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EAGER

tEchnologies And techniques for satcom beyond 5G nEtwoRks

WHITE PAPER

Architectures, services, and technologies towards 6G Non-Terrestrial Networks

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ARCHITECTURES, SERVICES, AND TECHNOLOGIES TOWARDS 6G NON-TERRESTRIAL NETWORKS

The first global standard for Satellite Communications (SatCom) was published in April 2022 as an outcome of 3GPP Rel. 17. It specifies the features enabling 5G systems to support a Non-Terrestrial (NT) component. More than technical specifications, it also enables the integration of the satellite industry in the 3GPP ecosystem, involving more than 700 organizations at worldwide level to ensure a global market. The Non-Terrestrial Networks (NTN) standard is the result of a joint effort between stakeholders of both the mobile and satellite industries, leading to a two-fold benefit: i) the possibility to truly achieve global service continuity and resiliency, for 3GPP; and ii) the access to the unified and global 3GPP ecosystem and the possibility to reduce the costs through economy of scale, for the satellite industries. Moreover, before NTN, there was not inter-operable standard in SatCom; thus, the inclusion of a non-terrestrial component in 3GPP based systems can also lead to huge benefits for the SatCom industry as ground systems exploiting equipment coming from different providers are now available. This standard is also supported by vertical stakeholders (Public Safety, transportation, automotive, etc.) calling for: i) the seamless combination of satellite and mobile systems; and ii) the support of all 5G features across the access technologies.

However, while the current Rel. 17 NTN standard provides a solid ground for future satellite networks integrated in the 5G system, a significant innovation breakthrough in technologies, techniques, and architectures is needed to prepare for next generation satellite networks based on Rel. 19 and beyond NTN standards, [1].

In this White Paper, we first discuss the path that led to the definition of the first set of specifications for NTN-based 5G systems in Rel. 17 and then provide an overview of the current activities, as well as what can be considered as candidate architectures and technologies, for 5G-Advanced and 6G NTN systems. The analyses and assessments reported in this document are currently being performed in the framework of the ESA Project EAGER (tEchnologies And techniques for satcom beyond 5G nEtwoRks), in which both mid-term (5G and 5G-Advanced) and long-term (6G) solutions for NTN systems are evaluated.

3GPP normative work

The NTN standard aims at supporting three general reference scenarios, reported in Table 1, where we can distinguish between:

Table 1. Targeted system scenarios defined in the 3GPP NTN standard.

	Direct connectivity (FR1)		Indirect connectivity (FR2)
Targeted terminals	IoT devices	handheld (smart phones) and car/drone mounted devices	VSAT and/or ESIM
Service	Narrowband hundreds of kbps	Wideband few Mbps	Broadband hundred Mbps
Orbit	GSO and NGSO	NGSO	GSO and NGSO
3GPP Radio interfaces	4G NB-IoT/eMTC	5G New Radio	5G New Radio
Market applications	Professional: utilities, agriculture	Consumer Professional: automotive, Public Safety, utilities, agriculture, Defense	Professional: telco (*e.g.*, backhaul), IPTV, SNG, transportation, Public Safety, Defense

- satellite access networks operating in Frequency Range 1 (FR1), which provide direct narrow-/wide-band connectivity to: i) outdoor handheld terminals and/or car/drone mounted devices, via the 5G NR standard; and ii) outdoor IoT devices, via the 4G NB-IoT/eMTC standard;

- satellite access networks operating in Frequency Range 2 (FR2), providing broadband connectivity to local access networks via Very Small Aperture Terminals (VSAT) installed on building rooftops or Earth Station In Motion (ESIM) terminals on moving platforms (vehicle, train, vessel, or airplane).

The 3GPP NTN standardisation activities took into account the specific characteristics of satellite networks and channels, which create new technical challenges compared to legacy terrestrial-only networks. More specifically, the NTN adaptations required to tackle issues related to the long propagation delays, large Doppler shifts and Doppler variations, and the generation of large moving cells on-ground due to the satellites' motion. The integration of the NTN component in the NR standard has thus first called for a thorough feasibility assessment in 3GPP Rel. 16, aiming at identifying the required adaptations for NR techniques, technologies, and protocols allowing the exploitation of NTN links based on State-of-the-Art (SoA) space technologies and industrial assets. The addressed NTN platforms, based on transparent payloads, include: i) Geosynchronous Orbit (GSO) or Non-GSO (NGSO) spaceborne satellites; and ii) airborne vehicles operating at altitudes typically between 8 and 50 km, *i.e.*, High Altitude Platform Stations (HAPS), encompassing Unmanned Aircraft Systems (UAS) including Lighter-Than-Air UAS (LTA) and Heavier-Than-Air UAS (HTA). In particular, 3GPP TR 38.811, [2], provided a solid background in terms of possible use cases, scenarios, and characterization of the NT channel. In addition, TR 38.811 also provided a preliminary analysis related to the impact of bringing the NR Air Interface and protocols on NTN links. Building on these outcomes, 3GPP TR 38.821, [3], reports the identified NTN architectures for the NR RAN and a detailed analysis on the challenges and proposed solutions related to Layer 1 (*e.g.*, physical layer procedures, including Random Access and Timing Advance), radio protocols (*e.g.*, HARQ, mobility management in the Control Plane), and architecture and interfaces (*e.g.*, tracking area management, management of the network identities). Figure 1 reports the major enhancement areas defined in Rel. 17 for NR-NTN.

