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Introduction to a Non-Terrestrial Network

Even with the deployment of five generations of cellular technologies, a significant portion of the planet's surface area and a large number of people still do not have access to wireless communications. Non-Terrestrial Networks (NTNs) are becoming increasingly important in providing wireless communications anywhere on the planet. This chapter defines an NTN and introduces different types of NTN platforms that help create an NTN. Since the NTN utilizes non-terrestrial platforms for radio coverage, a different network architecture is needed compared to a traditional terrestrial network (TN).

This chapter illustrates a simplified NTN architecture and explains its key components and interfaces. The motivation for the NTN is discussed from the perspective of three use-case categories—service ubiquity, service continuity, and service scalability. The Third-Generation Partnership Project (3GPP) has studied several NTN use cases, including user mobility between a TN and an NTN, satellite-based backhaul to support TN deployments in remote areas without the transport infrastructure, support for Internet of Things (IoT) devices, factories in remote areas, and offshore wind farms. The 3GPP roadmap on the NTN work is outlined to provide a historical perspective as well as potential future work. The NTN-related specifications work carried out by the 3GPP NTN is formally part of the fifth-generation (5G) and 5G-advanced cellular technologies. However, the NTN is expected to play an even more important role in the sixth-generation (6G) cellular technology. A glimpse of the NTN's role in 6G is also provided in this chapter.

1.1 Non-Terrestrial Networks: The Definition

A NTN is a wireless communication network that utilizes radio network equipment placed on an airborne or spaceborne vehicle. From this general perspective, if some radio network equipment is on an uncrewed aerial vehicle (UAV) or a drone, a network involving UAVs would qualify as an NTN. Indeed, in some literature, UAVs are considered to be part of an NTN. However, 3GPP NTN specifications consist of different types of satellites and high-altitude platform station (HAPS). A HAPS is an airborne vehicle that operates at an altitude between 8 and 50 km (3GPP 2024e). Examples of uncrewed/unmanned aerial systems (UASs) (3GPP 2021a) include lighter-than-air (LTA) UAS and heavier-than-air (HTA) UAS. Examples of the satellites include low Earth orbit (LEO), medium Earth orbit (MEO), and geosynchronous/geostationary Earth orbit (GEO) satellites. In general, LEO satellites operate at altitudes between 300 and

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1,500 km, MEO satellites operate at altitudes between 7,000 and 25,000 km, and GEO satellites operate at an altitude of 35,786 km.

The 3GPP formally defines the NTN to be "an NG-RAN consisting of gNBs, which provide non-terrestrial NR access to user equipments (UEs) by means of an NTN payload embarked on an airborne or spaceborne NTN vehicle and an NTN Gateway" (3GPP 2024e). The 3GPP-proposed NTN architecture is illustrated in Section 1.2.

1.2 Simplified 3GPP NTN Architecture

Figure 1.1 illustrates a simplified architecture of an NTN (3GPP 2024d,e). The NTN is one of the prominent 5G features defined by the 3GPP in Release 17. See Tripathi and Reed (2019) for details on 5G. While wireless communication is one of the most prominent features of a cellular system, the overall cellular system includes both wireless and wired links. A more detailed NTN architecture is described in Chapter 5 and 3GPP (2023).

An NTN UE communicates with an NTN payload using the radio interface protocol stack. The communication link between the NTN UE and the NTN payload is called the service link or the access link. A typical NTN UE is a handheld smartphone, an IoT device, or a very small aperture terminal (VSAT) device. The radio interface protocol stack may use technologies such as 5G new radio (NR), narrowband IoT (NB-IoT), and eMTC/LTE-M.[1] The NTN payload resides on an NTN platform. Examples of NTN platforms include satellites such as GEO satellites, MEO satellites, and LEO satellites and HAPSs such as stationary aircraft in the stratosphere.

The NTN payload communicates with an NTN-gateway (NTN-GW) using an implementation-specific radio interface. The communication link between the NTN payload and the NTN-GW is called the feeder link.

