY

Enterprises seeking to utilize NB-NTN connectivity should consult their MNO to ensure the necessary licensing is in place for the commercial use of Satellite IoT in specific countries. These authorizations, granted to the NB-NTN connectivity provider by national governments, enable them to transmit and receive signals within their relevant jurisdictions. The process for obtaining these landing rights and other authorizations can vary significantly by country. Furthermore, these rights are subject to change, requiring companies to stay informed about shifting regulations. While GEO satellites offer stable, high-quality coverage over large land areas, LEO satellites may provide flexible coverage in regions not yet served by GEO.

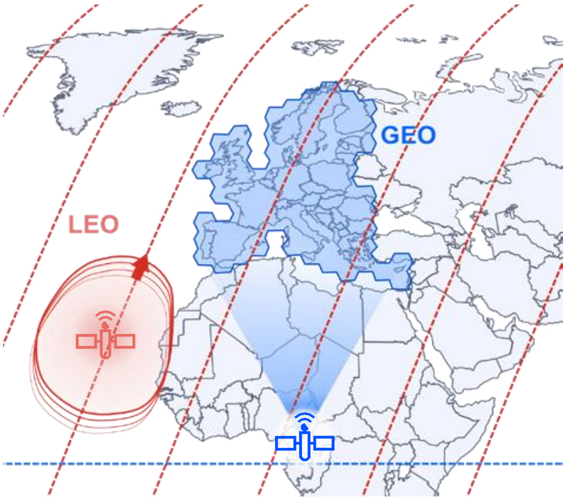


Figure 6: Example of GEO vs. LEO coverage

LEARN MORE

Viasat NB-NTN

Viasat is a global communications company that believes everyone and everything in the world can be connected. With offices in 24 countries around the world, our mission shapes how consumers, businesses, governments and militaries around the world communicate and connect. We help our customers connect their people and things with secure, flexible, global networks - with 40 years' experience of helping customers deliver safer, more efficient, more productive, and more sustainable operations. Viasat's global direct-to-device (D2D) solution is enabling MNOs, OEMs, chipset manufacturers and solution providers to help businesses across industrial IoT, automotive, and consumer mobile verticals to tap into the power of narrowband non-terrestrial (NB-NTN) technologies.

3. OPTIMIZING HARDWARE FOR NB-NTN

Optimizing hardware for Satellite NB-NTN connectivity focuses on key factors often overlooked in the initial development stages of satellite-connected IoT devices. These include antenna design and integration, enhancing antenna efficiency in small devices, proper GNSS reception integration, and selecting the right battery technology—all essential for power-optimized performance in constrained NB-NTN IoT devices. Successful hardware designs adhere to best practices in each of these areas. Additionally, selecting the appropriate module or chipset and ensuring compliance with certification requirements for operation on Satellite NB-NTN networks are critical considerations.

3.1. Device Power Class

3GPP groups cellular devices into different categories based on the output power used during transmission on the Uplink. These "power classes" determine the maximum transmit power allowed (Total Radiated Power, TRP) for different communication standards, such as NB-IoT or NB-NTN. This affects the device's battery life, signal range, and network compatibility. For example, a higher output power allows a device to transmit signals over a longer distance, while lower output aids in minimizing energy consumption, thereby extending battery life. Terrestrial NB-IoT devices fall into three possible power classes, the first two of which were defined in 3GPP Release 13, and the last in Release 14: Power Class 3 (23 dBm, or 200 mW), Power Class 5 (20 dBm, 100 mW), and Power Class 6 (14 dBm, 25 mW). 3GPP Release 17 inherited all these power classes for the non-terrestrial NB-NTN specification.

3GPP furthermore classifies NTN terminals into three performance classes, referred to as "Types," based on their TRP and Total Isotropic Sensitivity (TIS). TIS is a measure (in dBm) of the average sensitivity of a receiver-antenna system, averaged over the entire 3-dimensional sphere. The performance requirements of Type I (Industrial) and Type II (Consumer) NTN devices are summarized in Table 2 below. Specifically Type I is relevant for IoT device communicating over GEO NB-NTN service provider networks.

Band	TRP (dBm)		TIS (dBm)	
	Type I	Type II	Type I	Type II
B24 / n255 (L-Band)	≥ 20	≥ 16	≤ -112	≤ -108
n256 (S-Band)	≥ 20	≥ 16	≤ -112	≤ -108
B23 (S-Band)	≥ 20	≥ 16	≤ -112	≤ -108

Table 2: NTN Device Types (TRP and TIS Requirements)

RECOMMENDATION

Given the link budget limitations, it is highly recommended to use Power Class 3 IoT devices in non-consumer use cases for both terrestrial and non-terrestrial connectivity. Please note that many terrestrial NB-IoT networks have not been upgraded yet to support Power Class 6 terminals, as their feature sets have a Release 13 baseline.

3.2. Battery Technology

A key hardware component that influences the IoT device's performance is its power source, which is typically implemented with a non-rechargeable **primary battery.** Batteries (or "cells") store chemical energy and convert it into electrical energy via an electro-chemical reaction. When a cell is connected to an external circuit, a redox (reduction–oxidation) reaction occurs, releasing energy to the IoT device as an electrical current. This is done by transferring electrons from the battery anode (the electron donor or reducing agent) through the external circuit of the IoT device to the battery cathode (the electron acceptor or oxidizing agent). In parallel, ions move inside the battery from the anode to the cathode via a porous separator positioned between the two electrodes. This separator primarily serves as an electrical insulator. The entire system is enclosed in a sealed can and filled with an ionically conductive electrolyte which facilitates the ion movement between either end. As the primary battery discharges, the electron-providing anode is slowly and irreversibly consumed. Given the complexities of battery technologies, it is easy to make a wrong decision for your IoT device design. Several aspects that should be considered including the cell's chemistry, architecture, and self-discharge rate.

Battery chemistry must be chosen based on the electrical potential difference between the various chemical agents that are paired. The stronger the oxidation or reduction power of the agents, the greater the voltage between both poles. As illustrated in *Figure 7* below, the voltage between the cathode and anode can vary significantly. The most common type of batteries used in IoT devices worldwide are 1.5 V primary alkaline batteries. However, for NB-IoT applications, where long battery life or extending temperature range is important, primary lithium chemistries are recommended. Two main types are commercially available, and are compatible with the high continuous or pulsed currents consumption profiles used in NB-IoT and NB-NTN:

- **Lithium-thionyl chloride (Li-$SOCl_2$)** batteries use lithium as the anode material and thionyl chloride as the cathode. This chemistry is often the best choice for applications that require long battery life, since it combines high energy density, wide operating temperature range (from -60°C to 85°C), a rather stable lifetime voltage near 3.6 V, and low self-discharge (from 1% to 3% in storage at 20°C).

- **Lithium-manganese dioxide (Li-MnO_2)** implements lithium as the anode and manganese dioxide as its cathode. This technology is well-suited for applications with high continuous or pulsed current demands. Capable of operating across a broad temperature range (from -40°C to 80°C), Li-MnO_2 stands out due to the absence of significant passivation effects. This greatly minimizes the voltage drop typically observed during the pulsed discharges of other primary battery technologies. Although this chemistry is widely adopted for high-power applications, its lower nominal voltage (3 V) presents challenges as it is close to the IoT device circuitry's cut-off voltage (normally 2.5 V to 2.8 V); this situation has improved in recent years with the introduction of low-consumption electronic components.

Figure 7: Voltage of different battery chemistries

It is critical to note that temperature has a significant impact on the overall chemical reactions in the battery. Devices that are installed outdoors may encounter significant performance variations across the seasons, and even between evening and daylight hours. Additionally, consider the effects of aging and temperature on the battery's pulse performance. As such, it is recommended to contact your battery supplier for further questions and to perform accurate lifetime modelling.

Cells are designed and constructed with a distinct **battery architecture** that determines how much contact surface exists between the electrodes, directly influencing their performance:

- **Bobbin construction:** This is the traditional battery type, known for its high capacity and energy density. They feature a simple cylindrical design, with an electrode pole running along the axis of the battery, electrically isolated from the can, and connected to the positive battery terminal (cathode). A layer of lithium metal on the can serves as the negative terminal (anode). The design is completed by filling the available space inside the can with a liquid electrolyte. Bobbin-type cells are ideally suited for long-term use with low currents (ranging from µA to a few mA) and limited pulse currents (from 5 mA to 100 mA).

  Bobbin cells typically offer higher energy density, and a lower self-discharge compared to spiral-type cells, due to the smaller contact surface between the electrodes. However, their limitation lies in the restricted current and pulse current capabilities, which are often needed in NB-IoT and NB-NTN applications (as much as 23 dBm). To address this, consider pairing this battery with a pulse-sustaining component, such as a capacitor, EDLC, or hybrid layer capacitor, to support a higher pulse current profile. Some lithium-thionyl chloride batteries come in bobbin construction.

- **Spiral construction:** This architecture increases the surface area of the electrodes, leading to far higher current capability, which is ideal for power applications. This architecture typically uses a design that rolls layered sheets of anode, separator, and cathode into a bundle that placed in a can filled with electrolyte. The increased surface area between the electrodes reduces internal resistance and enhances current capability, but results in a lower energy density compared to bobbin cells. However, this larger contact surface may also contribute to a higher self-discharge rate. Lithium-thionyl chloride batteries and lithium manganese dioxide cells use a spiral construction.

Apart from chemical and structural aspects, it is important to assess the specific rate of **self-discharge** of the battery. This is crucial for devices that rely on them to provide power over extended periods of time. It's important to differentiate between the self-discharge of the battery during its storage period (from manufacturing date to its first operation in a device), as well as self-discharge while in use, powering the IoT device is its normal operating mode. Self-discharge typically follows a non-linear pattern, influenced by both the inherent properties of the battery technology and the conditions in which the device is operating. It is strongly advised to reach out to your battery supplier for further guidance.

Lastly, it's important not to directly compare the peak currents of your IoT device with the peak currents listed in battery product datasheets. These documents typically provide example values that may not be relevant to your specific application. Simply matching your hardware's peak current with the "pulse capability" or peak current of a battery is not recommended, as these values are determined under controlled test conditions. For instance, they are usually specified for specific periods of time, burst frequencies, and temperatures (typically room temperature), any of which may not align with your project’s requirements.

RECOMMENDATION

When choosing a battery for the long-term operation of IoT devices, multiple factors must be considered. IoT applications using NB-IoT and NB-NTN are preferably implemented with lithium-based chemistries, such as lithium-thionyl chloride (Li-SOCl2) and lithium-manganese dioxide (Li-MnO2), for their energy density and ability to handle high currents. The internal structure of the battery also affects performance, with spiral-type architectures having characteristics making them better suited for the bursty and medium-to-high pulse power communication of these 3GPP protocols. Finally, outdoor temperature variations, chemical aging, and the rate of self-discharge must also be factored in to ensure reliability over time. For these reasons, it is advised to contact your battery supplier to perform accurate lifetime modelling of the battery you intend to use in your IoT solution.

3.3. Cellular Modem

The cellular modem enables an IoT device to connect to the Internet via mobile networks, utilizing protocols such as NB-NTN or NB-IoT. It converts the digital data generated by the IoT device's application into a signal that can be transmitted wirelessly to the ground-based eNodeB of the connectivity provider's radio access network, and vice versa. In the case of non-terrestrial networks, as mentioned earlier, 3GPP data packets are routed between the device and eNodeB through a GEO satellite bent-pipe channel, before being transmitted back to Earth. Cellular modems are available in three stages of integration: from plug-and-play devices to radio frequency components and baseband chips. Depending on the IoT device manufacturer's R&D capabilities, available physical space in their device, and ability to manage costly certifications, they will choose one of these integration options:

- **Wireless communication chipsets** are the critical components responsible for processing the digital application data in baseband and for (de)modulating all information exchanged wirelessly with the ground-based eNodeB of the connectivity provider's radio access network. The chipset operates the NB-NTN or NB-IoT protocol stack on the device side and is positioned just before the separate radio frequency front-end (RFFE) radio circuit, a matching circuit, and the antenna. It may also include internal memory, GPIOs, resource and power management functions, connectivity interfaces (e.g., I2C, SPI, UART), a receive Analog-to-Digital Converter (ADC), and a transmit Digital-to-Analog Converter (DAC). As illustrated in *Figure 8*, the chipset is responsible for setting up, maintaining, and dismantling the radio resource bearer within the Connectivity Layer, which transfers application payload data encapsulated in transport and networking protocols (such as UDP/IP, TCP/IP, or Non-IP). While there are numerous benefits to directly integrating a wireless cellular chipset in the hardware design, such as its smaller footprint, high degree of customization, lower bill of material (BOM) cost, and optimized power management, the integration can require the most development effort because it involves designing the RF and baseband circuits, managing power consumption, and handling a myriad of certification processes. While it can be the most cost-effective for large-scale production, it often demands specialized knowledge, making it impractical for many IoT products.

- **Wireless communication modules** are embedded electronic systems that package the wireless communication chipset, an RFFE, and peripheral components, offering a convenient solution for integrators who want to avoid the complexity of directly integrating a wireless communication chipset. Due to the sensitivity of radio circuits and the precise layout and component requirements needed to operate at specific frequencies, only large enterprises with substantial investment typically opt for a direct chipset integration. Modules, in contrast, simplify the process by ensuring compliance with legal regulations governing radio circuits, including conformance testing and certification by standardization bodies such as the European Telecommunications Standards Institute (ETSI) or the Federal Communications Commission (FCC). By integrating a module in lieu of the chipset, the device manufacturer can profit from the module's existing certifications to comply with multiple market-specific regulatory requirements. The module supplier may include a separate protocol stack in the component, for wrapping payload in CoAP, HTTP, or MQTT(-SN). During the integration process, it is directly connected to the cellular antenna over a 50 Ohm matching circuit. Additionally, radio modules may include a GNSS receiver or a microcontroller (MCU) for running the IoT device application natively. Like chipsets, modules are controlled via an AT-command interface, streamlining their integration with the device application.

- **Wireless communication modems** bring the highest degree of integration simplicity in IoT devices, but at a higher cost. These fully integrated, ready-to-use devices require minimal setup, and are often plugged into the IoT device via standardized interfaces, such as USB. They come with a built-in module and antenna, and package multiple communication protocols, making it easier to integrate without requiring any deep technical expertise. This plug-and-play capability makes it ideal for both manufacturers and end users who prefer the highest degree of simplicity or want to retrofit legacy products with new access technologies. Due to their large size, modems may not easily fit into the specific form factors or constraints of a particular product, especially if space or size is a concern. Additionally, they may include features or processing capabilities that are not needed for simpler applications. This can result in unnecessary overhead, both in terms of cost and power consumption.

Given these three options, NB-NTN device manufacturers will likely choose to integrate 3GPP Release 17-compliant wireless communication modules, as they offer an optimal balance of cost, power efficiency, and time to market. Cellular modules come in various form factors, often featuring proprietary pinouts, device management services, and additional vendor-specific value-added services. Manufacturers may opt for single-mode NB-NTN modules or multi-mode hybrid modules which combine terrestrial LTE-M, NB-IoT, and/or 2G (E-GPRS) with non-terrestrial NB-NTN. The terrestrial NB-IoT and LTE-M protocol supported by the latest generations of hybrid modules typically include Release 14 compliance.