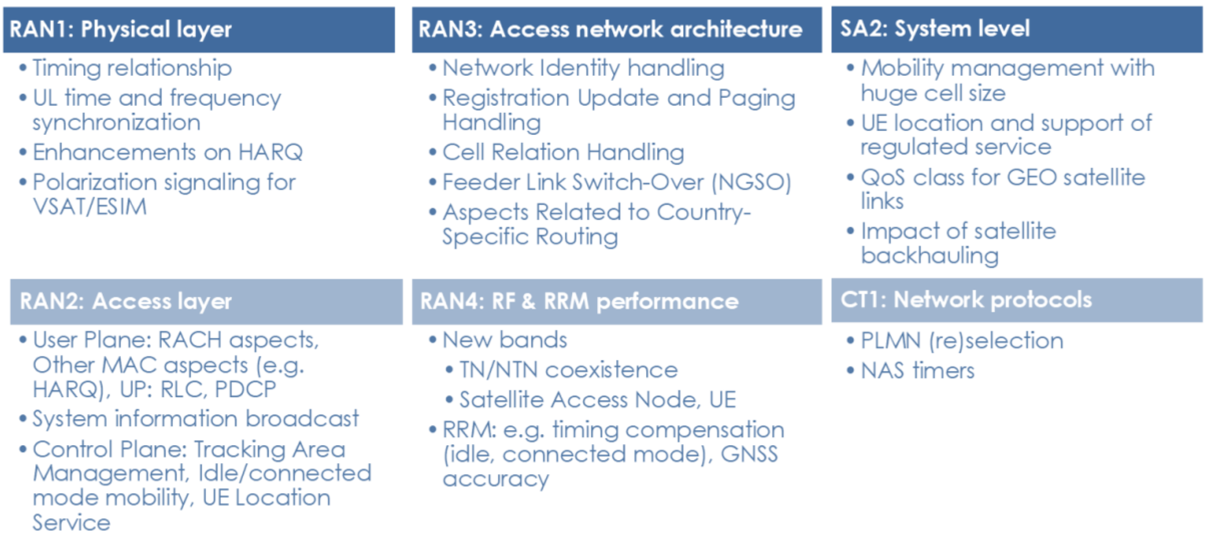

Figure 1. 3GPP NR-NTN specifications impact per TSG WG. Courtesy of: Mohamed El Jaafari, "3GPP NTN standardization: status and prospect," ASMS/SPSC conference, September 2022.

For instance, in Rel. 17, RAN4 activities focused on the introduction of NTN satellite Mobile Satellite Service (MSS) bands (n256, n255) and on coexistence analysis with adjacent TN bands, defined the Radio Frequency (RF) requirements for both Satellite Access Node (SAN) and NTN User Equipment (UE), and provided performance requirements and conformity testing for SAN. As a result of RAN4 3GPP work, three completely new Rel. 17 Technical Specifications (TS) were finalised, including TS 38.108 [4], TS 38.101-5 [5] and TS 38.181 [6]. NTN Radio Resource Management (RRM) requirements have also been updated in the existent TS 38.133, [7].

After the finalisation of Rel. 17, the 3GPP work in Rel.18 has already started as part of 5G-Advanced, which will introduce several enhancing features to further improve the performances and/or to provide brand new capabilities. Moreover, the discussion on the contents of Rel. 19 for satellite-enabling features has already started in the service requirement working group of 3GPP. In fact, while the current Rel. 17 NTN standard provides a solid ground for future satellite networks integrated in the 5G system, a significant innovation breakthrough in technologies, techniques, and architectures is needed to prepare for next generation satellite networks based on Rel. 19 and beyond NTN standards.

With respect to the recently started activities related to Rel. 18 NTN, further enhancements for the NG-RAN based NTN are being specified according to the following assumptions: i) GSO and NGSO systems; ii) Earth-fixed tracking area with Earth-fixed/moving cells for NGSO; iii) FDD mode; iv) UEs with GNSS capabilities; v) VSAT devices with directive antenna (including fixed and moving platform mounted devices) and commercial handheld terminals (*e.g.*, Power class 3) supported in FR1; and vi) only VSAT devices with directive antenna (including fixed and moving platform mounted devices) supported in FR2 (above 10 GHz). These assumptions include an implicit compatibility to support HAPS and Air-To-Ground (ATG) scenarios.

Table 2. NTN features to be defined as part of 3GPP Rel. 18.

	eMBB (5G New Radio)	mMTC (4G NB-IoT, 4G eMTC)
SA2	• Network based UE location determination • Specifying system enhancements to support satellite discontinuous coverage	• Specifying system enhancements to support satellite discontinuous coverage
RAN WGs	• Coverage enhancements • NR-NTN deployment in above 10 GHz bands and support for VSAT/ESIM NTN UE • NTN-TN and NTN-NTN mobility and service continuity enhancements • Network based UE location	• IoT-NTN Enhancements in Rel. 18 to address remaining issues from Rel. 17 • Mobility enhancements • Further enhancement to discontinuous coverage

In this context, Table 2 lists all the features that will be defined by 3GPP as part of Rel. 18 for enhanced NTN systems according to the services: eMBB for NR and mMTC for 4G NB-IoT/eMTC, while Table 3 reports the performance enhancements and new capabilities that will be addressed within Rel. 19.

Table 3. Potential NTN features to be defined as part of 3GPP Rel. 19.