Figure 1.1 utilizes a transparent NTN payload, where the NTN payload does not carry out technology-specific baseband processing but performs conversion of signals between the service link

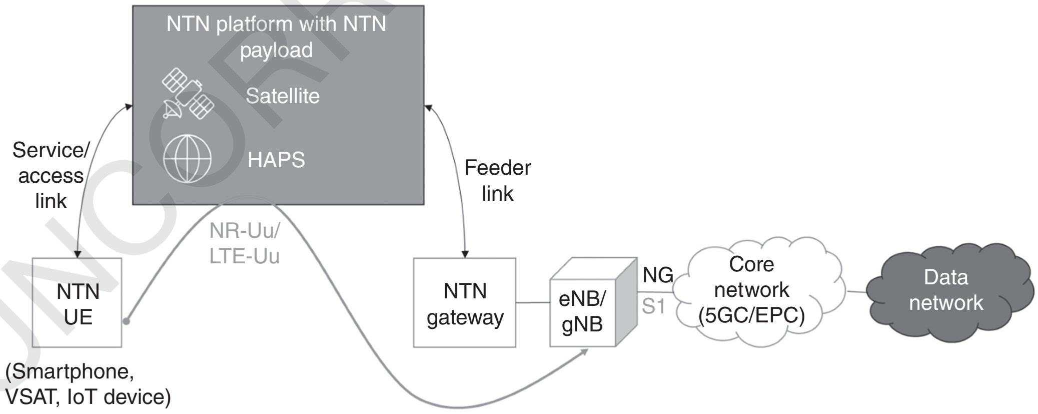

Figure 1.1 Simplified NTN Architecture

1 eMTC is the enhanced MTC, MTC is the machine-type communication, and LTE-M is the long-term evolution-MTC.

and the feeder link. In the downlink from the gNB/eNB to the NTN UE, the NTN payload receives the signal from the NTN-GW and performs functions such as radio frequency (RF) filtering, frequency conversion, and amplification[2] and transmits the RF signals that the NTN UE can process using a suitable 3GPP-defined radio interface such as 5G NR, NB-IoT, and eMTC/LTE-M. In the uplink from the NTN UE to the gNB/eNB, the NTN payload receives the RF signal from the UEs in the cell on a suitable 3GPP-defined carrier frequency and transmits the RF signal to the NTN-GW on a different carrier frequency after suitable filtering and amplification.

The interface between the NTN-GW and the gNB/eNB is undefined in the 3GPP specifications. This interface can be internal to the gNB/eNB, where both the NTN-GW and the gNB/eNB are integrated into one entity. When this interface is external to the gNB/eNB, it can be a wired or wireless interface.

Similar to a TN, the gNB/eNB connects to the core network using 3GPP-defined interfaces. In general, the gNB connects to the 5GC in the case of NR-NTN, and the eNB connects to the EPC in the case of IoT-NTN. The core network connects to data networks such as the Internet, as in a TN.

1.3 Motivation for the NTN

A TN can provide good quality of service (QoS) to users when the users are in the radio coverage of the TN. Service providers carry out coverage and capacity planning to determine the number and locations of base stations in a target service area to meet the expected traffic demands. These base stations need to connect to other base stations to support features such as handover through a transport network. The base stations also need to connect to the core network via a transport network, because the core network interfaces with data networks such as the Internet.

Cost-effective deployment of the base stations and the associated transport network is not feasible in areas with sparse populations and remote and vast areas on land, such as mountains, deserts, and national parks. In cases such as large portions of oceans and remote islands, deployment of a terrestrial cellular network is challenging due to inadequate land infrastructure and the lack of a business case.

An NTN offers an attractive solution in the challenging environments mentioned earlier. Figure 1.2 shows three NTN use-case categories identified by the 3GPP (2018b). These use case categories represent one of the key motivations behind the design and deployment of an NTN because TNs cannot adequately address the related use cases. Examples of use cases that belong to one or more of these categories are briefly described in Section 1.4.