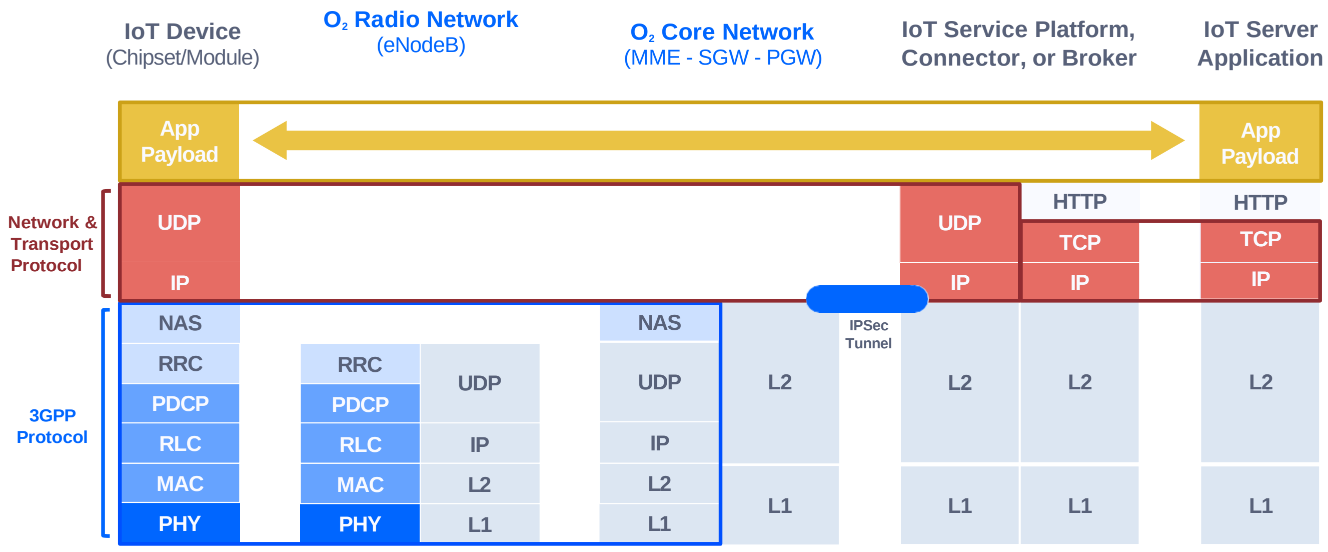


Figure 8: Data transmission of over NB-NTN, protocol stack view

It is essential to consult with your MNO regarding the certification status of the wireless communication chipset or module you may plan to use. For example, GEO NB-NTN connectivity provider Skylo requires using Skylo-certified IoT communication modules and radio baseband chipsets on their network. For more details, please refer to online catalog of Skylo-certified modems (https://www.skylo.tech/certified-devices). Additionally, IoT devices integrating these modems are expected to qualify for use on the Skylo network by successfully completing the Skylo Certification program (https://www.skylo.tech/skylo-certification-program). This applies to Telefónica Germany/O2 Business customers, whose IoT applications must comply with technical requirements outlined in the tariff which refer to Skylo certification. As of the date of the whitepaper, Viasat has aligned their certification requirements with those of Skylo.

RECOMMENDATION

It is important to consult with your connectivity service provider to confirm which wireless communication chipsets and modules are authorized for use on the various NB-NTN networks. Additionally, you should clarify any certification requirements for your device. For example, O2 Business customers are exempt from the Skylo Certification process but must adhere to specific technical requirements for communication over NB-NTN, as well as terrestrial NB-IoT, LTE-M, and 2G. This ensures optimal resource utilization and secures a high service level for all customers on both networks.

3.4. GNSS Receiver

NB-NTN devices must consider additional challenges for their communication, including higher Doppler effects from fast-moving LEO satellites, larger non-terrestrial cell footprints, and longer link distances that affect timing advance (TA) and Uplink frequency compensation. Release 17 enhancements included a requirement to provide location information to the device for network acquisition as well as periodic Tracking Area Updates (TAU). The TAU messages are used to notify the network of the device's whereabouts, thereby optimizing paging performance on the network, as well as maintaining the device's registration session active. As mentioned above, NB-NTN wireless communication modules may include an integrated Global Navigation Satellite System (GNSS) receiver. The most prominent GNSS constellation in use by the IoT industry is the Global Positioning System (GPS). In case that NB-NTN communication is sent over the L-Band (5G-band n255), the cellular module may be connected to a single antenna that supports both GPS reception and NB-NTN bidirectional communication, provided that these two functions are properly sequenced. Take careful note of your cellular module supplier's requirements for antenna selection, particularly the choice of using an active or passive GNSS antenna. Finally, positioning data from an external GNSS receiver chip can be instead fed into the separate microcontroller, or "Host MCU", which passes the information to the NB-NTN module via AT-commands. For proper NB-NTN operation, the selected GNSS must have an accuracy of at least 95% circular error probability (CEP) ≤ 100m.

In many cases, using an **external GNSS receiver chip** is a better choice for mobile applications, as it allows for more control and optimization by the Host MCU. They typically provide a serial interface that outputs various NMEA (National Marine Electronics Association) strings containing different sets of location-related information. The Host MCU must consider this implementation and conversion of data formats between GNSS output and NTN module input. Many open-source libraries exist for GNSS and NMEA parsing to assist with integration. In contrast, integrated GNSS will simplify or even automate the interface between GNSS and NTN without this added complexity of NMEA.

The complexity of managing the GNSS-configurations of individual devices in volume deployments is challenging. An **integrated GNSS** (i.e., in the cellular module) is a sensible choice if it can be configured in a static mode that is used only during the device's initial boot and acquisition sequence. Static applications therefore do not technically require a separate GNSS receiver if the location is known in advance and/or can be easily and reliably configured during the device installation. IoT applications that are mobile, however, will need regular and accurate GNSS-positioning information to maintain their connection and perform tracking area updates. Specific use case requirements like geofencing may also drive a more intensive use of the GNSS receiver. This means that GNSS can rapidly become one of the more power-hungry processes in such devices. In situations where a continuous power source is available, for instance, vehicle tracking, the GNSS power consumption is normally not a major concern; however, it may negatively impact the overall power consumption of battery-powered applications if its settings are not carefully configured and optimized.

The dominant contributor to power consumption for GNSS is **acquisition time,** when the receiver is active. The Time to First Fix (TFF) is a primary consideration for power-constrained applications, as is the availability of accelerators such as Space-Based Augmentation Service (SBAS). Please consult the GNSS manufacturer's specifications and application notes to determine the best settings for your use case. Various techniques can be used to help speed up GNSS acquisition, thereby reducing its percentual contribution to the overall power consumption. The use of an integrated GNSS must be therefore carefully evaluated in terms of its performance in both location quality, acquisition time, and power consumption.

Sequencing of GNSS reception and NB-NTN communication is also critical, since the transmission of NB-NTN data in the L-Band could saturate the GNSS receiver, potentially causing damage. Integrated GNSS typically provides safeguards for this, but the Host MCU is generally still responsible to manage the sequencing through various AT-commands. The physical management of the signals may also be required in cases where the antenna is shared and switched between GNSS and NB-NTN to reduce cost and size.

A final consideration is the selection of actual GNSS constellation that is used. It may be necessary to use another system than GPS to comply with specific local regulations, for example, GLONASS in the Russian Federation or BeiDou in the People's Republic of China. Many commercial GNSS implementations support multiple GNSS constellations, and the ability to select between these using configuration settings and AT-commands.

RECOMMENDATION

For static/fixed IoT applications please consider using modules with integrated GNSS or an installation strategy making the configuration of location information easy and reliable during the installation. For mobile applications consider using either a module with a high-quality integrated GNSS or an external GNSS receiver chip. The Host MCU can optimize the handling of GNSS reception to optimize power consumption for a myriad of use cases. For battery-powered applications. please be sure to spend sufficient engineering effort to carefully design and measure the effect of GNSS on your power budget.

3.5. Antenna Technology and Integration

Antennas are critical components in NB-NTN networks, enabling communication between ground-based devices and GEO and LEO satellites orbiting the Earth. When transmitting electromagnetic (radio) waves, the antenna converts electrical output signals from the cellular modem transmitter into electromagnetic waves that radiate into space. When receiving, it intercepts the electromagnetic waves propagating through the air, converting them back into electrical signals that can be processed by the modem's receiver. Antennas therefore ensure efficient signal transmission and reception, which is essential for reliable data transfer and system performance.
As antenna design and placement significantly impact the coverage, link budget, and overall performance of any Satellite IoT network, it is of paramount importance not to view these components as a "secondary design factor" when developing IoT devices with hybrid NB-NTN and terrestrial NB-IoT connectivity. Factors such as gain, beamwidth, polarization, and pointing accuracy are crucial for optimizing signal strength and minimizing interference. Any sub-optimal selection and integration of an antenna component in such devices will lead to multiple problems that affect coverage performance, battery life, user experience, and ultimately business case viability of your product. Antennas in NB-NTN devices must possess specific characteristics that ensure reliable communication over vast distances. As the antenna is a passive element that does not create (amplify) energy, but rather shapes the way it is radiated, there are key parameters to consider:

- **High gain** toward the satellite: To compensate for the significant path loss associated with satellite links, antennae with high gain are crucial. This characteristic is a measure of how well the antenna converts input power into radio waves in a specific direction, or how effectively it radiates or receives electromagnetic energy compared to a standard reference antenna (such as an isotropic radiator or a dipole antenna). It is often expressed in decibels (dB) and indicates the directivity and efficiency of the antenna focuses on the transmitted signal in a specific direction, maximizing the power received by the satellite. There is usually a trade-off between antenna gain and beamwidth (the width of the antenna's radiation pattern). A higher gain often leads to a narrower beamwidth, which can improve the signal in a specific direction but limit coverage. It is important to understand the gain profile of your selected antenna in the target frequency range, for example 1.5GHz to 1.6GHz for L-band NB-NTN (LTE band 255).

- **Polarization** refers to the orientation of the electric field of the radio wave as it propagates through space. Polarization is crucial because, for optimal signal reception, the transmitting and receiving antennas must have matching polarizations. Satellites often use Circular Polarization (Right-Hand Circular Polarization (RHCP) or Left-Hand Circular Polarization (LHCP), where the direction in which the electric field of a radio wave rotates distinguishes the two). The antenna embedded in the device must have the same circular polarization for reducing mispolarization and maximizing performance. Viasat's L-Band NB-NTN services, for example, use RHCP.

- **Wide bandwidth** considers the range of frequencies over which an antenna can effectively operate while maintaining acceptable performance in terms of parameters like **impedance matching**, radiation pattern, and efficiency. An antenna with a wide bandwidth can support a broad range of frequencies, making it suitable for applications that require operation over multiple channels or varying frequency bands. Satellite IoT devices often operate over a range of terrestrial NB-IoT, LTE-M, and 2G frequencies, as well as multiple NB-NTN bands, as discussed above. Antennas with wide bandwidth capabilities can support communication across different cellular bands globally and accommodate future system upgrades. One of the main factors in antenna bandwidth is impedance matching. For an antenna to perform well, its impedance should match that of the transmission line (typically 50 ohms in most communication systems). An antenna with a wide bandwidth can maintain this impedance match over a wide range of frequencies, ensuring efficient power transfer and minimal signal reflection.

- **Size and placement constraints** are crucial considerations when selecting an antenna, especially for applications where the device size is small and the physical space inside is limited. These constraints can affect the antenna's performance and the overall system integration. In many cases, size and weight limitations are critical, especially for small, battery-powered IoT devices. For example, when an antenna is placed right over the battery, it will significantly reduce the efficiency of the antenna. The antenna should not have any metal immediately around it to be able to radiate efficiently; therefore, any battery in its immediate vicinity can detune it and even absorb energy. The second factor is the size of the ground plane; the smaller the size of the ground plane (which is typical in IoT devices), the lower the efficiency especially in low bands such as 4G Band 20 (800 MHz) and Band 8 (900 MHz) will be. PCB size and antenna placement are thus the most important factors to consider for embedded antenna integration.

Cellular antennas play an important role in hybrid IoT devices, supporting communication over both satellite and terrestrial networks and enabling more robust and resilient products for the remote management of assets. This is why some of the antennas that are designed for NB-NTN can also cover 4G cellular bands at the same time. By having one antenna for both technologies, it reduces the complexity and the hardware cost of the system. These antennas must support several frequency bands, however, making it extremely difficult in a small form factor to achieve circular polarization over all the bands. These multifrequency antennas are therefore most of the time linearly polarized.

KYOCERA AVX actively tracks emerging cellular technologies and has built a diverse portfolio of antennas covering NB-NTN and cellular standards for terrestrial networks. From the embedded FR4 (1004795 and P822601), to the off-board FPC (1002289), and external antennas (X9003334), this broad range of standard antennas are designed to cover different types of IoT devices and application needs (refer to *Figure 9*). It's important to highlight that not every cellular antenna can cover Satellite IoT. Cellular antenna designs for NB-NTN must be re-tuned to cover the S-Band and L-Band, as described in Table 1 further above.

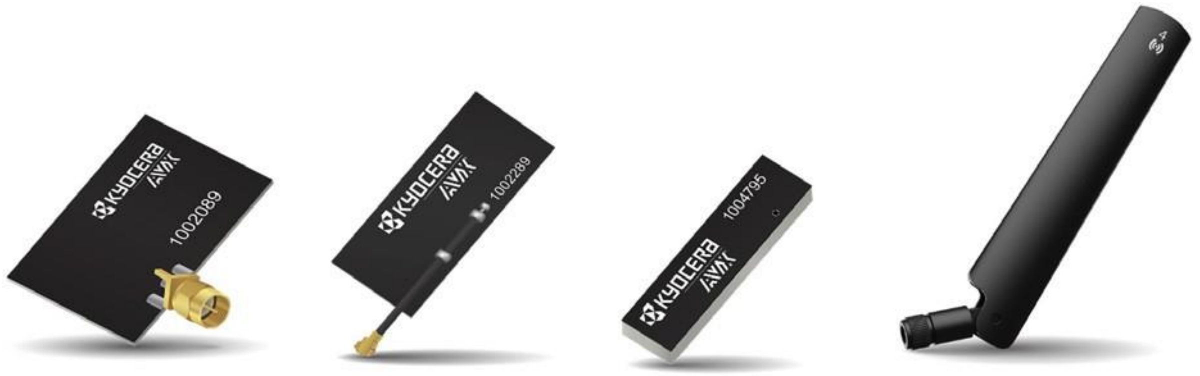


Figure 9: Examples of KYOCERA AVX cellular + NB-NTN antennas (Source: KYOCERA AVX)

GNSS antennas enable devices to determine their precise location, which is essential for various applications such as asset tracking, fleet management, and precision agriculture. Supporting multiple GNSS constellations (GPS, GLONASS, Galileo, BeiDou, among others) improves the position accuracy and reliability, especially in areas with limited satellite visibility.

Polarization is a crucial parameter in such GNSS antennas and is often carefully chosen when the position and orientation of the device versus the satellite in the sky is known and can be controlled. When device orientation is unknown, linear polarized antennas are more often chosen. In the case of GNSS, the accuracy of the location depends on the number of satellites that the device can see at any given location. Device manufacturers must therefore not look for a high gain towards the zenith but more of an average gain from the zenith to the horizon. If circular polarization is to be used, ceramic patches are the most recommended antennas, especially on account of their narrow bandwidth of about 5%, making them highly suitable for GNSS applications. This is why S-band services, for example, may require two patches to cover both transmit and receive frequency ranges (1980 - 2020 MHz and 2170 - 2200 MHz, respectively). KYOCERA AVX designed the 9003329 and 9003330 antennas to cover the full S-band.

Figure 10: Examples of KYOCERA AVX GNSS antennas (Source: KYOCERA AVX)

The choice of antenna should be considered during the very early stages of IoT device development. Parameters such as antenna placement and size must be calculated from the beginning to avoid fundamental design problems during the product development. This is because the antenna is a crucial component and at the same time very sensitive to its surroundings.

Antennas are typically deployed in diverse environments, ranging from open fields to densely populated urban areas. It is therefore crucial to also recognize that not all antennas will perform equally well in these real-world conditions. Factors like the presence of metal structures in the vicinity, human bodies, and other electronic devices can significantly impact an antenna's performance, leading to signal attenuation, reflections, and interference. Therefore, meticulous antenna design and thorough testing should account for the environmental losses. Neglecting to consider the IoT device's location, surrounding environment, and intended usage can result in significant performance degradation and a suboptimal system operation in real-world conditions.

The impact of the **cable loss** is also a crucial factor to take into consideration when designing an IoT product with cabled off-board or external antennas. The longer the cable the more losses will be added to the system. The link budget of NB-NTN communication with an antenna of low gain may not allow for much more cable losses than 1-2 dB. Also, the cable position is very delicate and sensitive, as the cable may also radiate or catch noise, significantly impacting the overall device performance.