Service	Performance enhancements	New capabilities
eMBB (5G NR)	• NTN-NTN or NTN-TN asynchronous Multi-Connectivity & Carrier Aggregation • DL PAPR optimization • Coordinated transmission • Beam management and BWP association enhancements • Half Duplex FDD • Positioning enhancements	• Regenerative payload (including edge computing) • Support of MBS • Relay-based architecture for NTN (for VSAT and ESIM) • UE without GNSS • Intermittent/temporary satellite connectivity • NTN-TN Spectrum coexistence • Architecture for AI/ML 5G-NTN workflow to address specific SatCom issues
mMTC (4G NB-IoT/ eMTC)		• Support for store-and-forward on-board NTN payload • Location reporting by UEs • Architecture for AI/ML data-flow for the optimization of IoT-NTN systems • UE without GNSS

In order to cope with such demanding and challenging requirements, it is widely recognised that the unification of the terrestrial and non-terrestrial infrastructure components will be fundamental. In fact, as shown in Figure 2, before 5G, TN and NTN were independently optimised; then, with 5G and 5G-A, the objective has been the optimisation of the TN and integration of the NTN component with minimum impact. However, only with 6G systems TN and NTN will be jointly optimised in a unified and fully integrated multi-layered infrastructure. Such architecture will combine terrestrial, airborne, and spaceborne radio access networks for the envisaged convergence of the physical, human, and digital worlds. With this approach, there is a great opportunity to optimize the 6G service performances (throughput and service rate) over the satellite component taking into account its specific characteristics and operational constraints.

Moreover, thanks to a native support of multi connectivity and mobility across access technologies based on space assets at different orbit together with terrestrial access technologies, the Quality of Experience (QoE), the service reliability are expected to be greatly improved.

6G NTN is clearly an unexplored area within 3GPP, as it will be addressed from Rel. 20. However, in the following sections, we will discuss our view on the use cases, architectures, and technologies for 6G, evolving from those defined in 5G (Rel. 15-Rel. 17) and in the on-going Rel. 18/19 (5G-A).

Use cases and performance requirements

A set of use cases for 5G NTN was initially identified in 3GPP TR 22.822, [8]. In this technical report, it is reported that NTN can bring an added value to complement the terrestrial RAN in terms of service continuity, ubiquity, and scalability. The definition of new satellite-based use cases has been addressed also within ITU-R, which published a report about vision, the requirements and evaluation guidelines for the satellite component of IMT-2020. Inspired by terrestrial NR, three categories are considered: i) enhanced Mobile Broadband via satellite (eMBB-s); ii) massive Machine Type Communications via satellite (mMTC-s); and iii) High Reliability Communications via satellite (HRC-s). Based on both 3GPP and ITU-R discussions, Figure 2 depicts the envisioned potential use cases for 5G NTN, in which the main characteristics for each scenario, discussed below, are highlighted, [9].

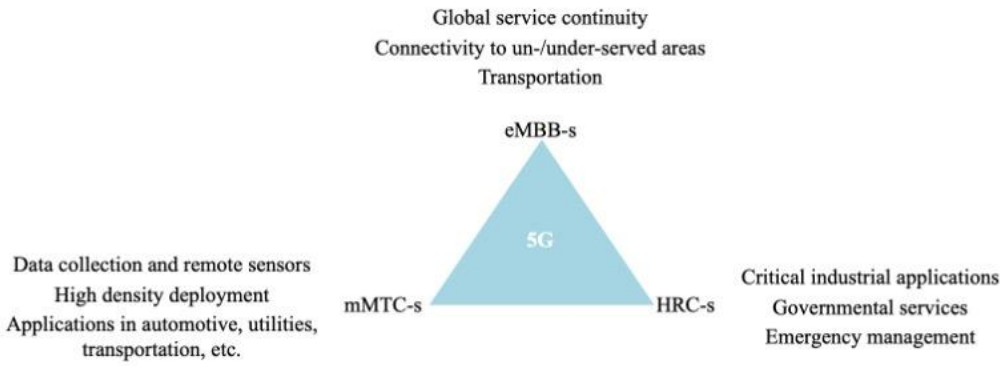

Figure 2. 5G NTN use cases based on ITU-R IMT-2020 vision for satellite systems.

Currently, within 3GPP it is not foreseen to introduce novel use cases or services for NTN-based 5G-A systems (*i.e.*, in the framework of Rel. 18 and Rel. 19). Clearly, it can be expected that the evolution in terms of technologies, architectures, and techniques, described in the other sections of this document, will positively impact the performance of the above discussed 5G services in the context of 5G-A. However, it is worthwhile highlighting that, since Rel. 14, 3GPP introduced features to enable MNOs to directly provide television services over standardised interfaces. In the context of Multicast and Broadcast Services (MBS), in which an ever increasing capacity request is being experienced (*e.g.*, due to the increase in the number of Ultra-High Definition (UHD) programs in broadcasting services), satellite networks provide an efficient access option to:

- serve users located in un-served areas;
- serve users with the required QoS when the MNO is saturating due to the large traffic requests, *i.e.*, for traffic off-loading.