Service ubiquity. An NTN platform can create large beams to provide radio coverage anywhere on the Earth. Remote land areas, homes, and IoT devices (e.g., devices in smart farms and manufacturing plants) in underserved or unserved rural areas with sparse populations, vast mountains, and oceans can all be illuminated by beams from spaceborne vehicles. Furthermore, the infrastructure of TNs may be damaged or destroyed due to natural disasters (e.g., earthquakes and floods) and armed conflicts such as wars. Through a suitable design, NTN platforms can connect to data networks on the Earth's surface via a gateway. Such a design obviates the need

2 Since the NTN platform carrying the NTN payload can be quite far away from the Earth's surface, a large propagation path loss is expected between the UE and the NTN payload and between the NTN payload and the NTN-GW. Hence, the NTN payload's amplification of the received signal before transmitting such signal is important to maintain a reliable communication link.

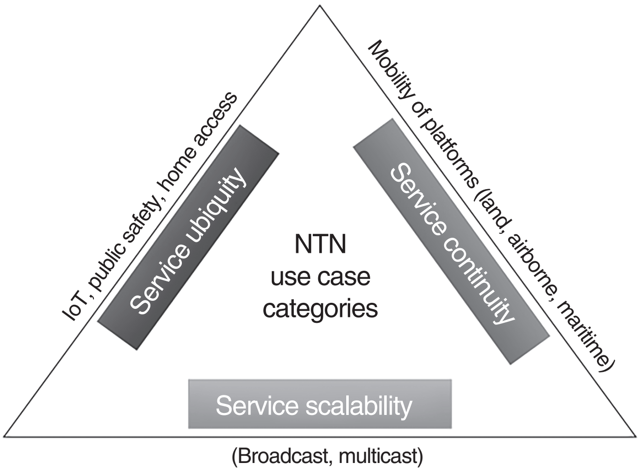

Figure 1.2 NTN Use Case Categories

for the radio equipment to be near the geographic area that is being served. An NTN thus avoids the constraint a TN faces, where the radio equipment needs to be near or inside the area being served.

Service continuity. There are several cases in which the cellular subscriber moves out of the radio coverage of cellular networks. For example, moving out of a suburban area into a rural area, boarding a cruise ship, or during the takeoff in case of air travel often results in the loss of radio coverage and services. Cellular subscribers and IoT devices may be on moving land platforms (e.g., cars, trains, and trucks), airborne platforms (e.g., commercial or private aircraft), and maritime platforms (e.g., cruise ships and container or cargo ships). An NTN can provide service continuity in such cases by providing radio coverage in the areas that are not covered by a TN.

Service scalability. Cellular systems aim for high efficiency to optimize the network performance and the user experience while meeting resource constraints such as the available amount of spectrum. When the same service content needs to be sent to a target set of users in a large geographic area, all the base stations in such a geographic area need to consume precious radio resources. An NTN cell covers a much larger area compared to a TN cell, resulting in increased efficiency. Examples of the services that can benefit from large-area broadcasts include over-the-air software updates and selected entertainment programs, such as live games and prescheduled movies and shows.

A word of caution...all the target use cases may not be supported in initial NTN deployments. However, as NTN deployments become more capable and widespread, more use cases would become feasible.

1.4 An Overview of NTN Use Cases

An NTN can play an important role in numerous use cases. Table 1.1 lists the use cases identified by the 3GPP as part of a study on using satellite access in 5G (3GPP 2018b).

Table 1.1 Examples of NTN Use Cases

Use Case ID	Brief Use Case Description
1	Roaming/movement between terrestrial and satellite networks
2	Broadcast and multicast with a satellite overlay
3	Internet of Things with a satellite network
4	Temporary use of a satellite component
5	Optimal routing or steering over a satellite
6	Satellite transborder service continuity
7	Global satellite overlay
8	Indirect connection through a 5G satellite access network
9	5G fixed backhaul between NR and the 5G core
10	5G moving platform backhaul
11	5G to premises
12	Satellite connection of the remote service center to the offshore wind farm

These use cases are briefly described later.