RECOMMENDATION

When using GNSS and NB-NTN cellular antennas with circular polarization, we recommend placing patch antennas in the middle of the PCB to increase gain and directivity. Cellular antennas should be placed on the shortest edge of the PCB. Also make sure that the PCB length is sufficient to cover the lowest frequency band with good performance. When integrating several antennas onto the same PCB, please make sure they have enough space between each other to avoid coupling. If no standard antennas fit into your device, there is always an option to use a custom antenna that is more adequate to your specific requirements. It is recommended to reach out to your antenna supplier for guidance and support.

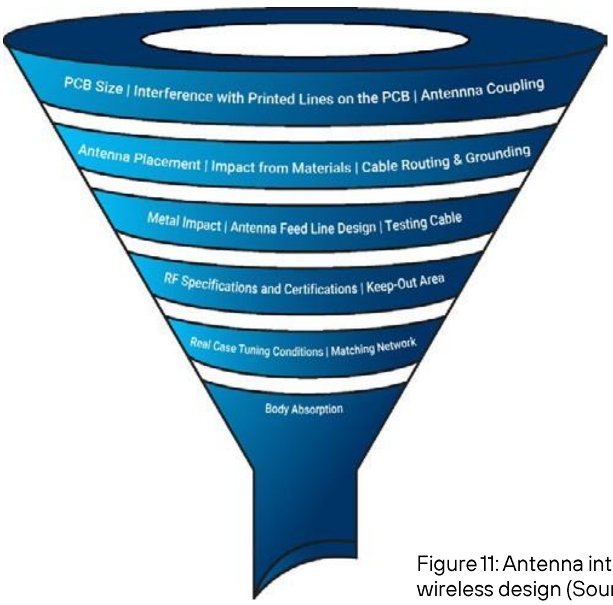


Figure 11: Antenna integration considerations for successful wireless design (Source: KYOCERA AVX)

SUMMARY

When designing IoT device hardware for hybrid operation on non-terrestrial NB-NTN and terrestrial NB-IoT networks, it is important to take careful considerations in the selection and integration of key components. In this chapter the following elements were considered: battery, cellular modem, GNSS receiver, and the cellular and GNSS antennas.

The performance of battery-powered IoT devices is significantly influenced by the characteristics of their power source, typically a non-rechargeable primary battery. The choice of battery chemistry is crucial for ensuring long-lasting and reliable performance in IoT applications. Lithium-based chemistries, such as lithium-thionyl chloride (Li-$SOCl_2$) and lithium-manganese dioxide (Li-MnO_2), are commonly used in devices like NB-IoT and NB-NTN due to their high energy density and suitability for continuous or pulsed current demands. Battery architecture, such as bobbin or spiral construction, affects energy density and current capabilities, with spiral construction offering higher current capacity. Temperature and aging also impact battery performance, especially in outdoor environments, necessitating accurate lifetime modeling. Additionally, self-discharge rates, both during storage and use, should be considered when selecting batteries for extended IoT device operation.

Most NB-NTN device manufacturers will opt to integrate a 3GPP Release 17-compliant wireless communication module in lieu of a chipset, as the former offers a balance of cost, power efficiency, and time to market. Such modules may be single-mode or multi-mode, supporting protocols like LTE-M, NB-IoT, and 2G alongside GEO NB-NTN. It is crucial to verify the certification status of the chosen module with your connectivity provider, as their GEO roaming partners, like Skylo, require certified modules and IoT device compliance with their certification programs.

3GPP Release 17 enhancements for NB-NTN require devices to provide location information for network acquisition. NB-NTN-only or hybrid devices must include modules supporting an integrated GNSS receiver, typically using GPS, or connect these to an external GNSS receiver for greater control, particularly in mobile applications. Power consumption from the GNSS may become a key concern, especially in battery-powered devices, and must be carefully optimized for applications requiring frequent location updates. The selection of the GNSS constellation, antenna type, and proper sequencing of GNSS and NB-NTN communication are crucial to prevent interference and ensure reliable operation. Additionally, regional regulations may require support for specific GNSS systems like GLONASS or BeiDou.

Antennas are not just components; they are the foundation of successful Satellite IoT and hybrid (terrestrial and non-terrestrial) IoT devices. Their performance directly impacts the feasibility, scalability, and overall success of this emerging segment of products. The characteristics of cellular antennas are crucial for ensuring reliable and efficient communication in Satellite IoT and cellular networks, enabling seamless data transmission and reception across vast distances and flexible fallback to terrestrial coverage. By considering the specific aspects outlined in this section, GNSS antennas can also provide accurate and reliable positioning information to NB-NTN devices, enabling a wide range of applications and driving innovation in this growing field.

LEARN MORE

KYOCERA AVX Antennas

KYOCERA AVX is a subsidiary of Kyocera Corporation, specializing in the design and manufacturing of advanced electronic components. It offers a diverse portfolio of advanced antenna solutions designed for a variety of applications, including automotive, telecommunications, IoT, and consumer electronics. Their antennas are known for high performance, compact designs, and reliability, serving needs in wireless communication systems, including 5G, 4G, Satellite IoT, Wi-Fi, Bluetooth, GPS, and other RF technologies.

KYOCERA AVX antennas are engineered to meet the demanding requirements of modern wireless connectivity, providing enhanced signal reception, and enabling low power consumption with minimal interference. Their portfolio includes standard antennas and custom solutions tailored to specific customer needs. These antennas are widely used in applications such as automotive telematics, wearable devices, and smart home products, where size, performance, and durability are critical.

KYOCERA AVX has an expansive global footprint comprised of several dozen research, development, and manufacturing facilities spanning more than 15 countries and staffed with talented personnel dedicated to innovation, component quality, customer service, and enabling a brighter future through technology. KYOCERA AVX state-of-the-art global design centers support customers from the concept phase to mass production, including validation and pre-certification testing such as TRP/TIS measurements. For more information regarding the products listed above, please refer to the following links:

1002089: https://www.kyocera-avx.com/product/lte-pcb-antenna-with-sma-connector-1002089/

1002289: https://www.kyocera-avx.com/product/lte-cellular-wide-band-fpc-embedded-antenna-1002289/

P822601: https://www.kyocera-avx.com/product/universal-broadband-fr4-embedded-lte-lpwa-antenna-p822601/

1004795: https://www.kyocera-avx.com/product/universal-broadband-fr4-embedded-lte-lpwa-antenna-1004795/

X9003334: https://www.kyocera-avx.com/product/x9003334/

9002137: https://www.kyocera-avx.com/product/9002137-gnss-glonass-beidou-galileo-chip-antenna/

1001011: https://www.kyocera-avx.com/product/gps-glonass-beidou-galileo-antenna-1001011/

9001157: https://www.kyocera-avx.com/product/9001157-gps-glonass-smt-patch-antenna/

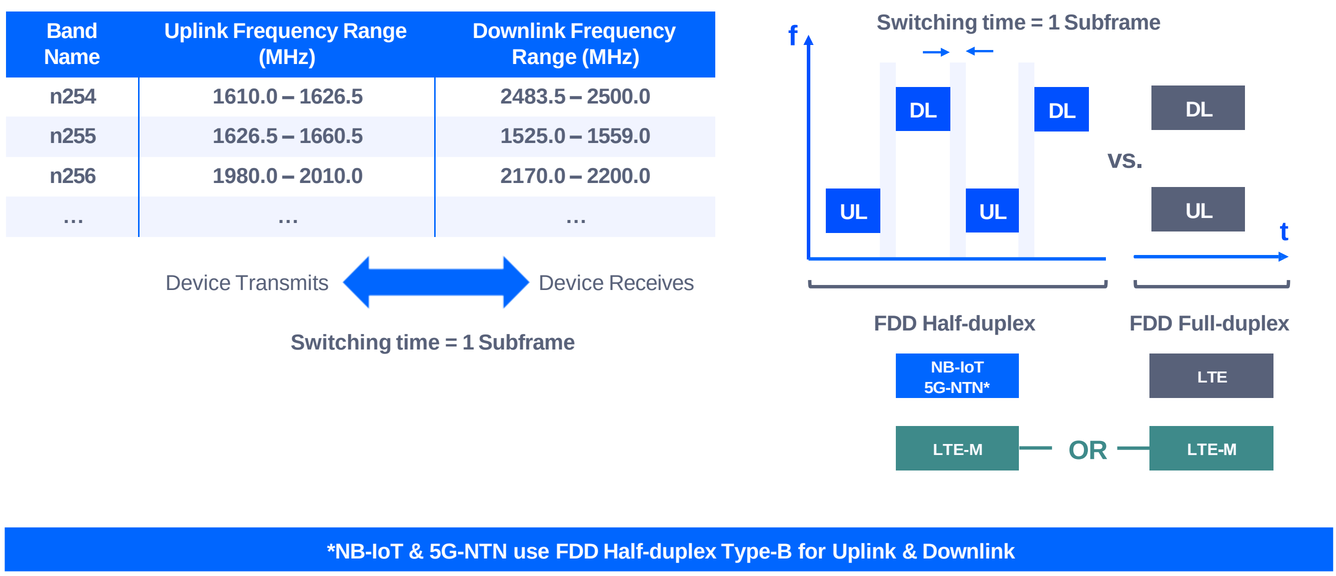
X1005247: https://www.kyocera-avx.com/product/x1005247-gnss-external-antenna/

4. CHARACTERISTICS OF THE NB-NTN CONNECTIVITY LAYER

This chapter explores the key characteristics of the Connectivity Layer of NB-NTN and terrestrial NarrowBand IoT and LTE-M, focusing on their respective frequency division duplex (FDD) schemes, coverage optimization techniques, and typical performance metrics such as throughput, latency, and network quality indicators. Additionally, we will discuss the power-saving features supported in each system, examples of how they are configured, and assess their implications for IoT device battery life and overall network efficiency. Through this comparison, we aim to highlight how these features address the needs of diverse IoT applications and the trade-offs they present.

4.1. Frequency Division Duplex

The 5G Non-Terrestrial Network (NTN) Physical Layer (represented by the layer "PHY" in *Figure 8*) between the IoT device and the eNodeB employs frequency-division duplexing (FDD) for transmitting and receiving data. This method defines a NB-NTN carrier by pairing a frequency block of 180 kHz for device transmission (Uplink) with a frequency block of 180 kHz for device reception (Downlink). Multiple FDD carriers can be operated within the swath of available NB-NTN spectrum, the latter of which is deployed in blocks of 5, 10, 15, or 20 MHz, depending on the specific 5G band. NB-NTN communication over each carrier is performed in half-duplex, a technique that is used as well by terrestrial NB-IoT and LTE-M, whereby the device alternates between transmitting on the Uplink frequency block and receiving on the Downlink frequency block, with a switching time of 1 subframe in-between (refer to *Figure 12*). In contrast, terrestrial 4G (and LTE-M, optionally) supports full-duplex communication, transmitting and receiving simultaneously.



Band Name	Uplink Frequency Range (MHz)	Downlink Frequency Range (MHz)
n254	1610.0 – 1626.5	2483.5 – 2500.0
n255	1626.5 – 1660.5	1525.0 – 1559.0
n256	1980.0 – 2010.0	2170.0 – 2200.0
…	…	…

Figure 12: Frequency Division Duplex in NB-NTN

4.2. Coverage Optimization Mechanisms (Terrestrial vs. Non-terrestrial)

One important aspect of terrestrial NB-IoT and LTE-M networks is how they optimize their radio interface based on the received signal quality at the IoT device. The functionality, known as **Coverage Enhancement** (CE), provides for superior deep-indoor coverage than LTE, UMTS, or E-GPRS. This is achieved by conditionally switching power-controlling off in the device transmitter and using maximum output power (23 dBm in Power Class 3 devices) for the transmission and by repeating physical channel messages containing signaling or application payload data. The IoT device application does not need to be programmed to repeat any packets, for the underlying 3GPP stack automatically takes care of this. The higher the number of packet repetitions, the farther the coverage may extend, yet the lower the throughput, and the longer the latency (round-trip delay).

The wireless communication chipset assesses signal quality by measuring the RSRP values received at the IoT device and comparing them to network-defined RSRP thresholds which delineate the transition between each CE-Level. These terrestrial network thresholds will vary from operator to operator, or even within the same PLMN, as these are generally not harmonized across the industry. Telefónica Germany, for example, sets its CE-Level thresholds at the values shown below. A final note to consider is that chipset may factor in proprietary optimizations for CE-Level selection, including using the SINR level in combination with RSRP to decide what CE-Level to request from the network.

The following values are a subset of the repetition configurations that Telefónica Germany's network uses in its CE-Levels. Please note that this parametrization will change while roaming onto different terrestrial NB-IoT VPLMN networks or even across different infrastructure areas of the same VPLMN, as such configurations are generally not harmonized across MNOs and infrastructure providers worldwide. Coverage quality will therefore impact device battery life and performance unequally across different MNO networks, or parts thereof.

NarrowBand IoT Coverage Enhancement Levels

- **NB-IoT CE-Level 0:**
  - Commonly referred to as **NB-IoT "Outdoor" operation**
  - Power-controlled Uplink transmission
  - Measured RSRP > -114 dBm
  - NarrowBand Physical DL Shared Channel (NPDSCH): 1 repetition
  - NarrowBand Physical UL Shared Channel (NPUSCH): 1 repetition
  - NarrowBand Physical DL Control Channel (NPDCCH): 1 repetition
  - NarrowBand Physical Random Access Channel (NPRACH): 2 repetitions
  - ACK-NACK (Msg4): 1 repetition

- **NB-IoT CE-Level 1:**
  - Commonly referred to as **NB-IoT "Indoor" operation**
  - Maximum power Uplink transmission
  - NB-IoT CE-Level 1: -114 dBm ≥ Measured RSRP > -124 dBm
  - NarrowBand Physical DL Shared Channel (NPDSCH): 8 repetitions
  - NarrowBand Physical UL Shared Channel (NPUSCH): 2 repetitions
  - NarrowBand Physical DL Control Channel (NPDCCH): 16 repetitions
  - NarrowBand Physical Random Access Channel (NPRACH): 8 repetitions

- **NB-IoT CE-Level 2:**
  - Commonly referred to as **NB-IoT "Deep Indoor" operation**
  - Maximum power Uplink transmission
  - NB-IoT CE-Level 2: -124 dBm ≥ Measured RSRP > -140 dBm (coverage lost)
  - NarrowBand Physical DL Shared Channel (NPDSCH): 32 repetitions
  - NarrowBand Physical UL Shared Channel (NPUSCH): 32 repetitions
  - NarrowBand Physical DL Control Channel (NPDCCH): 128 repetitions
  - NarrowBand Physical Random Access Channel (NPRACH): 32 repetitions

LTE-M Coverage Enhancement Levels

- **LTE-M CE-Level 0 (CE-Mode A):**
  - Commonly referred to as **LTE-M "Outdoor" operation**
  - Power-controlled Uplink transmission
  - LTE-M CE-Level 0 (CE-Mode A): Measured RSRP > -117 dBm
  - MTC Physical DL Shared Channel (MPDSCH): 1 repetition
  - MTC Physical UL Shared Channel (MPUSCH): 1 repetition
  - MTC Physical DL Control Channel (MPDCCH): 1 repetition
  - MTC Physical Random Access Channel (MPRACH): 1 repetitions

- **LTE-M CE-Level 1 (CE-Mode A):**
  - Commonly referred to as **LTE-M "Indoor" operation**
  - Power-controlled Uplink transmission
  - LTE-M CE-Level 1 (CE-Mode A): Measured RSRP ≤ -117 dBm
  - MTC Physical DL Shared Channel (MPDSCH): 4 repetitions
  - MTC Physical UL Shared Channel (MPUSCH): 4 repetitions
  - MTC Physical DL Control Channel (MPDCCH): 4 repetitions
  - MTC Physical Random Access Channel (MPRACH): 4 repetitions

- **LTE-M CE-Level 2 / CE-Level 3 (CE-Mode B):** Not supported currently by LTE-M networks.