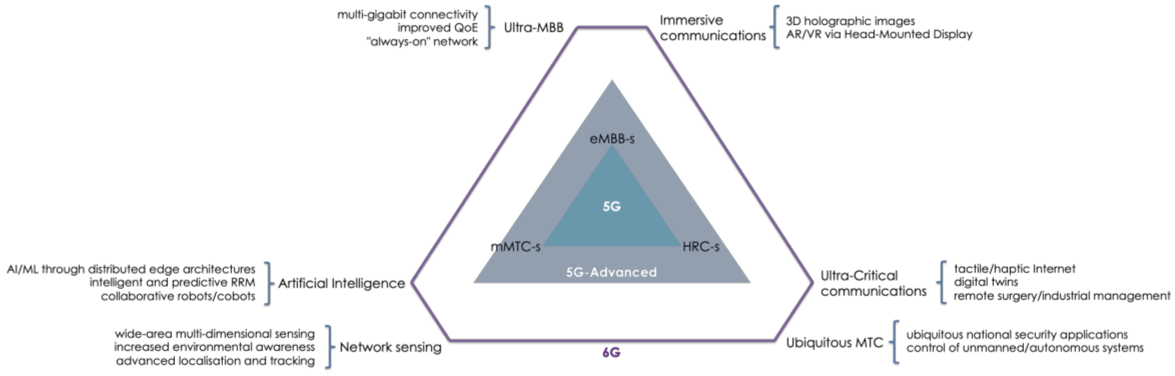

Figure 3. Service evolution from 5G, to 5G-Advanced, to 6G.

As for 6G NTN systems, it is expected that they will enable diverse use cases with extreme range of requirements. Compared to legacy design requirements, the biggest difference is the diversity of use-cases that 6G networks must support and the new opportunities it will create compared to today's networks, [10], [11]. These use cases can be grouped into the following six usage scenarios for 6G that are being discussed in the industry, extending and expanding those of 5G, as shown in Figure 3: Ultra-Mobile Broadband, Immersive Communication, Ultra-Critical Communications, Ubiquitous MTC and Ultra massive connectivity, Network Sensing, Artificial Intelligence.

With respect to the target performance, different service requirements for different deployment contexts and terminal types shall be defined. In particular, the following use cases are deemed to be the most relevant for future 5G-A and 6G NTN systems:

- 5G-Advanced: i) handheld outdoor terminals, for pedestrian users and Public Safety services; and ii) VSAT on mobile platforms or building mounted.
- 6G: i) handheld terminals, outdoor or in light indoor conditions; and ii) vehicle or drone mounted terminals.

Table 4 reports the target performance for the above mentioned deployment scenarios.

Table 4. Target performance requirements for 5G-Advanced and 6G services.

Terminal and deployment		Experienced data rate (DL/UL) [Mbps]	Latency [ms]		Reliability	Position error [m]	Position acquisition time [s]	UE speed [km/h]
			UP	CP				
5G-A	Handheld, outdoor	1/0.1	GEO <600 MEO <180 LEO <50	<40	99.99%	<1	<2	3 (pedestrian)
	Handheld, outdoor Public Safety	5/5			99.999%	<1	<1	100
	Mobile platforms and building mounted VSATs	50/25			99.99%	<1	<2	<250
6G	Handheld, light indoor	1/0.1 (at least emergency services)			99.999%	<0.1	<1	N/A
	Handheld, outdoor	20/2			99.999%	<0.1	<1	3 (pedestrian)
	Vehicle or drone mounted	80/40 (<6 GHz) 300/150 (>6 GHz)			99.999%	<0.1	<1	100

With respect to the deployment scenarios involving mobile platforms, it is worthwhile highlighting that, as part of 5G-Advanced, the objective is to enhance NTN so that platform-mounted relays (IAB nodes) can be deployed. This will allow to embark an access point on board the transportation platforms, such as trains, ships, and airplanes, that can be connected through the 5G NTN access network. In 6G, the specific installation constraints of car-/drone-mounted installations, such as the volume, shape, and energy efficiency, shall be taken into account when designing the NTN connectivity. Thus, this deployment scenario is considered for 6G systems.

Architecture evolution

The Rel. 17 NTN system architecture in 5G-NR systems is based on transparent payloads and operations in FR1, *i.e.*, below 6 GHz (see Section 1 for information on the normative work). In order to cope with the above challenging requirements and users' demands for 5G-Advanced and 6G systems, an innovation breakthrough is needed in terms of the architecture as well. As represented in Figure 4, such evolution will encompass the inclusion of three additional solutions for 5G-A: i) regenerative payloads; ii) indirect access via Integrated Access and Backhaul (IAB) nodes; and Multi-Connectivity (MC).

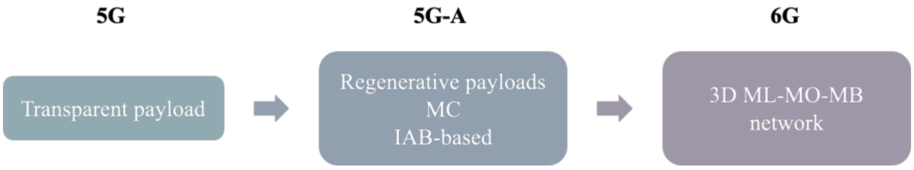

Figure 4. NTN architecture evolution from 5G to 5G-Advanced and 6G.

For regenerative payloads, radio frequency filtering, frequency conversion and amplification as well as demodulation/decoding, switch and/or routing, coding/modulation are implemented on-board. This is effectively equivalent to having all or part of the gNB protocol stack on the NTN platform. The exploitation of regenerative payloads allows, among the others, to implement various functional split options and Inter-Satellite Links, which might operate in RF or optical frequency bands.

Figure 5. NTN architecture with regenerative payload and direct access, full gNB on-board.