Roaming/movement between terrestrial and satellite networks. A device may move out of the TN coverage area. For example, a container ship may have containers with IoT devices to track the locations of the containers. On the land and near the shore, such IoT devices can connect to the TN. However, when the ship is away from the shore, these devices lose connectivity with a server that tracks the device/container locations. An NTN can be used to provide continuous location tracking. When two different operators own the TN and the NTN, a suitable roaming agreement is needed between the operators, just like two different TN operators. If the same operator owns both the TN and the NTN, a roaming agreement is not needed, and the mobility management is relatively simple.

Broadcast and multicast with a satellite overlay. A variety of digital content, including videos, can be broadcast or multicast to numerous devices simultaneously using a standalone receive-only mode or as a complement to a two-way communication mode. Some content may even be free. A TN may be congested, or a subscriber to the TN operator may be temporarily out of coverage of the TN. In such cases, the NTN can provide broadcast/multicast services to UEs. A UE may also receive services simultaneously from both the TN and the NTN.

Internet of Things (IoT) with a satellite network. IoT devices in a remote area may not have radio coverage from a TN. In such cases, the NTN can provide coverage to the IoT devices. One possible application is location tracking, which is similar to the container ship example discussed above. In smart farms, sensors can be connected to an NTN. GEO satellites or LEO satellites can be used to serve these IoT devices. LEO satellites can be helpful if the transmit power of an IoT device is a challenge. In contrast, a GEO satellite can cover a large area without requiring any significant mobility management-related processing by IoT devices.

Temporary use of a satellite component. In case of a crisis, such as an earthquake, flood, or war, the TN infrastructure in a given geographic area may be partially or fully destroyed. An NTN can be used to provide communication services so that people needing help can be contacted and medicines, food, and other supplies can be delivered. Services such as logistics and security can also be facilitated by the NTN.

Optimal routing or steering over a satellite. Factories in remote areas may not have adequate coverage from a TN. These factories can be connected with each other and a central command or management center via an NTN. A variety of data, including videos and control signaling, can be transported via a satellite. LEO satellites can be used to reduce end-to-end delays and support higher data rates.

Satellite transborder service continuity. This use case involves the use of the NTN for users moving between countries. One TN operator may serve areas in one country, while another TN operator may serve areas in another country. Hence, when a user goes from one country to another on a business or personal travel, an NTN can be used to provide services across countries regardless of which TN operator the user has subscribed to, as long as there are business agreements between TN operators and the NTN operator.

Global satellite overlay. A multinational company typically has offices in different countries with potentially hundreds or thousands of kilometers between the offices. An NTN can be used to connect such offices with custom QoS in support of target applications. Example applications include high-frequency trading (HFT), banking, or corporate communications. For low-latency applications, LEO satellites can be quite attractive.

Indirect connection through a 5G satellite access network. In areas without radio coverage of a TN, some UEs may not have the capability to communicate with an NTN (e.g., legacy pre-Release 17 UEs). Such UEs cannot communicate with far-away UEs or a web server on the Internet. In such cases, an NTN can act as a relay and transport packets between non-NTN-capable UEs and the NTN, enabling even non-NTN UEs to access communication services.

5G fixed backhaul between NR and the 5G core. It is economically challenging to provide TN coverage in remote areas such as villages due to the lack of a suitable transport network, such as a fiber network, and low population density. In one possible solution, a TN base station can connect to the 5GC using a satellite-based backhaul. Such an arrangement provides users in remote areas access to the Internet and the desired services.

5G moving platform backhaul. Trains are an important means of transportation in many countries. A train operator may want to offer entertainment services such as video streaming or other programs or basic Internet access. However, the train may not have coverage throughout its journey, preventing travelers from enjoying a seamless service experience. 5G gNBs can be placed on the train to provide 5G NR access to 5G UEs on the train. The gNBs can connect to the 5GC via a satellite.