As seen in the list above, LTE-M CE-Mode A includes two CE-Levels which are both power-controlled. IoT devices on the field using terrestrial LTE-M will generally experience less of change to battery life when switching between CE-Level 0 and CE-Level 1, as opposed to terrestrial NB-IoT, where the battery life deteriorates exponentially when moving from "Indoor" operation (CE-Level 1) to "Deep Indoor" operation (CE-Level 2), due to the significant increase in the repetition of packets at maximum transmit power (as evidenced by the flattening of the curves shown in *Figure 13*). This is the cost of connecting wireless devices in basements or other hard-to-reach places; for this reason, NB-IoT affords better in-door coverage than LTE.M. Ultimately, a long battery life of over 8 years can only achieved in installations permanently under CE-Level 2 conditions if the time between messages consecutive increases.

Apart from the quality of the received network coverage (CE-Level), the battery life of NB-NTN hybrid devices on NB-IoT and LTE-M terrestrial networks will be affected by communication patterns (frequency, size of messages), battery aspects (self-discharge over time, battery capacity as a function of temperature, battery voltage, etc.), the antenna efficiency and placement, the frequency of network scanning procedures, and the configuration of power saving features. *Figure 13* shows an example of battery life on a terrestrial NB-IoT network for a condition monitoring application transmitting 500 Bytes payload on the Uplink, using CoAP over UDP/IP without DTLS encryption on the Transport Layer.

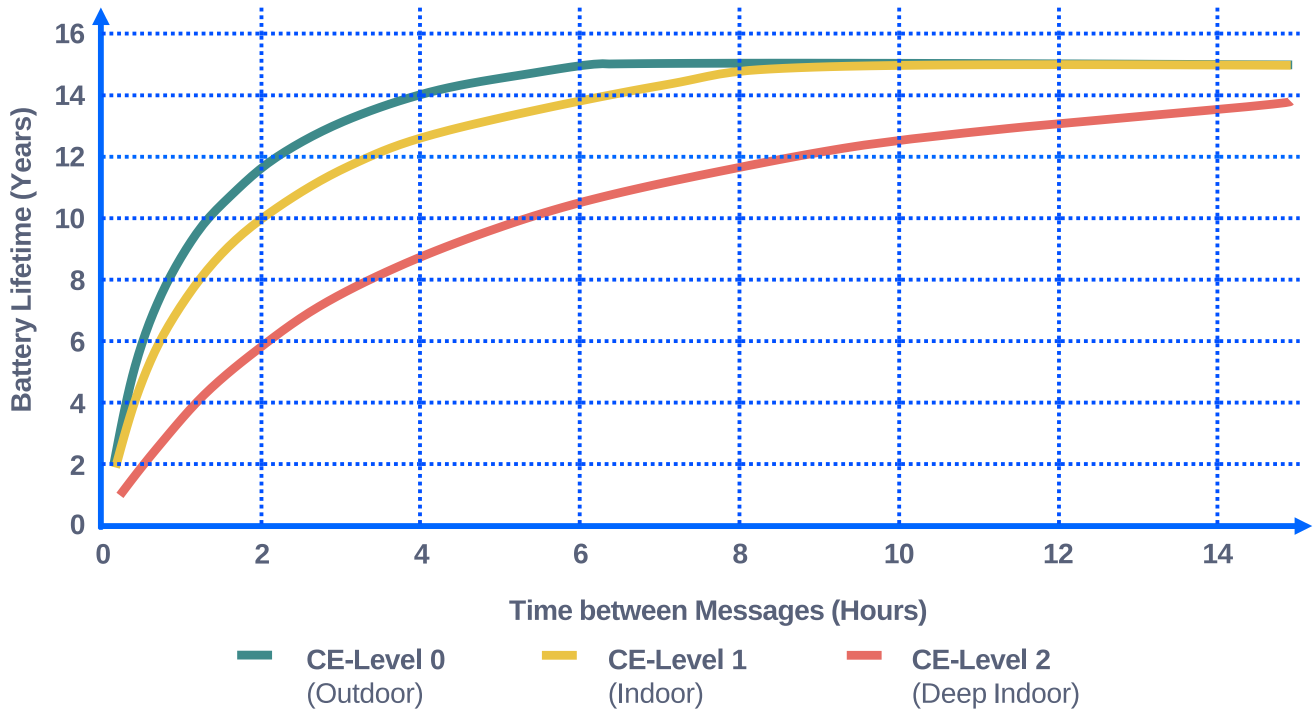


Figure 13: Dependency of Battery Life on Messaging Period and NB-IoT CE-Level

Closing the communication link with the GEO NB-NTN network is far more challenging compared to its terrestrial LPWA analogs. Not only are the satellites much farther from a cellular IoT device than an eNodeB in a terrestrial LPWA network, resulting in very high latencies, but coverage is only available outdoors, with a direct line of site to the satellite. This complexity has led to disabling the Coverage Enhancement feature altogether Release 17 GEO NB-NTN networks, and postponing improvements until future 3GPP releases. For the time being, cellular modems transmit their packets at maximum power on the Uplink when using the non-terrestrial network. The number of repetitions is determined in part via the NB-NTN network's SIB2 message, which sets the radio resource configuration. The values below are a subset of the repetition configurations that the Viasat network uses. As there is more consistency in the network configuration of the few GEO NB-NTN providers, the power consumption behavior on IoT devices is more predictable, and subject to less variation.

NB-NTN (NTN) Coverage Optimization:
- CE-Levels not supported in Release 17
- Maximum power Uplink transmission
- Measured RSRP > -138 dBm (coverage lost)
- Measured SINR > -9 dB
- NarrowBand Physical DL Shared Channel (NPDSCH): 8 repetitions
- NarrowBand Physical UL Shared Channel (NPUSCH): 8 repetitions
- NarrowBand Physical DL Control Channel (NPDCCH): 8 repetitions
- NarrowBand Physical Random Access Channel (NPRACH): 8 repetitions

RECOMMENDATION

Hybrid devices operating on terrestrial NB-IoT networks should consider adapting the cadence of their communication based on the serving CE-Level. This serving CE-Level can be queried by the module whenever sending data and used to plan the next communication window with the server. By extending the time between application messages, battery powered devices can prolong their battery lives even under CE-Level 2 ("Deep Indoor") conditions, reaching the battery lives seen in devices that communicate under a better CE-Level 0 ("Outdoor") environment. Applications that adapt their communication patterns allow service providers to make the most of their business cases, as the battery lives will be maximized; that said, some specific applications may require a strict reporting sequence or may have event-based reporting. Contrary to the situation on terrestrial networks, power consumption on NTN is more predictable, as CE-Levels are disabled, and a static maximum number of repetitions is used. As transmissions are sent with maximum power, the power consumption of NB-NTN lies between that experienced in CE-Level 1 ("Indoor") and CE-Level 2 ("Deep Indoor").

4.3. Expected Performance

In NB-NTN and NB-IoT networks, the performance of the radio channel is largely determined by two quality metrics which are actively measured by the cellular modem:

- **RSRP (Reference Signal Received Power)** is a key measurement in mobile networks, particularly in 4G and 5G systems, used to assess the quality of the radio signal received by a device. It measures the power level of a reference signal broadcasted by the eNodeB and punctured as discrete OFDM symbols into the transmitted data stream. RSRP is used to aid in tasks such as cell search, handovers, and channel estimation. The measurement of RSRP considers the power of the reference signal in dBm (decibels milliwatts) over a specific bandwidth, typically a subframe or slot. A more positive value indicates a stronger received signal, i.e., better coverage and signal quality.

  For signals received from GEO NB-NTN satellites, RSRP values above -138 dBm are generally sufficient for service, with values above -130 dBm being preferred for optimal performance. Below -138 dBm coverage is generally lost. It's important to note that these values can vary significantly depending on a device's geographic location, particularly due to factors such as atmospherics and the satellite elevation angle, the latter of which is generally more sensitive to the device's latitude than its longitude. For instance, a device at a location in Southern Canada with a 30° elevation angle may measure a different RSRP value than the same device with a lower elevation angle in Scandinavia. A high-gain antenna can be used to improve the RSRP. The channel model of the device deployment (static or moving conditions) will have minimal impact on the signal, as the rate of change in the elevation angle of the GEO satellite at high speeds is negligible.

- **Signal to Interference plus Noise Ratio (SINR)** is another crucial measurement in wireless communication systems, quantifying the quality of a received signal in comparison to the interference and background noise. It helps determine how effectively a device can demodulate a signal in the presence of interference and noise, impacting data throughput and connection reliability. When it comes to SINR, values from GEO NB-NTN communication below -9 dB will lead to a loss of coverage. For optimal performance, SINR values between 5 and 7 dB are ideal, with service possible still possible when the SINR reaches -1 or -2 dB. Below this, it becomes impossible to extract the information from the received signal.

One factor to consider is that specific geographies may be covered by more than one GEO NB-NTN satellite of the same non-terrestrial network. Devices can perform reselections between satellites if they happen to move into the shadow of the serving satellite (i.e., enter in an area where an obstacle blocks the line of sight). The European continent is mainly serviced by Viasat's "EMEA Satellite;" however, beams from other regions, like those of the "IOE - Indian Ocean" satellite can also be detected at multiple locations in Europe. If a satellite reselection occurs, no performance differences (in terms of RSRP and SINR) are seen, even if there is a slightly longer distance that the signals must travel through space.

A common performance benchmark in any communication system is the effective **data throughput.** This is the rate at which data is successfully transmitted or processed over a communication network, typically measured in bits (or Bytes) per second. It reflects the efficiency and capacity of a network or device to handle data. Effective throughput takes real-world conditions into account, including factors like network congestion, interference, packet loss rate, latency, and signal quality. These aspects can reduce the average throughput from its peak measured values, which are usually temporary. Uplink and Downlink throughput is significantly lower in NB-NTN as compared to terrestrial NB-IoT CE-Level 2 (Deep Indoor), as evidenced in Table 3. The slightly smaller MTU supported by the cellular modem in GEO NB-NTN limits the size of the application messages that can be transmitted somewhat. Due to the high path losses in the link budget and the limited transmit power of the device, the GEO bent-pipe system of the transparent satellite network delivers Uplink throughputs that are a small fraction of those achieved by terrestrial systems. In contrast, the Downlink throughput is significantly higher, as the satellite utilizes greater power to transmit the signal back to Earth. Please note that Downlink throughput degrades significantly if the device is in high mobility, such as when traveling at an average speed of 50 km/h or more.

	Terrestrial NB-IoT			GEO NB-NTN
	CE-Level 0	CE-Level 1	CE-Level 2	
Payload Size (Bytes)	200	200	200	50
UL Throughput (Bytes / second)	2,000	1,288	213	6 (static) 6 (mobility)
DL Throughput (Bytes / second)	23,250	9,000	1,750	54 (static) 27 (mobility)

Table 3: Average Throughput, Terrestrial NB-IoT vs. GEO NB-NTN

Latency (round-trip-delay) measurements are presented in Table 4, whereby the device initially finds itself in Idle Mode and is either paged to receive a Downlink message or uses the access channel to request radio resources for an Uplink data transmission. The Uplink and Downlink latency of NB-NTN is somewhat better than that of terrestrial NB-IoT CE-Level 2 (Deep Indoor) but may worsen depending on the configuration of specific Idle Mode power saving features, including eDRX and PSM. These mechanisms may force the server to wait until the device is reachable again on the Downlink, after waking up from its sleep cycle. For more information on Idle Mode and power saving features, please refer to Section 4.4. Finally, it is relevant to note that a slight increase in latency may occur when IoT applications communicating

	Terrestrial NB-IoT			GEO NB-NTN
	CE-Level 0	CE-Level 1	CE-Level 2	
Payload Size (Bytes)	200	200	200	50
UL Latency (seconds)	2	3	15	10 (static) < 13 (mobility)
DL Latency (seconds)	4	6	19	12 (static) < 15 (mobility)

Table 4: Average Latency, Terrestrial NB-IoT vs. GEO NB-NTN

RECOMMENDATION

Given the differences in latency and throughput between terrestrial NB-IoT and GEO NB-NTN networks, hybrid IoT applications must be designed to accommodate longer round-trip times and significantly lower throughput over satellite links. While GEO NB-NTN latency is slightly better than terrestrial NB-IoT CE-Level 2 (Deep Indoor), its throughput is less than 10% of the latter's performance. This highlights the need to optimize hybrid applications for very small data payloads (ideally at around 50 Bytes) and use lightweight transport and messaging protocols.

4.4. Power Saving Features

NB-NTN modules (NTN-only or hybrid) will exhibit changes in power consumption during their operating lifetime due to initial or periodic network acquisition scans, the transmission of Uplink messages and reception of Downlink messages to/from the application server, the transmission and reception of control channels (e.g., the Uplink Random Access Channel and Downlink Paging Channel, for instance), and the continuous or discontinuous activation of the receiver in order to listen for incoming Downlink messages. These procedures are performed during two distinct states that the cellular modem toggles between – Connected Mode and Idle Mode:

- **Connected Mode** is the state that the NB-NTN cellular module temporarily enters to transmit or receive application data to/from the IoT server application. During this state, the modem has an active data pipe set-up via the Layer 3 Radio Resource Control (represented by the layer "RRC" in *Figure 8*) with the eNodeB. Data packets are exchanged over the Control Plane on Non-Access Stratum (NAS) messaging. IoT devices remain in Connected Mode for the duration of a network-specific **RRC Activity Timer**, which initiates once the last packet is sent or received. Any subsequent data transmission that occurs over the data pipe before the Activity Timer expires will reset it and prolong the time that the device stays in Connected Mode. The value of the Activity Timer varies across terrestrial VPLMNs. Networks may configure a static value across all Coverage Enhancement Levels; alternatively, different values may be used based on the CE-Level that the device finds itself in. As coverage quality improves, the round-trip latency decreases, thanks to the repetitions described earlier. The Telefonica Germany network, for instance, configures a different Activity Timer per CE-Level:
  - 5 seconds in terrestrial NB-IoT CE-Level 0
  - 10 seconds in terrestrial NB-IoT CE-Level 1
  - 20 seconds in terrestrial NB-IoT CE-Level 2

  As mentioned earlier, Release 17 GEO NB-NTN networks do not support any CE-Levels. They use an RRC Activity Timer of 80 seconds. This extended timer is implemented as such due to the longer round-trip delay in sending packets over the satellite link. This results in a far higher power consumption in Connected Mode when using non-terrestrial NB-NTN as opposed to terrestrial NB-IoT or LTE-M.

  An exception to this pattern of behavior on both terrestrial and non-terrestrial networks is when the cellular modem periodically sends a TAU message, right before the expiration of the **Standard TAU Timer (T_{3412})**. As discussed earlier, terrestrial networks are not harmonized and set this value to different durations. For example, the Telefónica Germany terrestrial NB-IoT and LTE-M networks use a value of 43,200 seconds (12 hours). Any IoT device which fails to send a TAU before the expiration of this timer will have its session capped and will be deregistered. If the device does manage to enter Connected Mode prior to expiration to transmit the TAU message, it will immediately fall back to Idle Mode; there is no need to remain in Connected Mode until the RRC Activity Timer expires in this case. The Standard TAU timer of GEO NB-NTN networks is about 3 hours, as the network cells (beams) are hundreds of kilometers in size. The sending of a TAU message on any cellular network is automatically performed by the underlying cellular modem; the IoT application does not manage it; however, the former may configure a longer periodic TAU timer instead (more on this further below).