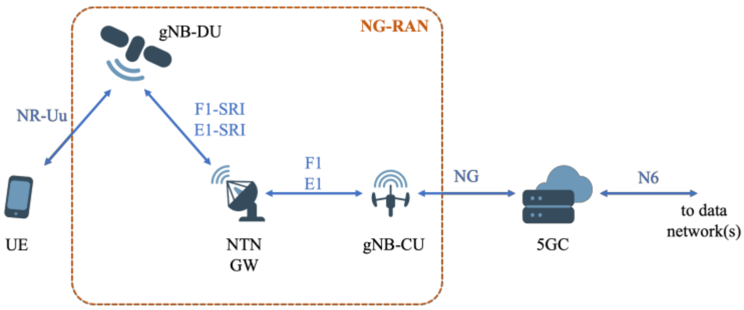

Figure 6. NTN architecture with regenerative payload and direct access, gNB-DU on-board.

Depending on the selected functional split options, different operations will be performed on-ground (gNB-CU) and on-board (gNB-DU). Figure 5 shows the architecture with a regenerative payload and the entire gNB implemented on-board. In this case, the NR-Uu protocols are entirely terminated on-board, *i.e.*, this Air Interface is only present on the user service link. Consequently, the gateway (GW) basically acts as a Transport Network layer node, terminating all transport protocols and connecting to the 5G Core network (5GC) and the on-board gNB via the NG interface. This Air Interface is logical, *i.e.*, it can be implemented by means of any Satellite Radio Interface (SRI), as, for instance, the DVB-S2, DVB-S2X, or DVB-RCS2. This architecture option allows to significantly reduce the over-the-air latency, since all NR-Uu protocols are dealt with by the regenerative payload on-board; however, it is also more complex and the cost of the satellite, and, thus, of the overall NTN system, is increased.

Figure 6 shows the architecture option with a regenerative payload and only the gNB-DU on-board. On the one hand, this allows a scalable solution based on Network Function Virtualisation (NFV) and Software Defined Networks (SDN) concepts, so as to tailor the system to different use cases and vertical services, in addition to an overall improved performance in terms of network management. On the other hand, the overall system cost and complexity are (even significantly) increased.

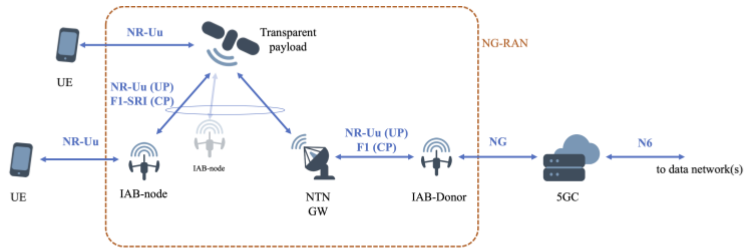

Figure 7. NTN architecture with transparent payload and IAB-based access.

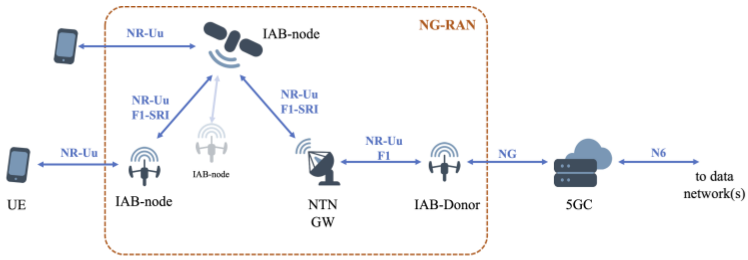

Figure 9. NTN architecture with regenerative payload and IAB-based access, on-ground IAB-Donor.

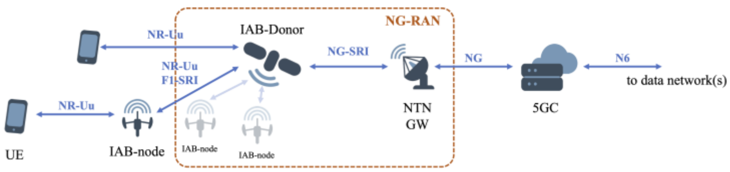

Figure 8. NTN architecture with regenerative payload and IAB-based access, on-board IAB-Donor.

As discussed in 3GPP TS 38.401, [12], it shall be mentioned that: i) a gNB can be split into a gNB-CU and one or more gNB-DUs; ii) each gNB-DU can be connected to a single gNB-CU, while a single gNB-CU can manage multiple gNB-DUs; and iii) the gNB-CU and the gNB-DU(s) are connected through the F1 and E1 Air Interfaces for the UP and CP, respectively. These interfaces are again logical and, thus, can be implemented by means of any SRI as long as specific signalling operations are guaranteed. This architecture poses a challenge related to the F1 interface since it requires a *persistent connection* between the gNB-DU and the gNB-CU and it cannot be closed and re-activated on-demand; as such, with moving satellites as in a NGSO non-stationary scenario, all of the connections towards the served UEs would be dropped once the satellite is outside of the visibility of the current gNB-CU. Smart implementations of the F1 interface and/or the functional split in NTN shall thus be designed.