5G to premises. In hard-to-reach areas such as remote vacation spots or remote communities, providing TN coverage to homes and businesses is not economically viable. An NTN can provide communications services to such areas without requiring any physical infrastructure in remote areas.

Satellite connection of the remote service center to the offshore wind farm. This use case targets a scenario where a wind farm is located offshore. There is a need to connect this farm to an inland service center. Since the wind farm is offshore, there is no TN available. An NTN can connect the wind farm to a remote service center. Such NTN use cases empower businesses to increase efficiency and economic output.

1.5 3GPP NTN Roadmap

The 3GPP specified the NTN as a new feature in Release 17 and has been enhancing the NTN for Release 18 and beyond. However, the preparatory work on the NTN started before Release 17 (3GPP 2021a). See 5G Americas (2022) for an overview of pre-Release 17 and Release

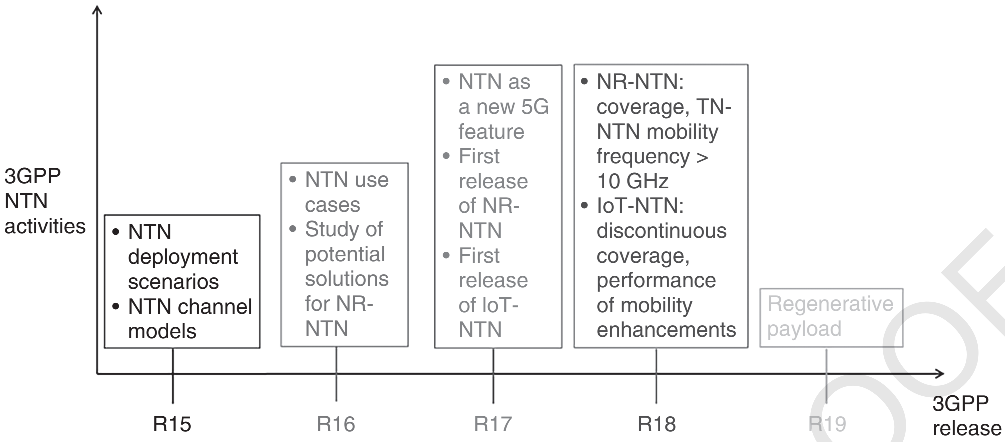

Figure 1.3 3GPP NTN Roadmap

17 3GPP activities. Figure 1.3 summarizes key 3GPP activities and accomplishments related to the NTN.

1.5.1 Release 15 (R15)

The 3GPP started the work on the NTN in 2017, with a Study Item in Release-15 in 3GPP RAN WG1 that focused on NTN deployment scenarios and channel models (3GPP 2020). Since an NTN possesses unique propagation characteristics compared to a TN, new NTN-specific channel models are needed for the NTN analysis. Details of the NTN channel models can be found in 3GPP (2020).

1.5.2 Release 16 (R16)

The 3GPP Service and System Aspects (SA) working groups discussed use cases for a satellite-based NTN as part of the study item on satellite access in 5G (3GPP 2017). The study identified three main categories of use cases for satellite-based NTN service continuity, service ubiquity, and service scalability (3GPP 2018b), which are discussed in Section 1.2.

The work in R16 also included a comprehensive study in the radio access network (RAN) working groups on solutions for the NR to support an NTN to determine the necessary features to enable the NR support for the NTN (3GPP 2019). These studies provided a baseline for the normative work on the NR-NTN in R17 for the transparent payload (3GPP 2023).