- **Idle Mode** is the condition that the IoT device finds itself during most of the time. The cellular modem enters this state right after the initial network acquisition scan, upon attaching to the terrestrial or non-terrestrial network. While in this state, the modem is registered on the network and listening to incoming pages on the Downlink. It is not able to send or receive data unless it re-enters Connected Mode by performing an Attach procedure with the RACH control channel. 3GPP initially attempted to extend battery life during Idle Mode by introducing the **Idle Discontinuous Reception (iDRX)** feature, which is today supported by all terrestrial NB-IoT and LTE-M networks and devices worldwide. With iDRX, the IoT device activates its receiver during periodic paging windows, searching for any Downlink message requests. These listening windows are synchronized

with the network, which knows exactly when each device will be listening, and is therefore reachable. In-between, the device receiver is disabled, significantly reducing overall device power consumption. NB-NTN modules support this feature while operating on terrestrial networks, and it is not configurable on the device-side; the IoT device will simply perform iDRX if the network requires it in the SIB1 message. This innovation helps to reduce signaling overhead, improve resource allocation, and the ability to support a larger number of connected devices on the same cell. On the device side, it provides for significantly lower power consumption, but it alone is not sufficient to guarantee years of battery life. The Telefónica Germany network, for instance, configured this parameter at
10.24 seconds. While in roaming, the value of iDRX will change from network to network; industry-level harmonization of this setting across PLMNs is not in place.

Release 17 GEO NB-NTN networks do not activate iDRX, for the wake-up Paging Cycle windows are too short to accommodate the greater variance in latency caused by the larger distances the signal must travel. Instead, NB-NTN leverages newer power saving features, described further below. The TiDRX Timer is therefore set on non-terrestrial networks to 0 seconds (disabled).

Within the context of the framework of Connected and Idle Mode, 3GPP specified additional capabilities for power saving in Releases 8, 12, and 13. We will explore these functionalities and compare terrestrial vs. non-terrestrial configurations and their impact on battery life.

4.4.1. Connected Mode Power Saving Features

Within the context of the framework of Connected and Idle Mode, 3GPP began specifying new capabilities for power saving in Releases 12 and 13. We will explore these functionalities and compare terrestrial vs. non-terrestrial configurations and their impact on battery life.

- 3GPP Release 8 specified the **Connected Discontinuous Reception (cDRX)** feature, which mirrors in Connected Mode the same pattern of listening and sleeping cycles that iDRX provides in Idle Mode. The DRX listening windows occur at a period defined by DRX Cycle Timer (TcDRX) and are triggered upon the expiration of a DRX Inactivity Timer. Many terrestrial NB-IoT and LTE-M networks worldwide do not support the cDRX feature, and it is currently listed as "recommended" in the GSMA Deployment Guide. The Telefónica Germany network supports cDRX in parts of Germany, where the TcDRX = 2.048 seconds. Please note that IoT devices are forced to use cDRX whenever the network has the feature activated. This may result in additional latency on terrestrial networks if the TcDRX cycle is set too long. Non-terrestrial GEO NB-NTN networks disable cDRX, for the same reasons as in iDRX outlined above.

- The lack of support for cDRX on a VPLMN is generally not an issue for most IoT use cases, as there is another functionality which allows them to promptly exit Connected Mode "on-demand" and enter the more power-efficient Idle Mode whenever no further data is expected on the same RRC connection. This is the **Release Assistance Indication (RAI)** feature, which both terrestrial and non-terrestrial networks support. The IoT device application can essentially instruct the cellular modem via AT-command to terminate the RRC session with the network's Mobility Management Entity (MME, refer to *Figure 4*) before the expiration of the RRC Activity Timer. This is done by setting either a control bit either in the last application data packet that the device application generates, using a dedicated AT-Command, or by preparing a small packet transmission later during the RRC Activity Timer window (i.e., a ping message to the server) with the control bit set. It is important to avoid using the RAI feature prematurely; any device that abruptly terminates Connected Mode after sending data to the IoT server application, then falls into Idle Mode, only to be shortly paged back into Connected Mode to receive a response message, will consume far more energy than if were to have simply waited a bit longer in the original RRC session.

  Please note that there are two variants of RAI defined in the standards. Release 13 RAI brought in support for the early release of radio resources on the Control Plane C-IoT EPS Optimization (whereby data is sent alongside Non-Access Stratum signaling messages); all MNO networks support this feature. Release 14, however, extended the RAI feature by supporting a release of User Plane resources (data sent over the Access Stratum). When this AS RAI functionality is activated on the network, IoT devices may trigger a Buffer Status Report (BSR) of 0-Byte size, indicating to the eNodeB that no additional data will be sent in coming the period. AS RAI is typically not supported by terrestrial NB-IoT and LTE-M networks: NB-IoT are configured to use only NAS signaling, and LTE-M networks have not been upgraded to Rel.14 in their entirety. Non-terrestrial GEO NB-NTN networks support both variants of RAI functionality.

4.4.2. Idle Mode Power Saving Features

As in the case with Connected Mode, the 3GPP standards introduced various power saving optimizations that help to optimize Idle Mode. IoT devices will stay in Idle Mode for most of the time. This means that multiple processes required optimization: the TAU cycle was extended, the DRX cycles were adapted for applications that only receive messages at infrequent intervals, and a prolonged deep sleep mode was introduced – primarily for Uplink centric applications. These three features, described in detail below, can be combined in any manner that best addresses the application's needs.

- Most terrestrial cellular networks worldwide configure their **Standard TAU Timer (T_{3412})** for 54, 180, or 720 minutes. Waking up at this short interval to send periodic tracking area updates can quickly deplete the battery of IoT devices, solely for the purpose of informing the network of their whereabouts and maintaining an active session (registration). 3GPP improved this situation in its Release 12 by allowing IoT devices to request an extended TAU duration using the **Long Periodic TAU (LP-TAU) Timer ($T_{3412ext}$)**. The standard now allows IoT devices to postpone their tracking area updates by up to 413 days (35,712,000 seconds). The bulk of terrestrial MNOs, however, set this dynamic timer to run up to 310 hours (1,116,000 seconds), thereby keeping track of a manageable number of IoT devices. These can dynamically request a value between a network-specific minimum value (usually 3,600 or 4,200 seconds) and the maximum. Non-terrestrial NB-NTN networks generally support configuration of the TAU Timer to a maximum of 86,400 seconds (24 hours); this is recommended for IoT applications that are static (not mobile). Any rejected value sent via AT-command will result in being assigned a network-specified default value, which may be the higher setting. Please note that the available non-terrestrial GEO NB-NTN networks configure this standard T3412 timer to 86,400 seconds (24 hours). In static applications the TAU can be configured by the Host MCU to a maximum of 24 hours on the Viasat GEO NTN network.

- The mandatory Idle Mode energy optimization feature **Power Saving Mode (PSM)** was introduced in 3GPP Release 12 to address Uplink centric uses, where the IoT application does not expect any Downlink messages to be sent. This universally supported functionality uses a PSM Activity Timer (T_{3324}) that is started once the device enters Idle Mode. Its length can be configured on terrestrial networks from 0 - 11,160 seconds (which mirrors Telefónica Germany's configuration); non-terrestrial dynamically support requested values between 144 seconds and 1036 seconds. Upon expiration of the T_{3324} Timer, the IoT Device disables its receiver, entering a deep sleep mode. This ultra-low-power state may last until the next Uplink application message is sent, or at the latest, the transmission of a TAU message. In-between, the device is not reachable. Networks will buffer up to 1024 KB of data during the time that the IoT device is offline and deliver the data once it reachable again.

- As the vast majority of LPWA use cases are Uplink-centric, i.e., sensors which periodically report data to the server, and rarely need to be paged on the Downlink, the attempt was made to increase the time between listening windows. 3GPP Release 13 introduced **Enhanced Discontinuous Reception (eDRX)** to further optimize the existing iDRX feature for battery-powered devices. So-called "Paging Transmission Windows" (PTW) were kept during which a short sequence of DRX paging cycles, each offset by T_{iDRX}, were catered to. These PTW of T_{PTW} duration were still necessary as paging attempts often fail in the first attempt but are then received in the second or third listening window in the PTW. Each PTW is furthermore started at the expiration of a periodic eDRX Timer, TeDRX, which is adapted to the IoT applications' reachability needs on the Downlink. As the parametrization is use case or even solution-specific, the network defaults can be overridden by the IoT device by setting the desired configuration via AT-commands. Use of eDRX is typically only advantageous for applications that need to be reached from the server side and where there is no Application Layer logic implemented for predefined Downlink messaging intervals (for example, tracking of lost goods. When seen over longer periods of time, the energy of these listening cycles begins to accumulate, shortening the battery life of the IoT device. For this reason, eDRX is only used in LPWA device design when it is necessary. It can also be combined with the PSM feature (described next) to implement a staged fallback into more energy-efficient power states where the device becomes increasingly unreachable from the server side.

  The GSMA Network Deployment Guide does not list eDRX as a mandatory terrestrial network feature; many terrestrial NB-IoT and LTE-M networks, including Telefónica Germany, do not support it currently. The roaming terrestrial VPLMNs which do support eDRX may grant TPTW setting requests between 2.56 and 40.96 seconds, and TeDRX ranging from 20.48 to 10485.76 seconds. These configurations are not aligned among supporting MNOs, resulting in fragmentation and potential difference in battery life between deployments of the same solution on different networks. NB-NTN, eDRX however, is supported. The T_{eDRX} can range from 20.48 (default) to 10485.76 seconds, with T_{PTW} accepting values between 5.12 (default) and 20.48 seconds. iDRX is disabled, enabling continuous reception during the PTW. During the time between PTWs, when it finds itself in sleeping mode, the IoT device is not reachable on the Downlink. For this reason, it is possible to buffer up to 3 KB of messages, which are delivered to the device once the network knows it has entered the next PTW listening window.

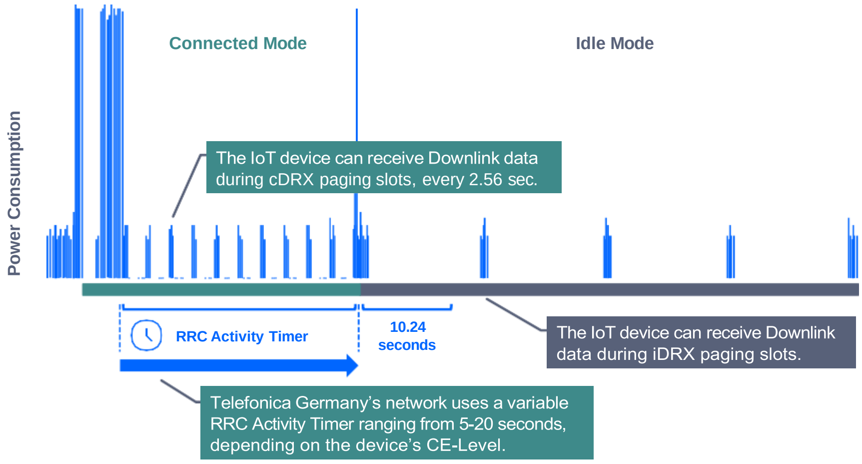


Figure 14: Terrestrial NB-IoT – Connected & Idle Mode power consumption vs. time

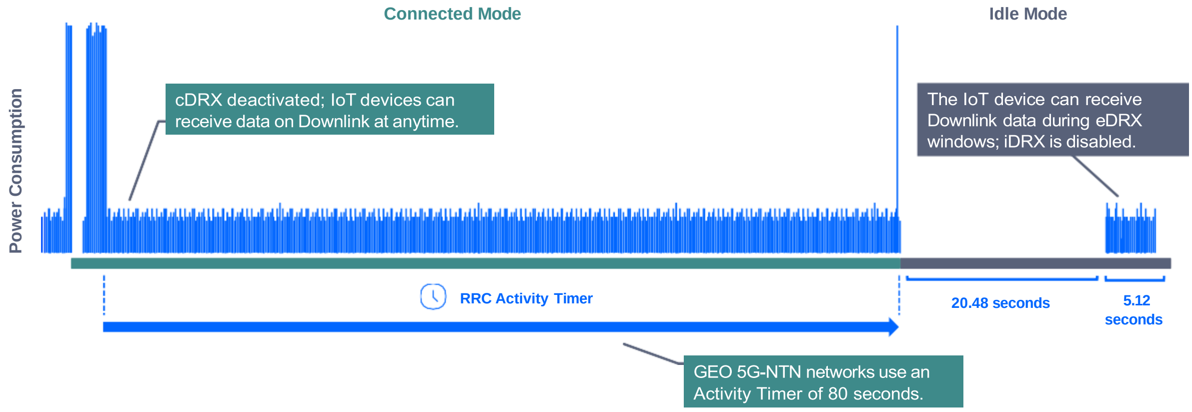


Figure 15: GEO NB-NTN – Connected & Idle Mode power consumption vs. time

	Terrestrial NB-IoT Telefónica Germany low power profile SIM		**GEO NB-NTN**	
Power ON	145 seconds	6.4 mWh	90 seconds	4.7 mWh
App message (200 Bytes) every 10 min	2 hours	3.74 mWh	2 hours	135 mWh
App message (200 Bytes) every 60 min	2 hours	0.27 mWh	2 hours	113 mWh

Table 5: Power Consumption Comparison – Terrestrial NB-IoT vs. GEO NB-NTN

A visualization of the power consumption profiles that result from the network power saving feature configuration can be seen in *Figure 14* for terrestrial NB-IoT and *Figure 15* for GEO NB-NTN, both of which are drawn to scale. It is evident that GEO NB-NTN networks are adapted to support much longer round-trip delays for the communication over satellites. This is seen in their much longer RRC Activity Timer in Connected Mode, during which continuous reception is possible, followed by eDRX cycles in Idle Mode with continuous reception during each Paging Transmission Window. The impact to power consumption is shown in Table 5, where measurements of the procedure for powering on the module, performing an initial network scan, and Attach, as well as the transmission of 200 Bytes application messages (sent at intervals 10 minutes and 60 minutes) are compared for terrestrial NB-IoT and GEO NB-NTN. Please note that the communication over satellites requires a much higher minimum power consumption than over terrestrial networks, where the required power can be optimized to very low values with power-controlled transmissions, discontinuous reception, and a shorter Connected Mode.

RECOMMENDATION

When developing hybrid applications, it is important to account for the differences in the power consumption profiles of terrestrial and non-terrestrial networks. Different power saving feature configurations should be requested via AT-commands when operating on either network, and the cadence of application messages may need to be reduced on non-terrestrial networks to compensate for the higher power consumption caused by the longer continuous reception windows mandated by GEO NB-NTN networks. Please also consider overriding the non-terrestrial network's default value of TeDRX with a longer cycle in case that the IoT application can support greater latencies.

4.5. Short Message Service (SMS)

While communicating over terrestrial NB-IoT networks, IoT devices may opt to use SMS to carry out routine tasks. If a service provider intends to use SMS, they should consult with their MNO to understand what SMS architecture has been deployed in the HPLMN over NB-IoT and the level of support for SMS among the MNO's roaming partners (VPLMNs). Telefónica Germany, for instance, supports SMS in NB-IoT over the SGs interface, whereas other regional operators may not. Since most LTE-M networks support SMS, a hybrid cellular modem can send and receive short messages while connected to an LTE-M cell. These messages can be used, for example, to trigger software or firmware updates (Firmware over the Air, FOTA), wake up devices, or carry out routine tasks.

Application developers should consider whether they wish to use SMS for the IoT application while on terrestrial NB-IoT networks, or if sending a UDP or Non-IP Data Delivery (NIDD) message is more appropriate. If SMS is preferred, developers should work with their MNO to understand which architecture SMS has been deployed over NB-IoT, and the extent that it is supported by the MNO's roaming partners on VPLMNs. Most LTE-M networks support SMS, meaning that at least while the hybrid cellular modem is camped on an LTE-M cell, it can send and receive short messages. These can be used, for instance, to trigger software or firmware updates (Firmware over the Air, FOTA), wake up devices, or perform routine operations.

Select GEO NB-NTN networks support SMS service only for mobile phones (direct-to-device). There is currently no integration of SMS for IoT devices in place, although this may become available later. Please note that MNOs may need to renegotiate SMS pricing with the GEO NB-NTN provider and integrate before enabling SMS roaming over the GEO NB-NTN VPLMN.

RECOMMENDATION

We do not recommend relying on SMS for triggering operations on hybrid devices operating over terrestrial NB-IoT or non-terrestrial GEO NB-NTN networks. The inconsistent feature support across various VPLMNs makes SMS an unreliable communication bearer for such devices. In contrast, terrestrial LTE-M networks offer consistent global support for SMS, making it a potential option for device communication if multi-mode modules are used and the device reselects to LTE-M.