In relay-based access solution, the UEs do not directly connect to the gNB, but to an Integrated Access and Backhaul (IAB) node. This network element was introduced in Rel. 16 as a flexible and scalable solution for multi-hop backhauling and to address dense deployment scenarios (basically, an evolution of LTE Relay Nodes). Currently, indirect access solutions based on IAB are considered for further study within 3GPP; and as such can be considered for 5G-A. As detailed in TR 38.809, [13], and TR 38.874, [14], an IAB-Donor acts as gNB and it is connected to the 5GC through NG Air Interface. It includes the CP/UP of the IAB-Donor gNB-CU and then one or more IAB DUs which manage other IABs in a hierarchical architecture. Each IAB DU: i) is connected to one or more IAB-nodes, in particular to their Mobile Termination (MT), through the F1 logical interface on the CP and the NR-Uu interface on the UP; and/or ii) is connected to the UEs to be served via the NR-Uu Air Interface. It is also worthwhile mentioning that the IAB-Donor implements PDCP/SDAP and upper layers, while the IAB-nodes only implement the PHY, MAC, and RLC layers.

Figure 7 shows the architecture with a transparent payload and indirect access. The IAB-Donor is connected to the 5GC via the NG interface; the connection between the IAB-Donor and the IAB-node(s), *i.e.*, both the user access and feeder links, is implemented by means of the NR-Uu (UP) and logical F1 (CP) Air Interfaces. Figure 8 shows the architecture with IAB-access when the IAB-Donor is on-ground and the IAB-node is on-board. In this case, the same Air Interfaces as those discussed above for the transparent payload case shall be implemented. Figure 9 shows the case with an on-board IAB-Donor.

Here, the feeder link connecting the IAB-Donor to the 5GC via the system GW shall be implemented as a NG-SRI interface.

Finally, 3GPP studied the simultaneous Protocol Data Unit (PDU) session MC of a UE over terrestrial RAN and satellite-based NG-RAN and decided not to include it in Rel. 17 specifications. However, it does not preclude the deployment of a UE that may simultaneously run separate Registrations and PDU Sessions in NTN and TN with different Public Land Mobile Networks (PLMN). The 5G system is expected to support service continuity between 5G terrestrial access network and 5G satellite access networks owned by the same operator or owned by two different operators having an agreement. In principle, NSA (Non standalone) operation between NTN and TN, such as running one leg connection with NTN and another leg connection with TN, is not precluded in standards, but it can be potentially challenging. Running Xn connections between an NTN gNB and a terrestrial gNB is itself very challenging due to the many constraints like UP flow control and other factors.

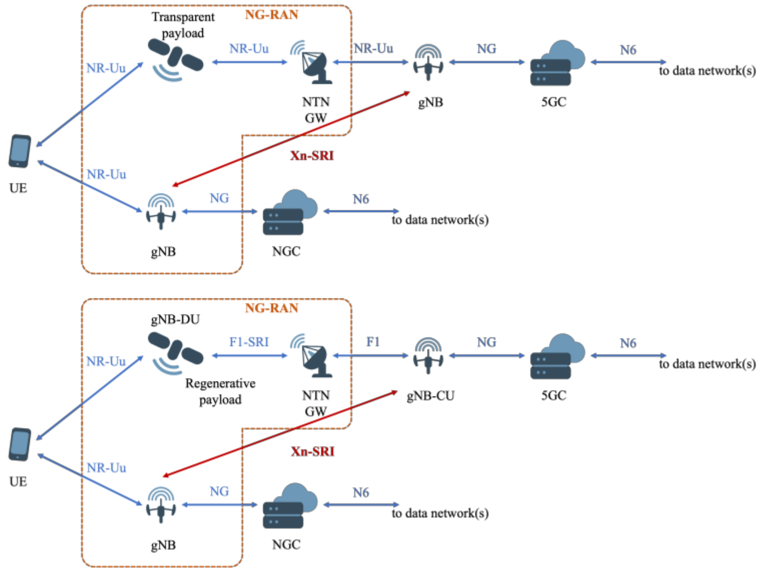

Figure 10. NTN architecture with Dual Connectivity provided through TN and NTN accesses with transparent (above) and regenerative (below) payloads.

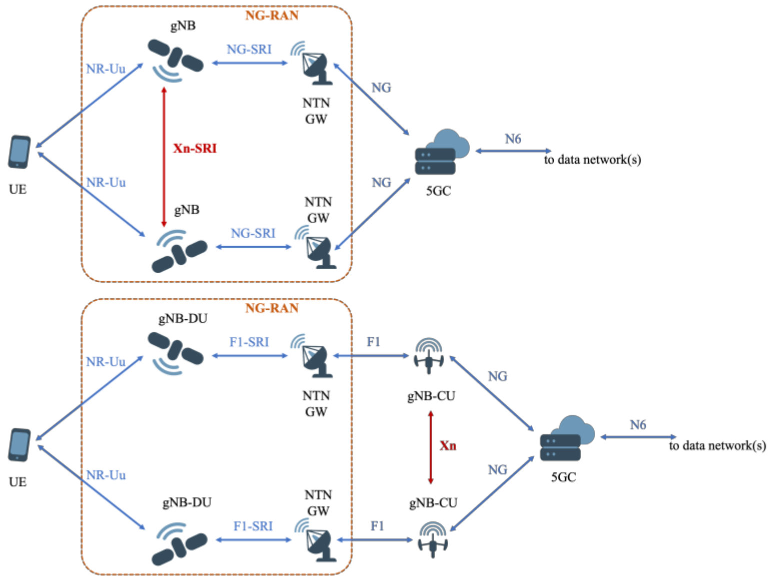

Figure 11. NTN architecture with Dual Connectivity provided through two NTN accesses without (above) and with (below) functional split.