1.5.3 Release 17 (R17)

The 3GPP introduced the NTN as a new feature in R17 by developing specifications for the NR-based NTN (3GPP 2024c). The R17 NTN specifications create a strong foundation for future enhancements in subsequent 3GPP releases. R17 NTN specifications assume UEs with a global navigation satellite system (GNSS) capability and a transparent NTN payload. R17 NTN enhancements to the basic NR specifications are related to synchronization, timing adjustments, system information, protocol timers, hybrid automatic repeat request (H-ARQ), timing and frequency precompensation by UEs, tracking or registration area management, handover, QoS, user location reporting, and feeder link management.

The SA Working Group 2 (SA2) created a study item on architecture aspects for using satellite access in 5G (3GPP 2018a) to identify key issues for satellite-based NTN in the 5G system architecture and provide solutions for both direct satellite access and satellite backhaul (3GPP 2021b). The SA2 normative work in R17 includes mobility management with large coverage areas and with moving coverage areas, delay in satellites, QoS with satellite access and with satellite backhaul, RAN mobility with non-geostationary orbit (NGSO) regenerative-based satellite access, and regulatory services with supernational satellite ground station. SA WG5 addressed management and orchestration aspects in their study (3GPP 2021d). The 3GPP Core Network and Terminals (CT) working groups created a study item to address aspects of the 5GC architecture for satellite networks. The Release17 work in CT working groups concentrates on aspects related to the public land mobile network (PLMN) selection (3GPP 2021c).

The 3GPP also worked on the IoT-NTN in R17. This work is based on the previously defined 3GPP Release 13 features of narrowband IoT (NB-IoT) and enhanced machine-type communication (eMTC) (also referred to as long-term evolution- machine type communication [LTE-M]) (3GPP 2021e). Enhancements to NB-IoT and eMTC specifications are made to support these features in an NTN. Since NB-IoT and eMTC are based on 4G LTE specifications, the NTN makes use of the 4G Evolved Packet Core (EPC) instead of the 5GC. The IoT-NTN work utilizes the studies carried out for NR-NTN and NR-NTN specifications as a baseline and adds enhancements unique to NB-IoT and eMTC.

1.5.4 Release 18 (R18)

The NTN enhancements continue in 5G-Advanced. 5G-Advanced refers to the 5G specifications defined in Release 18 and beyond. In Release 18, key NTN enhancements for the NR-NTN include coverage enhancement to support voice and low-rate data services, mobility and service continuity enhancements for mobility between the TN and the NTN, support for frequencies greater than 10 GHz, and network verification of the UE location. The IoT-NTN enhancements in Release 18 include discontinuous coverage enhancements (e.g., support for the UE movement across areas with and without NTN coverage), mobility enhancements (e.g., neighbor cell measurements), and performance enhancements (e.g., disabling of H-ARQ feedback and improved GNSS operations).

1.5.5 Release 19 (R19) and Beyond

The Release 19 workshop held by the 3GPP in June 2023 identified the NTN as one of the candidate areas for normative specifications in Release 19. The R19 work began in summer 2024 and is expected to complete in late 2025. The NR-NTN enhancements in Release 19 aim to enhance downlink coverage, enhance uplink capacity, support the multimedia broadcast service (MBS), support selected 5G network functions (NFs) on the NTN platform, including a regenerative payload, and support reduced capability (RedCap) UEs (3GPP 2024a). Two key enhancements targeted by the 3GPP for the IoT-NTN Phase 3 in Release 19 include the support for store and forward and uplink capacity enhancements (3GPP 2024b). See Chapter 10 for more details on Release 19 NTN enhancements.

1.6 Role of the NTN in 6G

While the 3GPP's NTN specifications for 5G provide a strong foundation for NTN deployments, 6G is expected to significantly expand the scope and applicability of the NTN in practice. 6G is anticipated to be deployed in the 2030s. While specifications for 6G are not yet being worked on, organizations worldwide, such as Alliance for Telecommunications Industry Solutions (ATIS) in North America, are defining a vision and requirements for 6G. Several organizations have published white papers describing their 6G vision and mentioned the NTN as one of the important aspects of 6G. See Chapter 10 for more details on 6G.