SUMMARY

This chapter compares the Connectivity Layers of GEO NB-NTN and terrestrial NB-IoT and LTE-M systems, focusing on key similarities and differences. Terrestrial LPWA networks optimize coverage for indoor and outdoor deployments, with an adaptive "Coverage Enhancement" feature that provides higher throughputs and lower power consumption in outdoor environments, as compared to Rel.17 non-terrestrial networks which lack this feature altogether. Presented performance metrics for throughput and latency clearly underscore these differences. Furthermore, the IoT application's configuration of power-saving features and its communication cadence also impact the device's battery life, whereby it is recommended for hybrid devices to adjustment their power-saving configurations and reduce their message cadence to optimize energy usage while communicating over satellite-based systems. With careful optimization of the application, it is possible to narrow the performance gap in power consumption between both types of communication bearers.

LEARN MORE

Skylo Technologies NB-NTN

Skylo Technologies is a global Non-Terrestrial Network service provider offering a service that allows smartphone and IoT cellular devices to connect directly over existing satellites. Skylo's direct-to-device service is now live across four continents, with more than 50 million square kilometers of coverage, in partnership with multiple satellite operators, mobile network operators (MNOs), Tier-1 chipset makers, and OEMs. Devices connected over satellite are managed and served by Skylo's commercial NTN vRAN, featuring a 3GPP standards-based cloud-native base station and core. Skylo works with existing satellite operators, network operators, and device makers to provide subscribers an anywhere, anytime connectivity solution that seamlessly roams between terrestrial and satellite networks. Skylo's focus is on enabling connected services for people outdoors and connected workflows for machines at work across critical industries such as agriculture, maritime, logistics, mining, and others, in addition to mass-market consumer devices. For more information, visit www.skylo.tech.

Skylo operates the industry's only device certification program for NB-NTN. It is designed to continue expanding the ecosystem of off-the-shelf cellular devices so that customers have maximum choice in deploying Skylo's satellite network for enterprise IoT applications. Skylo works closely with chipset manufacturers at the firmware level to make certification straightforward. Skylo also offers technical consultation for device manufacturers looking to become Skylo Certified.

5. OPTIMAL PROTOCOL STACK FOR NB-NTN COMMUNICATION

Application developers may choose to encapsulate their application data in specific protocols to enhance data integrity for improved QoS, encrypt the data for security, streamline communication between the IoT device and server using synchronous request/response or publish/subscribe models, or facilitate the management of device configurations and software updates. To these means, specific protocols can be combined with each other, as shown in *Figure 16*. In this section, we will travel down the stack, identifying which protocols are suitable for use in NB-NTN and hybrid services, and which are not. Please keep in mind that using any of these protocols will increase the overall amount of data that is transferred over the NB-NTN network, so a cost-benefit analysis must be conducted to ensure the business viability of use.

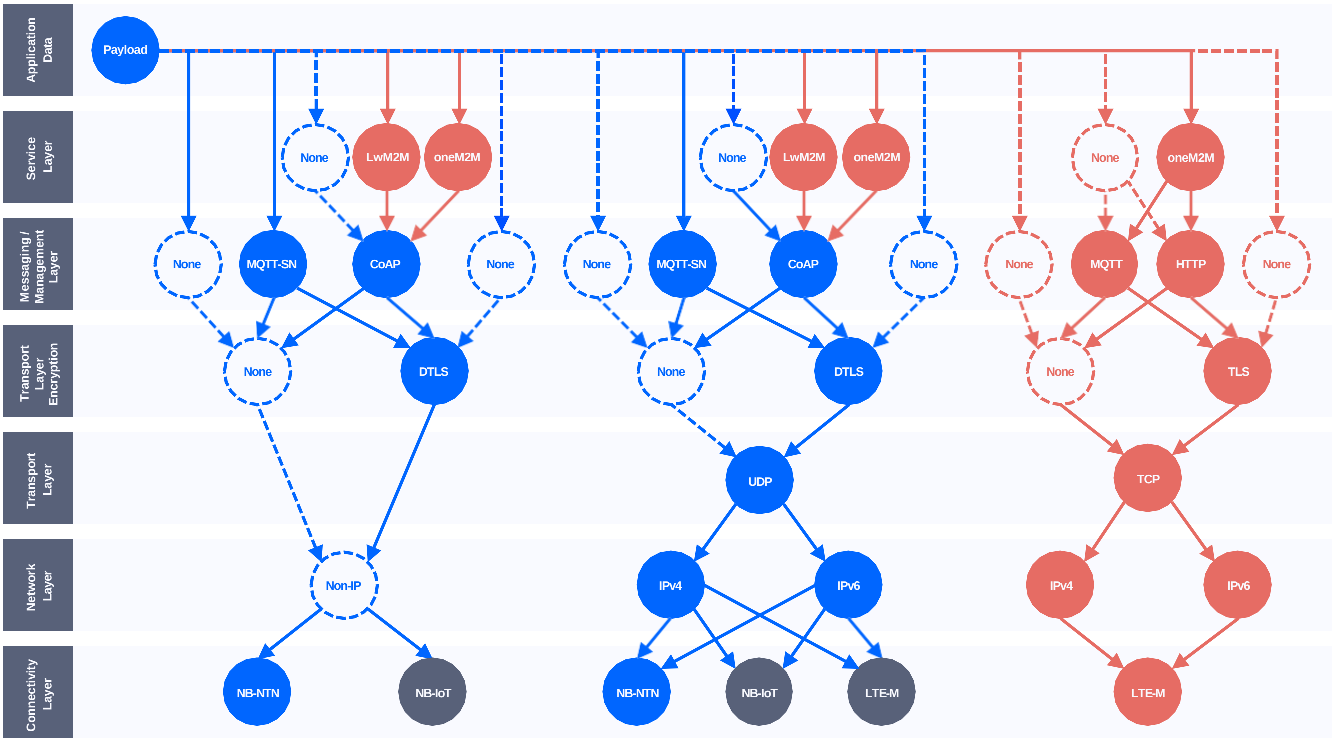


Figure 16: Protocol encapsulation options for payloads sent over NB-NTN (in blue)

5.1. Service Layer Protocol

IoT device applications generate and receive payloads that can be initially wrapped in a Service Layer wrapper. There are two commonly used protocols for service enablement – the OMA LwM2M device management protocol and the ETSI IoT framework, oneM2M:

- **Lightweight M2M (LwM2M)** is a device management and monitoring protocol from the Open Mobile Alliance designed for IoT applications, particularly in environments with constrained devices and networks. It enables efficient communication between IoT devices and servers for tasks such as remote monitoring, configuration, and software updates. LwM2M uses a lightweight, resource-efficient approach, making it ideal for low-power, low-bandwidth applications like smart cities, industrial IoT, and connected devices. It provides interfaces to bootstrap and (de-)register device clients, manage their configurations and states (read, write, execute, create, delete, write attribute, and discover), and provides information reporting (observe, cancel observation, notify).

- **oneM2M** is a standardized Service Layer for the development of IoT applications. It enables seamless interoperability between different IoT systems by defining common specifications for registration, discovery and announcement, subscription and notification, data management, data communication, network service exposure, semantics, interworking, group management, device management (LwM2M), application and service management, security, location, and service charging and accounting. oneM2M is designed to simplify IoT deployment by serving as a standardized operating system for IoT devices, creating common interfaces and protocols, ensuring that devices from various manufacturers and networks can work together efficiently and securely across different domains and industries.

RECOMMENDATION

Both LwM2M and oneM2M are not recommended for use on GEO NB-NTN networks, given the limited MTU size of 1172 Bytes, which can be transmitted over UDP/IP, unless these protocols are to be used in hybrid devices while operating on terrestrial networks. When such devices fall back to NB-NTN, it is recommended to disable these protocols to avoid the risk that the network rejects any oversized data packets.

5.2. Messaging / Management Layer Protocol

Messaging and management protocols for IoT devices enable efficient, optimized communication, reducing data usage and conserving bandwidth, which is essential for resource-constrained environments. The IoT application may wrap its payload in it, a process that normally occurs within the MCU. Two possibilities exist for hybrid devices that will communicate over GEO NB-NTN and NB-IoT networks, both of which run over UDP/IP:

- **The Constrained Application Protocol (CoAP)**, which has gained popularity in recent years on terrestrial NB-IoT networks, is also recommended for use on GEO NB-NTN networks. As a synchronous request/response protocol, CoAP is an excellent alternative to HTTP, particularly for content delivery to individual endpoints. CoAP offers moderate QoS and is optimized for memory- and power-constrained devices with 8-bit microcontrollers and limited memory. The CoAP specification is designed to minimize overhead and parsing complexity, support URI and content-type translation to HTTP, enable service resource discovery, provide multicast support, allow resource subscription and push notifications, and facilitate simple caching based on max-age. It typically adds 20-30 bytes of overhead.

- **MQTT for Sensor Networks (MQTT-SN)** is a lighter variant of the publish/subscribe MQTT protocol that can be used on GEO NB-NTN and NB-IoT terrestrial networks. MQTT-SN allows for predefined Topic-IDs, thereby making topic subscriptions (SUB, SUB ACK) for individual clients in a known network optional. Furthermore, shorter topic names of 2 characters can be used instead to reduce overhead. MQTT-SN gateways are deployed to bidirectionally translate MQTT-SN (towards the IoT devices) into MQTT (towards the application server). These gateways also buffer messages so that constrained device clients can save power in sleeping states. Clients can find the gateways automatically using the DISCOVERY command. MQTT-SN overheads can range from 29 Bytes for the Connect (CON) command to 7 Bytes for the Subscribe (SUB) and Publish (PUB) commands.

In *Figure 16*, both messaging and management protocols HTTP and MQTT are not supported on GEO NB-NTN and NB-IoT networks due to an underlying compatibility issue with TCP/IP, whose acknowledgements (ACK) regularly time-out on account of the long latencies in the round-trip communication. Both protocols are unsuitable for the communication of hybrid devices:

- The synchronous, request/response, and REST-based **Hypertext Transfer Protocol (HTTP)** is a plain text protocol that creates relatively large overheads. This makes it unsuitable for constrained protocols such as NB-IoT or NB-NTN. Depending on the content, HTTP headers can be larger than 500 Bytes, which makes the protocol top-heavy for the 1200 Byte MTU size of NB-NTN networks.

- **Message Queuing Telemetry Transport (MQTT)** is a publish/subscribe messaging protocol and telemetry technology used to interconnect IoT applications. It is optimized for embedded systems with limited processing power and memory, whereby clients can subscribe to topics and publish updates on said topics. This allows for the intelligent management of information and forwarding of data to interested parties via a broker. Whereas the largest MQTT overheads can range from 39 Bytes for the Connect (CON) command to 15 Bytes for the Subscribe (SUB) and Publish (PUB) commands, the protocol requires the use of acknowledgements (CON ACK, SUB ACK, and PUB ACK) which can timeout on GEO NB-NTN and NB-IoT networks.

HTTP and MQTT are only recommended for 2G or LTE-M communication on multimode cellular modems. For NB-IoT or NB-NTN, please consider using a plug-and-play data broker service, such as the Telefónica Kite "IoT Data Ready" feature (refer to the Infobox below) when needing to send data to your hyperscaler cloud or IT back-end over HTTP.

RECOMMENDATION

It is recommended to use CoAP, a lightweight protocol based on UDP/IP, which supports a moderate QoS with both confirmable and non-confirmable messages. This will give the device and server indication of when data should be retransmitted, especially in scenarios where the probability of packet loss increases. This is relevant for GEO NB-NTN IoT applications that are in mobility (such as a vehicle or container tracker).

5.3. Transport Layer Encryption

Transport Layer encryption protocols provide secure communication by encrypting data, ensuring confidentiality and protecting it from unauthorized access. They also authenticate the communicating parties, preventing man-in-the-middle attacks and ensuring data integrity. These protocols help maintain privacy and trust in sensitive data exchanges, which is especially important in IoT and other networked environments. The IoT application will send its payload, pre-wrapped in messaging / management protocol, via AT-command from the MCU to the cellular modem, where it is processed for transport encryption in an established cryptographic session, a process that adds a Message Authentication Code (MAC) tag overhead of a few Bytes. Two specifications are widely used in IoT devices worldwide:

- **Transport Layer Security (TLS)** is a cryptographic security protocol for secure communication between servers and clients over TCP transport. It is a successor to Secure Socket Layer (SSL). TLS ensures secure data exchanges via encryption, authentication, and integrity. TLS employs long-term public and private keys to generate a short-term session key; the latter encrypts the data flow between the device and server. It is not supported on NB-NTN due to the lack of compatibility with TCP/IP, as mentioned above. Due to the complexity of TLS V1.2 handshakes, including the transmission of large X.509 certificates, and the dependency on an underlying TCP/IP session, it is not recommended to use it on GEO NB-NTN or NB-IoT terrestrial networks. TLS procedure must be repeated each time the underlying TCP session is lost and restarted, or when the current TCP session expires. As such, TLS is only recommended for 2G or LTE-M communication on multimode cellular modems.

- **The Datagram TLS (DTLS)** security protocol is a streamlined version of TLS, optimized for transferring small packets of information, where the delivery, arrival time, and order of arrival must not be guaranteed by the network. This makes it ideal for pairing with CoAP or MQTT-SN over UDP transport, providing similar security guarantees as TLS, including support for packet reordering, loss of datagrams, and larger data sizes. There is also support for terrestrial networks using NIDD (see further below). Please use DTLS with caution on NB-NTN and terrestrial NB-IoT networks, as the underlying UDP session will usually time-out. This will require a renegotiation of any previous DTLS session. The process can be streamlined by using DTLS V1.2 PSK handshake (e.g., ECDHE_PSK_WITH_AES_128_CBC_SHA256) without the fragment length, a verify request, and session ticket. As an alternative, please consider using a plug-and-play data broker service, such as the Telefónica Kite "IoT Data Ready" feature (refer to the Infobox below) when needing to send data to your hyperscaler cloud or IT back-end in a fashion that is end-to-end secure.

RECOMMENDATION

Consider using DTLS encryption only in cases where sensitive data is transmitted over a NB-NTN network. It will likely be the case that the DTLS session will need to be reestablished with each data transmission due to session timeout. The cost and battery life impacts will need to be considered during the IoT application's development. As an alternative, an MNO-hosted broker service can be used to maintain a HTTPS session in place with your IT backend. Device data sent over the air is encrypted by the 3GPP protocol and passed securely via the MNO network to the broker.

5.4. Transport Layer Protocol

Transport Layer protocols are essential for ensuring reliable communication between devices over a network. The cellular modem may wrap unencrypted or (D)TLS-encrypted payload with one of the following protocols:

- The **Transmission Control Protocol (TCP)** is a connection-oriented transport-layer protocol designed for end-to-end reliability and the transferring of large amounts of data with no real-time requirements. TCP sequentially numbers the data segments and repeats missed segments to reconstruct the correct order, making it ideal for applications requiring high reliability, such as web browsing or file transfer. This session-based protocol includes a set-up and tear-down, with acknowledgements (ACK) for message content exchanged therein. Unacknowledged packets must be retransmitted within TCP. This makes it unsuitable for communication over constrained NB-NTN and terrestrial NB-IoT networks with poor coverage (e.g., in CE-Level 2). TCP can add between 20-60 Bytes of overhead, depending on the use of available options. An additional pain point with TCP is that its sessions must be maintained with a keep-alive mechanism. A timer is configured by the IoT application which must be less than the MNO's TCP timeout timer; typically, this value ranges between 25-30 minutes. Each keep-alive ping generates costs and burns energy, impacting the device's battery life.

- **User Datagram Protocol (UDP**) is a connectionless transport-layer protocol which provides no protection against loss of data segments, or segments arriving in an incorrect order. UDP also neither requires acknowledgements (ACK) of packet receipt, nor does it retransmit unacknowledged packets. These optimizations ensure an efficient communication and long battery life. UDP is therefore best suited for applications where protection against loss of data is implemented in higher layers (e.g., with CoAP), or not required at all. Due to the less complex nature of UDP as compared to TCP, it can be implemented on simpler hardware.