NTN as currently considered does not support NSA with TN: even MR-DC (Multi Radio Dual Connectivity) and NR-to-NR Dual Connectivity (NR-NR DC) would be problematic. Thus, currently, NSA-based aspects (such as Xn mobility between NTN gNBs and terrestrial gNBs, MR-DC, secondary RAT data volume reporting, traces, etc.) are treated with low priority in 3GPP. A number of Xn specifications are not expected to need explicit updates for NTN, so such support is left for vendor implementation. It is expected the NG-based mobility should work to transition between NTN and TN. It is anticipated that NTN can interact with 5G, 4G, or even 3G terrestrial networks via legacy inter-RAT procedures.

Figure 10 and Figure 11 show an example of DC with TN-NTN and NTN only access types, respectively. As already mentioned, in the former case the complexity is significant due to the need for properly synchronise and align the transmissions over two very different channels. In both cases, the Xn interface over SRI is needed to tightly coordinate the master and secondary gNBs. Moreover, it shall also be mentioned that the RAN might flexibly select either the NTN or the TN gNB as master node, with the other acting as secondary gNB.

In order to cope with the advanced use cases and requirements previously outlined, a further leap will be needed to move to 6G communications and realise a truly unified terrestrial-satellite communication infrastructure that we envision as a three-dimensional Multi-Layer Multi-Orbit Multi-Band (3D ML-MO-MB) NTN, as shown in Figure 12.

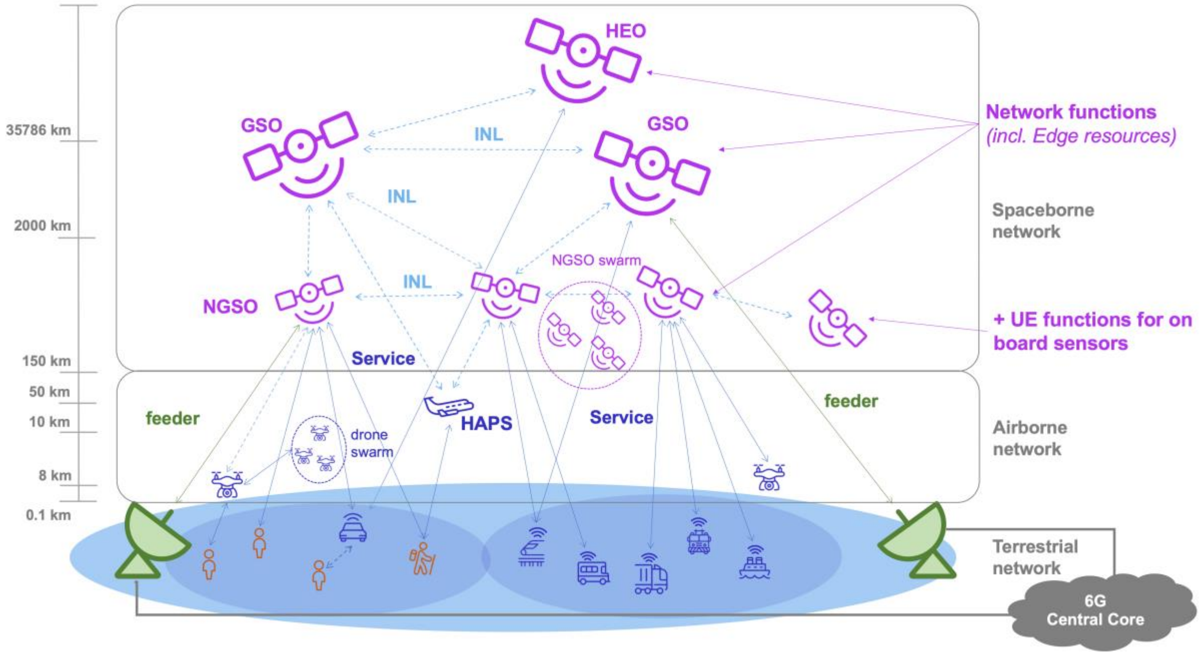

Figure 12. 6G NTN 3D Multi-Layer Multi-Orbit Multi-Band architecture.

In this system, while LEO satellites would require to solve handover challenges, even considering their large coverage, moving vehicles may interface with LEO satellites thanks to active antennas, or, to further reduce the handover and Doppler effect, the vehicle may interface with HAPS offering regional coverage for access to the network, while the data are relayed by the HAPS to LEO or GEO satellites, depending on the type of requested service, [1]. HAPS offer the opportunity for wide area access: their altitude allows for direct access by handheld devices, as well as the use of large antennas, and stationary coverage, collecting data on a large area reducing the impact of handover for moving vehicles. Additionally, their stationary flight allows for a noticeable reduction of Doppler issues, as only the vehicle would be moving. The size of HAPS allows them to mount directive active antennas able to follow a LEO satellite in flight, granting a longer visibility, which can be further improved through ISLs. The envisioned 3D ML-MO-MB system shall support several key system requirements defining the characteristics of the non-terrestrial component in the overall infrastructure, as shown in Figure 13.