ATIS has an initiative called Next G Alliance that has defined six audacious goals for 6G systems (NGA 2022a). These goals include (i) trust, security, and resilience; (ii) enhanced digital world experience; (iii) cost-efficient solutions; (iv) distributed cloud and communications; (v) AI-native networks; and (vi) sustainability related to energy efficiency and the environment. The NTN can play an important role in achieving resilience in 6G by providing an additional mode of communications beyond terrestrial communications to users including public safety personnel. As part of distributed sensing and communications, the NTN can help bridge the digital divide by providing communications services to unserved or underserved geographical areas on the planet. In particular, the NTN can provide cost-effective coverage when it is too expensive to deploy a TN.

Indeed, the NGA has identified the NTN as one of the key technologies to meet the requirements of 6G (NGA 2022b). The NGA has identified numerous technologies for 6G and classified them into the following five technical areas: (i) component technologies, (ii) radio technologies, (iii) system and network architecture, (iv) OA&M and service enablement, and (v) trustworthiness. The NTN plays an important role in the technical areas of "Radio Technologies" and "System and Network Architecture." The NTN represents a new type of connectivity in the context of radio technologies to meet varying user traffic demands and extremely wide coverage area requirements. The NTN also fundamentally changes the typical RAN architecture of a TN because of the connectivity between the UE and the NTN payload and between the NTN payload and the NTN-GW. The alternative coverage provided by the NTN in 6G is important to ensure global coverage.

1.7 Major Takeaways

The NTN is expected to play an important role as a key component of 5G and 6G in advancing the reach of wireless communications. Here are the major takeaways from this chapter.

- Even with the deployment of five generations of cellular technologies, a significant portion of the planet's surface area and a large number of people still do not have access to wireless communications.
- An NTN is a wireless communication network that utilizes radio network equipment placed on an airborne or spaceborne vehicle.
- The 3GPP formally defines the NTN as "an NG-RAN consisting of gNBs, which provide non-terrestrial NR access to UEs by means of an NTN payload embarked on an airborne or spaceborne NTN vehicle and an NTN Gateway."
- The 3GPP considers platforms such as several types of satellites and HAPS as part of the NTN. A HAPS is an airborne vehicle that operates at an altitude between 8 and 50 km. Examples of the satellites include LEO, MEO, and GEO satellites. Hence, drones or UASs that operate below the 8 km altitude are not formally part of the 3GPP NTN activities.
- Key elements of the NTN architecture include the NTN-capable UE, the NTN payload on an NTN platform, the NTN-GW, the non-NTN processing of the gNB/eNB, and the 5GC/EPC.
- The motivation for the NTN stems from the use case categories of service ubiquity, service continuity, and service scalability. Service ubiquity refers to the coverage in geographic areas unserved or underserved by a traditional TN. Service continuity enables continuous wireless

connectivity for the user as the user moves between the TN and the NTN. Service scalability refers to a large number of users in a large geographic area for broadcast/multicast services, increasing the resource utilization efficiency.

- The 3GPP has studied several NTN use cases, including user mobility between a TN and an NTN, satellite-based backhaul to support TN deployments in remote areas without transport infrastructure, support for IoT devices, factories in remote areas, and offshore wind farms.
- The 3GPP started the work on the NTN in Release 15 and introduced the NTN as a new feature in Release 17. The 3GPP R15 identified NTN deployment scenarios and NTN-specific channel models. The NTN use cases were identified, and potential solutions for NTN–NTN were studied in the 3GPP R16. Both NR-NTN and IoT-NTN were specified as formal features in the 3GPP R17. The enhancements in the 3GPP R18 are related to coverage, TN-NTN mobility, frequencies above 10 GHz for NR-NTN, and discontinuous coverage and mobility for IoT-NTN. The 3GPP R19 makes additional NTN enhancements, including support for regenerative payloads.
- While the 3GPP NTN specifications are part of 5G and 5G-Advanced, the NTN is expected to play a vital role in 6G as well by providing alternative coverage and resiliency.

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