  Although UDP protocol is connectionless, stateful firewalls and Network Address Translation (NAT) will treat packets with matching source and destination pairs, including their reversed counterparts, as part of a "connection" or dedicated session. Unacknowledged UDP communication can therefore eventually timeout. Traffic using a public APN on the Telefónica Germany NB-IoT network, uses a UDP timer of 60 seconds, whereas the GEO NB-NTN networks have the UDP sessions of their public APN typically capped at 30 seconds. Messages sent over a public APN on terrestrial and non-terrestrial networks will therefore likely regularly require a new UDP socket, whereby the DTLS session needs to be renegotiated for each new connection. This makes it essential to consider using a customer-specific, private APN, especially if the use of DTLS Transport Layer encryption and the reduction of data traffic and power consumption are key requirements for the IoT solution. Such private APNs are configured so that the UDP session is not dropped but instead persists on the home network. While in roaming, the private APN keeps the UDP open for the duration of the underlying Network Layer GTP-IDLE Timer (described further below).

RECOMMENDATION

The only Transport Layer protocol that is suitable to implement for communication over terrestrial NB-IoT and GEO NB-NTN networks is UDP. Please consult with your MNO when session timeouts for UDP occur on the HPLMN, as this may impact the feasibility of your application using DTLS for encryption with a Public APN. Using a Private APN generally solves the issue of UDP session timeouts, as these are kept for the duration of the GTP-IDLE Timer.

5.5. Network Layer Protocol

The Internet Protocol (IP) is a connectionless communication protocol for the Network Layer that enables devices on a network to address and route data packets to their correct destinations. It ensures that data is transmitted across diverse networks and allows devices to communicate with one another regardless of their physical location. The benefits of IP include scalability for large networks, support for multiple types of devices, and the ability to establish reliable connections across the Internet and private networks. As seen in *Figure 16*, the application data and all protocols described further above will be wrapped in a final layer of IP to enable their routing from the IoT device, through the Internet, and onwards to the application server. IPv4 adds 20 Bytes to each packet, whereas IPv6 adds 40 Bytes of data. Please note that the 1200 Bytes MTU supported for non-terrestrial communication over GEO NB-NTN networks include this IP header.

Whereas the GEO NB-NTN networks and Telefónica Germany support IPv4, dual stack IPv4v6, and IPv6 (with a private APN only), numerous terrestrial VPLMNs may not support IPv6. Devices using an IPv6 address that roam onto such IPv4-only networks, may face the issue that the local MME may not grant them a session. Please check the GSMA "Mobile IoT (LPWA) Roaming" website for the list of operator-specific settings, including the support for **IPv6 roaming** in multiple MNO terrestrial NB-IoT and LTE-M networks.

When communicating over a roaming VPLMN network, the data traffic is routed back to the HPLMN PGW, as outlined in Section 1.5. A GTP tunnel is set up between both networks to transfer data over an IP-Exchange (IPX) between the device in the visited network and its home network. An IPX firewall is found at the HPLMN-end of the GTP tunnel and uses a **GTP-IDLE Timer** to control how long it stays open and how long an outbound device can stay inactive in roaming before losing its connection. GEO NB-NTN networks, for instance, currently set the value of this timer to 60 minutes for their own, outbound customers. Terrestrial operator network customers, in turn, support higher values for their outbound traffic: 31 days for NB-IoT or 24 hours for LTE-M. These longer timer values are crucial for effectively utilizing the PSM feature while in roaming; otherwise, the device may awake from power saving mode only to find that the GTP tunnel has been disconnected.

Non-IP Data Delivery (NIDD) is a technique that leverages data transfer within a private network, such as that of a Mobile Network Operator (MNO), to eliminate the IP overhead in over-the-air communication. As traffic between IoT devices and the operator's Packet Gateway (PGW) is segregated from the public Internet, IP headers are not actually needed for data packets within NB-NTN and terrestrial NB-IoT and LTE-M networks. Instead, those network nodes that interface with the Internet may assign an external IP addresses to individual packets based on the device's IMSI number, with an "IMSI - IP Address" mapping table implemented at either the PGW or the Service Capability Exposure Function (SCEF). To the outside world, the devices continue to be addressable using the assigned IP address; within the MNO network, however, the IMSI is used instead as the identifier. It is important to note that while GEO NB-NTN networks support NIDD via SCEF, most terrestrial networks do not, and it is not integrated for outbound roaming with o2 Business tariffs.

LEARN MORE

Telefónica IoT Data Ready

IoT Data Ready is a plug-and-play, optional service within Kite, Telefónica's award-winning connectivity management platform (refer to *Figure 17*). It enables seamless integration of battery-powered NB-NTN devices with IT platforms and hyperscaler clouds, optimizing device design and battery efficiency. Primarily for LPWA (NB-IoT, LTE-M, NB-NTN), it offers a secure, bidirectional communication channel between devices and backends, eliminating overhead from heavy protocols like HTTPS. It converts UDP/IP to HTTP/TCP/IP and maintains active sessions with the cloud, all the while the devices can remain in power-saving mode. The service integrates easily with public clouds (AWS, Azure, Google Cloud) via APIs and stores the last 100 messages for filtering before forwarding in either direction. As IoT Data Ready encrypts all Internet-bound traffic with TLS, there is no need to implement DTLS on the device. This helps to reduce the risk of higher costs and shorter battery life when communicating over NB-NTN.

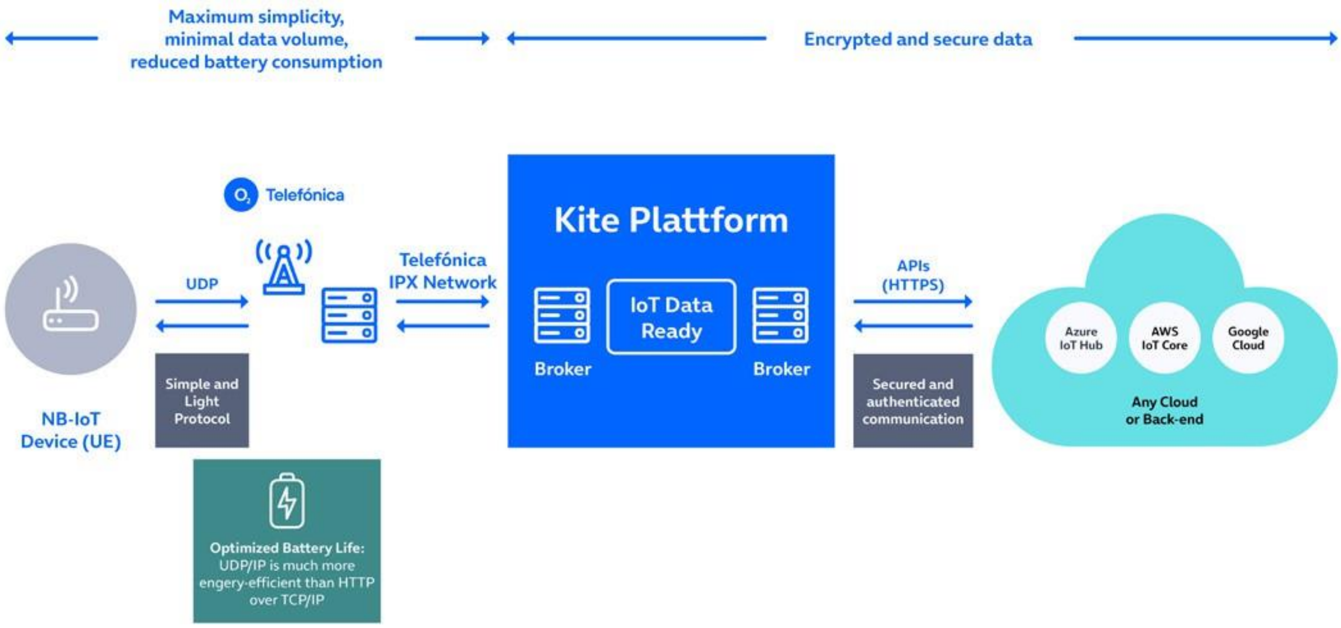


Figure 17: IoT Data Ready as broker service for battery-powered hybrid devices

SUMMARY

Application developers can optimize communication between IoT devices and servers by selecting the appropriate protocols to enhance data transmission, integrity, security, and efficiency. In this chapter, the IoT protocol stack was evaluated, and several scenarios were excluded due to their incompatibility with the bandwidth and latency limitations of the NB-NTN communication channel.

While some network operators may support Non-IP Data Delivery, it is not scalable due to the lack of inter-operator roaming, making the universally supported IP Network Layer protocol the preferred choice. UDP, which runs over IP, is suitable for the Transport Layer because its low overhead and connectionless nature can handle constrained bandwidth and high latencies where TCP may time out. CoAP, which runs over UDP is commonly used in terrestrial NB-IoT applications and is ideal for NB-NTN and hybrid services due to its low overhead and moderate QoS. Protocols like HTTP and MQTT are however unsuitable due to compatibility issues with their underlying TCP session.

A final aspect to consider is the encryption of the data session to ensure security. DTLS may be used, but session timeouts and large handshake setups may complicate its deployment. Alternatively, please consider using a mobile network operator's broker service to securely transmit and encrypt data over the Internet. Such broker services may maintain an HTTPS session with a cloud service in the background, while devices remain in deep sleep mode, conserving energy.

6. APPLICATION LAYER CONSIDERATIONS

When designing IoT applications for NB-NTN and its terrestrial LPWA counterparts, NB-IoT and LTE-M, it is crucial to consider factors such as MTU (packet) size, average data throughput, and round-trip latency. These key aspects, which significantly influence performance, have been explored in detail earlier in this document. The effect of NB-NTN and NB-IoT's limited, shared carrier bandwidth on the system performance, however, is often overlooked. Developers who recognize early on that applications designed for 4G or 2G (E-GPRS) will need to be redesigned or optimized for NB-NTN and its terrestrial alternatives can shorten their R&D cycles and reduce in-field issues.

In this section, we will focus on how the traffic model must be adapted to guarantee reliable communication over satellite links and terrestrial alternatives with minimal packet loss. We will also explore the best practices for NB-NTN and LPWA (Low Power Wide Area) application design which must be adopted to avoid network disruption and prevent unexpected service outages for other users. The following requirements are essential for deploying NB-NTN on Telefónica Germany's mobile network, as well as for roaming across terrestrial and NB-NTN partner networks. Service providers and IoT device manufacturers must take these factors into consideration to ensure more resilient, efficient, and sustainable IoT services.

6.1. Traffic Model

Considering that terrestrial networks are commercially deployed with only one NB-IoT carrier (180 kHz, or 1 PRB block) and/or one LTE-M carrier (1.08 MHz, or 6 PRB blocks), the number of devices that can simultaneously communicate on each network cell is significantly lower than over 4G. Each PRB is further divided into 12 multitone channels (or subcarriers) for Uplink or Downlink communication. These 15 kHz subcarriers are allocated dynamically to devices by the network-side scheduler at the eNodeB, whereby Resource Elements, i.e., OFDM symbols carrying modulated traffic or signaling data, and a punctured Reference Signal (for RSRP calculations) are rapidly assigned seven times within each 0.5 ms timeslot. This means that at any given moment, only a maximum of 12 devices can send or receive data or signaling information over the carrier. Depending on network congestion and the number of repetitions needed for the Coverage Enhancement Level the device is operating under, it may take hundreds of timeslots for larger messages to successfully be transmitted or received. For non-terrestrial NB-IoT in GEO NB-NTN networks, service providers typically implement a dynamic allocation of PRB blocks that can scale to fluctuating capacity needs during the day. While this appears to mitigate the capacity challenges faced by terrestrial networks at first glance, the reality is that GEO NB-NTN networks must handle the communication of a greater number of devices within their much larger, stationary cell coverage areas. This increases the risk of devices consuming the available capacity and blocking each other, which is significant enough to necessitate modem and device certification programs, as well as mandatory communication policies in the technical annex of operator tariffs. Therefore, it is essential to consider the following guidelines when developing NB-NTN and hybrid applications:

- **The maximum number of connection (Attach) requests** per day, per IoT device:
  - NB-NTN (non-terrestrial): 24 requests (1 request per hour, maximum)
  - NB-IoT (terrestrial): 24 requests (1 request per hour, on average)
  - LTE-M (terrestrial): 144 requests (6 requests per hour, on average)
  - E-GPRS (terrestrial): 144 requests (6 requests per hour, on average)

- **The maximum number of application messages** initiated per day, per IoT device:
  - NB-NTN (non-terrestrial): 120 application messages (5 messages per hour, on average, with no more than 12 messages in any given hour)
  - NB-IoT (terrestrial): 120 application messages (5 messages per hour, on average)
  - LTE-M (terrestrial): 720 application messages (30 messages per hour, on average)
  - E-GPRS (terrestrial): No restrictions

- **The average data volume consumed** per month, per IoT device (tariff restrictions apply):
  - NB-NTN (non-terrestrial): 1 Mbyte
  - NB-IoT (terrestrial): 1 Mbyte
  - LTE-M (terrestrial): 500 Mbyte
  - E-GPRS (terrestrial): Tariff-specific

Given the high latency on GEO NB-NTN networks, it is also recommended to **offset consecutive application messages** with a period that is longer than 60 seconds. The application logic must accommodate a one-way latency of minimally 30 seconds and must not time out and resend data that is not acknowledged on the Application Layer by the other side. Such design aspects are not necessary on terrestrial NB-IoT and LTE-M networks, where one experiences shorter round-trip-delays, even in Coverage Enhancement Levels 1 and 2, as seen in the tables above.

6.2. Best-practice Implementation

The GSMA Association regularly publishes updates to its GSMA TS.34 IoT Device Connection Efficiency Guidelines (https://www.gsma.com/solutions-and-impact/technologies/internet-of-things/gsma-iot-device-connection-efficiency-guidelines/), with the objective of gathering industry contributions on requirements and preventive measures for the efficient use of 3GPP mobile networks. While the primary focus has been on minimizing risks that IoT devices may pose to terrestrial cellular networks, many of these requirements are equally applicable to the more resource-constrained NB-NTN satellite networks. Among the key recommendations outlined in the document, the following stand out as particularly relevant for NB-NTN use cases. These should be regarded as mandatory requirements, as failure to comply may result in significant operational challenges in the field:

- It is strongly recommended that NB-NTN services utilize a **customer-specific APN** with a private IP address range. Due to the high latencies inherent in satellite communication, exacerbated by the interrupted coverage of smaller LEO constellations, there is a significant risk of session timeouts during roaming (caused by an expired IPX GRE-IDLE-Timer or UDP/IP session). When this occurs, the session is closed on the HPLMN side without any notification to the IoT device, resulting in a sudden loss of Uplink connectivity. Additionally, once the session expires, it will not be possible to poll the device on the Downlink using the previously assigned IP address. Having a private IP address range allows for direct addressing of individual IoT devices, which brings more reliability in reaching specific devices, or being identifiable to the IoT application server. This is also the case when power saving features, such as PSM is used, which can potentially suspend the modem for several days. The T3412ext Timer should not be greater than the APN Idle Timer, as the device would otherwise lose its session, and require a re-attach.

- It is crucial to avoid **synchronized network access and communication** across any cellular network. NB-NTN and terrestrial NB-IoT networks, with their limited communication bandwidth, are particularly susceptible to congestion and bottlenecks. Instead, communication should be randomized, ideally using a randomized timer to offset individual network attaches and communication attempts across a wider window of time. IoT services should never be configured to communicate at fixed times (e.g., at midnight), and efforts should be made to avoid peak traffic hours on terrestrial cellular networks. In the case of high device density in NB-NTN networks, it is essential to prevent heavy traffic concentrations in any single location.

- **Device polling** or triggering must only occur if the IoT application server knows it is attached. Please implement the IoT service in a way that the server only sends “wake up” triggers whenever the IoT device is known to be attached to the NB-NTN network.

RECOMMENDATION

The GSMA TS.34 “IoT Device Connection Efficiency Guidelines” is an excellent source of information that guides the development of IoT applications. Please consider reviewing this document carefully, as it may highlight potential or hidden risks and ultimately save significant costs or headache during your product’s lifecycle. To better support its customers, Telefónica Germany condenses the most relevant content from the TS.34 specification in the O_2 Business Whitepaper “*IoT Fundamentals – Kommunikationseffizienz*,” currently available in German at:

https://www.o2business.de/content/dam/b2bchannels/de/pdfs-o2-business/iot/iot-downloads/o2_business-iot_fundamentals_kommunikationseffizienz.pdf).

In addition to the best practices outlined in TS.34 for terrestrial NB-IoT and NB-NTN, there are further recommendations that customers should implement to ensure a smooth and trouble-free IoT deployment:

- **Firmware and software updates** for hybrid devices should be carried out over the terrestrial network, ideally using an LTE-M bearer. Application software should be designed in a modular manner, rather than as monolithic code, to enable delta updates of specific software components. A "resume" AT-command must be used during the firmware or software update process in case that a previous download attempt failed halfway through; this prevents having to download the entire software package again.

- When switching between radio access technologies to perform specific operations, the hybrid IoT device must employ a **randomized timer to trigger a RAT change** between terrestrial NB-IoT or LTE-M, and NB-NTN.

- As a result of the widespread **2G shutdowns** across the MNO ecosystem, manually forcing a reselection to E-GPRS service while roaming in various regions is not recommended. Even if a roaming operator in a particular market still offers GSM-based services, the congestion on their network may be high enough to significantly degrade service quality. In such cases, it is advisable to use terrestrial alternatives like NB-IoT and LTE-M, if available.

- Considering the limited bandwidth available for communication on NB-IoT and NB-NTN bearers, it is essential for the IoT device application to implement a **randomized Attach timer** with a minimum window of 40, 60, and 80 seconds for terrestrial NB-IoT CE-Levels 0, 1, and 2, respectively. For NB-NTN, a minimum window of 80 seconds is recommended. This randomization timer helps avoid network congestion and ensures efficient communication.

- If there are many devices in proximity (i.e., on the same network cell) it is important to implement a configurable time window across all devices to allow for **randomized Uplink application traffic**. Please design the duration spread window so that it accommodates within a period of one second:
  - Up to 60 attached IoT devices send Uplink application traffic on the terrestrial NB-IoT cell in CE Level 0 mode;
  - Up to 50 attached IoT devices send Uplink application traffic on the terrestrial NB-IoT cell in CE Level 1 mode; and
  - Up to 40 attached IoT devices send Uplink application traffic over the outdoor NB-NTN network or on the terrestrial NB-IoT call in CE Level 2 mode.

- Network attaches can take several minutes to finalize, depending on factors such as the IoT communication module or radio baseband chipset, the network conditions, and the configuration of the SIM card. The IoT device application must implement an **Attach duration timer** of sufficient length to ensure that NB-IoT TN and NB-NTN network attaches are allowed to complete successfully before any reattempt is made.

- **Avoid "last gasp" messages**, which notify the back-end server of regional power outages or other systemic failures. If many NB-NTN devices attempt to communicate simultaneously over the NB-NTN network or terrestrial NB-IoT or LTE-M networks, network capacity can quickly saturate, even if communication attempts are randomized. The IoT application on the server must be designed to detect anomalies in the IoT service based on messages from a much smaller subset of deployed devices.

- If the IoT service platform or server are **temporarily offline**, it should not send a command to all IoT devices once back online to synchronize at once. Instead, IoT devices should be notified of the platform's availability in a non-synchronous manner. Upon detecting that the IoT service platform is back online, the IoT device application must also use a randomized timer to trigger communication requests over the terrestrial NB-IoT or LTE-M networks, as well as NB-NTN network.

- The IoT service platform should generally **avoid using SMS as a wake-up or trigger** signal for IoT devices over the NB-NTN or NB-IoT networks, as many roaming networks do not support SMS over these bearers, or the sub- scription may not be enabled. Additionally, if the IoT device application detects that its mobile-originated SMS is barred by the network, it should retry any further connection requests with an increasing back-off period. The IoT device application should avoid rebooting the IoT communication module or radio baseband chipset to recover from this situation.

6.3. Network Selection

The 3GPP TS 23.122 specification (ETSI TS 123 122) outlines the standardized algorithms used by cellular modems to search for and attach to specific 3GPP networks – either the home network (HPLMN) or a roaming network (VPLMN) – when the device is in Idle mode. In this mode, the device is powered on but typically does not have a dedicated channel allocated. Additionally, the 3GPP TS 38.304 (ETSI TS 138 304) and 3GPP TS 36.304 (ETSI TS 136 304) specifications define the conditions that trigger these Idle mode functions when operating over 5G Access Networks (AN) or legacy 4G Radio Access Networks (RAN), respectively, including the high-quality criterion for PLMN selection, i.e., a measured RSRP value ≥ -110 dBm for terrestrial NB-IoT. Recent updates have also made provisions for satellite-based 5G NTN, reflecting the evolving network landscape.

In brief, the process involves the cellular modem selecting a PLMN either automatically or manually. This process is pictorially described in the PLMN selection state diagrams (Figures 2a/2b) of TS 23.122. Once a PLMN is found, the modem searches for a suitable cell within it, then camps on the cell to access available services and tunes into its control channel. If needed, the modem registers its presence in the cell's registration area by performing location registrations (LR). Whenever the modem loses coverage on the current cell or finds a better one, it will reselect and camp on another cell in the same PLMN. If this new cell is in a different registration area, the modem will perform an LR request. Finally, if coverage of the selected PLMN is lost, the modem either automatically reselects a new PLMN, or it prompts the application to manually select one from the available networks. If the device is in Connected Mode, the link simply breaks, as handover is not supported between any overlapping PLMNs, neither between terrestrial nor non-terrestrial networks, in any combination.

Specific mechanisms are also in place to regularly steer devices from lower priority VPLMNs to higher priority PLMN (HPPLMN), for example, to the Equivalent Home PLMN (EHPLMN) defined in the SIM card's EFEHPLMN elementary file, located in its file management system. A HPPLMN scan is performed at the time interval defined by the HPPLMN Search Timer in the SIM card's EF_{HPPLMN} file, for which 3GPP defines a default value of "1" – which translates into 2 hours for NB-IoT and LTE-M (refer to the TS 23.122 specification). By performing this HPPLMN scan up to 12 times per day, standard IoT SIMs may shorten battery life of devices communicating over terrestrial NB-IoT / LTE-M. Many MNOs therefore disable the timer completely in their LPWA SIM cards, thereby measurably improving battery life by a factor of up to 440%. The result is that IoT devices can remain on a VPLMN for the entire duration of time that they have coverage. For non-geographic SIM cards in roaming, it may even mean that a static IoT device may not fall back to a HPPLMN in the home country, unless the operator uses a network steering platform to force devices back. Furthermore, additional optimizations may also be present on these SIM cards to reduce power consumption, such as the UICC Maximum Power Consumption (EF_{UMPC}) parameter, that suspends und resumes the UICC during PSM deep sleep.

Major operators in Europe offer SIM cards with non-default, LPWA-optimized settings, often referred to as **"low power profile" SIMs.** Some operators may simplify the number of SIM card SKUs by disabling the EHPLMN scan feature on all SIMs sold in their entire LPWA business. If used in automatic mode, these low power profile SIM cards can cause IoT devices to remain connected to GEO NB-NTN networks if satellite line-of-sight and coverage are maintained, with static devices being more vulnerable. This can ultimately lead to higher costs for end customers, as the per-kilobyte price on terrestrial networks is significantly lower than on non-terrestrial networks. When using low-power profile SIM cards, it is strongly recommended to manually steer devices using a proprietary algorithm in the device application or to rely on MNO-specific SIM applets. One approach may be to **periodically scan for the EHPLMN** configured in the SIM's EF_{EHPLMN} file or alternative terrestrial VPLMNs, whenever the device is on a GEO NB-NTN network. This scan can occur at least every 2 hours, aligning with the default behavior that EF_{HPPLMN} normally provides on standard profile SIMs. Doing so limits the deactivated EF_{HHPLMN} timer's impact to terrestrial coverage. This strategy may reduce bill shock in IoT services where the NB-NTN network serves as a fallback that fills in terrestrial coverage gaps.

RECOMMENDATION

Please contact your O_2 Business sales representative for more information regarding our different SIM card profiles (standard and low power profile) available for use on NB-IoT, LTE, and NB-NTN networks, as well as our optional NB-NTN applet that optimizes costs in hybrid connectivity. Telefónica Germany / O_2 Business customers may configure custom alarms on the Kite connectivity management platform to track expenses and disable connectivity altogether if cost thresholds are exceeded.

SUMMARY

Terrestrial NB-IoT and LTE-M networks have limited capacity due to the limited spectrum allocated to users in each cell. This significantly reduces the number of devices that can communicate simultaneously as compared to 4G. In GEO NB-NTN networks, while the dynamic allocation of PRB blocks aims to address fluctuating capacity needs, the larger, stationary cell coverage areas will see a greater number of devices requesting service, leading to a risk of congestion and devices blocking each other. To manage this, many service providers have defined fair usage policies limiting the average number of daily connection and messages sent by individual devices, as well as data volume caps for different technologies. These guidelines may be stricter for non-terrestrial NB-NTN communication. Additionally, given the high latency and lower throughput of GEO NB-NTN networks, IoT applications must offset application messages by a greater period than on terrestrial networks and ensure they do not prematurely resend unacknowledged data due to time-outs shorter than the round-trip delay window.

In light of the challenges, it is ever more important to adopt industry best practice design when implementing IoT services for constrained 3GPP mobile networks, such as NB-NTN and NB-IoT. The GSMA TS.34 specification, for instance, highlights numerous areas that must be considered to avoid costly service interruptions, capacity bottlenecks, or even signaling storms on the serving networks. Additional examples come from best-practice, including the use if a customer-specific APN to mitigate problems caused by session timeouts, the randomization of network Attach procedures and Uplink communication attempts using timers of varying duration, and the avoidance of synchronized communication. Furthermore, the IoT application should only trigger wake-up commands when devices are attached and perform firmware or software delta updates on higher-bandwidth terrestrial bearers (LTE-M), if supported. These practices help optimize the efficiency and reliability of NB-NTN and hybrid connectivity deployments.

As a final note, the 3GPP TS 23.122 specification defines how cellular modems search for and attach to PLMNs in Idle mode, with additional conditions outlined in TS 36.304 and TS 38.304 for 4G and 5G networks. “Low-power profile” SIM cards, often used for NB-IoT and LTE-M business, may disable regular scans to save battery life, which can result in devices staying connected to a higher-cost non-terrestrial network. This may unintentionally lead to bill shock, especially if NB-NTN connectivity was meant to only be used as a fallback service for hybrid devices. To minimize this risk, it is recommended to monitor costs in the connectivity management platform and either have the IoT application manually steer the device in a proprietary manner, periodically scanning for the EHPLMN, or use SIM cards with an MNO-specific applet to manage steering on NB-NTN networks.

LEARN MORE

O_2 Business IoT Starter NTN Tariff
O_2 Business' new IoT tariff was launched in early 2025 for hybrid connectivity over the Skylo network (GEO NB-NTN), as well as NB-IoT, LTE-M, 2G, and 4G terrestrial networks. Our offer includes:

- 10 MB pooled data package per SIM card for terrestrial national roaming in Germany and most European countries, at just 0.10 € per month, with no recurring base fee;
- Pay-go billing in a tailored selection of non-European countries worldwide;
- GEO NB-NTN roaming on the Skylo network, with pay-go billing at 0.70 € per KB (standard price), with no activation or deactivation charges, and no recurring one-time fees; and
- (Option) "Low Power SIM" profile for longer battery life.

Prices listed above are subject to change.
Three additional products are available on-top to facilitate any backend integration towards your server or cloud:

- **Customer-specific APN** with static IP ranges;
- **IoT VPN Hub,** a shared VPN hub with independent routing, IP ranges, and firewall instances; and
- **IoT Data Ready**, a broker service for end-to-end security, natively integrated in our Kite connectivity management platform

In addition, we offer **IoT Expert Workshops for NB-IoT, LTE-M**, and **NB-NTN**, where you can learn how to leverage these technologies optimally for your business. To learn more about our IoT connectivity and service portfolio, visit us at: **www.o2business.de/iot/**

7. CONCLUSION

This whitepaper discusses the optimization of Internet of Things (IoT) devices for hybrid connectivity, leveraging terrestrial and non-terrestrial NB-NTN networks for global deployments. NB-NTN communication, which is standardized in 3GPP Release 17, enables the use of Low Earth Orbit (LEO) and Geostationary Orbit (GEO) satellites to support low-bandwidth NarrowBand IoT (NB-IoT) communication on energy-efficient devices. Furthermore, the integration of NB-NTN into existing terrestrial 3GPP architectures ensures seamless global connectivity and simplifies service management for enterprises, addressing issues like data fragmentation, multiple SLAs, and the high hardware and service costs associated with legacy satellite systems. Providers such as Telefónica Germany are among the first to demonstrate an ability to offer unified service agreements and connectivity management capabilities to orchestrate both terrestrial and non-terrestrial connectivity.

For enterprises looking to utilize NB-NTN, understanding regulatory frameworks is crucial. National governments grant specific licensing rights to NB-NTN providers, and obtaining such rights is a gating item with respect to the expansion of service coverage. Licensing regulations vary by country and may change over time, making it essential for businesses to remain informed. Varying satellite systems bring flexibility and challenges, requiring companies to carefully consider their coverage needs when deploying IoT devices.

To minimize time to market, it is essential to understand potential optimization aspects of the hardware design of IoT devices meant to operate using hybrid connectivity (NB-NTN and terrestrial NB-IoT). This requires the careful selection of components such as batteries, cellular modems, GNSS receivers, and antennas. Battery life is a critical factor, with lithium-based chemistries being preferred for their high energy density. The modem choice often focuses on 3GPP Release 17-compliant modules, certified by the GEO NB-NTN roaming partners, balancing power efficiency and cost. GNSS integration is necessary for hybrid devices to provide accurate location data, with consideration given to power consumption and antenna configuration to avoid interference. Additionally, the antenna design is fundamental for reliable communication, enabling seamless data transmission between terrestrial and satellite networks while ensuring the device's in-market performance and cost efficiency.

This paper also compares the performance of GEO NB-NTN and terrestrial NB-IoT networks, focusing on key differences in coverage performance, power consumption, latency, and throughput. While terrestrial NB-IoT and LTE-M networks offer adaptive coverage enhancements for outdoor and indoor deployments, NB-NTN lacks these features, resulting in higher power consumption and latency for IoT devices. Application developers are also advised to optimize their devices by adjusting power-saving features and communication frequencies to balance performance and energy efficiency. Moreover, selecting the appropriate protocols for data transmission is critical for ensuring the reliability and security of hybrid systems. Given the constraints of NB-NTN networks, UDP and CoAP protocols are recommended for their low overhead and suitability for low-bandwidth communication with latency tolerance. Operator broker services, such as Telefónica's IoT Data Ready service, allow IoT services to avoid heavy encryption protocols such as (D)TLS, all the while maintaining a secure communication from device to server, and with an outbound HTTPS session towards a hyperscaler cloud provider of choice. As a final note, enterprises must implement best practices, such as careful network steering and use of appropriate SIM card profiles, to avoid cost issues and optimize the operation of their IoT devices across both terrestrial and non-terrestrial networks.

Telefónica Germany and its partners Viasat, Skylo, and Kyocera AVX are proud to provide this valuable information to help our customers navigate the exciting world of hybrid connectivity and get to market faster. Should you have any questions or need assistance onboarding to this new technology, we are here to support you every step of the way. **With Satellite IoT, the sky's the limit!**

8. ACKNOWLEDGEMENTS

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- **Telefónica Germany GmbH & Co. OHG: cc.iot@telefonica.com**
- **KYOCERA AVX Components Corp.: antenna.info@kyocera-avx.com**
- **Viasat, Inc.: enterprisemarketing@viasat.com**
- **Skylo Technologies, Inc.: info@skylo.tech**