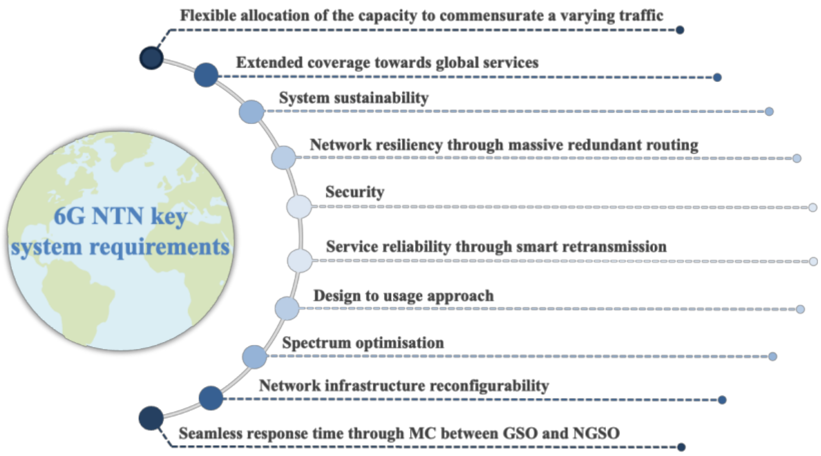

Figure 13. Key system requirements for 6G NTN systems.

Technology evolution

Leveraging Rel. 17 NTN specifications, and targeting the above mentioned use cases and system requirements, evolutions of both the available technologies (5G-A) and revolutionary concepts (6G) shall be developed for future NTN systems.

Table 5. Summary of advantages and challenges for 5G-A candidate technologies.

Technique/technology	Pros	Cons
Multi-User MIMO (standalone satellite)	- improved data rate - improved reliability - robustness to the UE speed - reduced latency with OBBF and DBC	- signalling overhead, in particular for CSI-based algorithms - security for location-based algorithms - on-board computational complexity for DBC - CSI or location aging due to the satellite movement (in particular for LEO systems) - traffic-based scheduling
Multi-Connectivity and Carrier Aggregation	- improved data rate - improved reliability - support for high speed UEs - reduced latency achieved by operating at layers above PHY	- adaptation of the F1 interface required with regenerative payloads - synchronisation and buffering, in particular for NTN-TN MC/CA - satellites movement and handover - scheduler complexity (out-of-order packets)
Beam management and bandwidth part association	- slightly improved data rate by means of more efficient beam resource allocation - improved reliability and support for high speed UEs by means of more efficient handover procedures	- applicable to option 3 only (multiple beams per cell) - system capacity issues
Duplexing	- improved data rate	- signalling and guard bands/times overhead - increased guard times in NTN scenarios compared to TN
L-band and higher frequency bands	- improved data rate - improved reliability	- spectrum harmonisation in terms of regulations and adjacent channel coexistence - possible challenges related to FDD operations in FR2 - identification of 3GPP-compliant parameters for PHY and TX/RX characteristics
User Equipment	- improved data rate - improved reliability	- coexistence to be assessed - TX/RX characteristics to be defined such that EMF constraints are met

NTN-TN and NTN-NTN mobility and service continuity	- improved data rate - improved reliability - support for high speed UEs	- latency and synchronisation challenges with NGSO platforms - procedures adaptations due to potentially frequent handover - potentially large overhead in signalling for handover measurements - synchronisation, in particular in the NTN-TN scenario

As previously discussed, service and capability enhancements are already being developed within Rel. 18. In particular, for mMTC, the evolution is being directed towards a performance improvement in discontinuous coverage and to deal with terminal mobility. As for eMBB, the following features are being addressed: i) network-based UE location determination; ii) coverage enhancements; iii) NR- NTN deployment above 10 GHz and support for VSAT/ESIM terminals; iv) NTN-TN and NTN-NTN mobility and service continuity enhancements.

Table 5 and Table 6 below provide an overview of the technologies and techniques that are expected to play a significant role for 5G-A and 6G NTN, respectively. The former includes some of the solutions that were de-prioritised in Rel. 18 and which might be considered as candidate features for Rel. 19. For 6G, *i.e.*, Rel. 20 and beyond, more revolutionary concepts are expected to realise the proposed 3D ML-MO-MB NTN architecture. The list of candidate technologies for 5G-A and 6G NTN discussed below is summarised in Table 6.

Table 6. Summary of advantages and challenges for 6G candidate technologies.

Technique/technology	Pros	Cons
Multi-User MIMO (multiple satellites)	- improved data rate - improved reliability - robustness to the UE speed - reduced latency with OBBF and DBC	- signalling overhead, in particular for CSI-based algorithms, also related to the swarm management - synchronisation - security for location-based algorithms - on-board computational complexity for DBC - CSI or location aging due to the satellite movement (in particular for LEO systems) - traffic-based scheduling
Waveform constraints and design	- improved data rate - improved reliability - robustness to the UE speed, in particular with OTFS and OFDM variants	- introduction of a new or modified waveform compared to 5G CP-OFDM - modulator/demodulator complexity - feasibility study required for OTFS in NTN
AI/ML	- improved data rate - improved reliability - robustness to the UE speed - reduced latency - improved positioning	- computational complexity when training the network on-board - system overhead when training the network on-ground - difficulty in obtaining real observations for the network training
Inter-Satellite Links	- improved data rate - improved reliability - robustness to the UE speed - reduced latency	- regulatory aspects related to ISLs to be addressed in WRC-23 - synchronisation and signalling - support for non-persistent F1 interfaces when functional split is implemented - assessment of the NR-NTN procedures in the presence of ISLs
Non-Orthogonal Multiple Access	- improved data rate - improved reliability - robustness to the UE speed, since no CSI is required	- increased complexity at the receiver - challenges related to power-based techniques, in particular for UEs in the same beam
Reflective Intelligent Surfaces	- improved data rate - improved reliability - improved positioning for indoor scenarios via NTN	- signalling and synchronisation - computational complexity - feasibility assessment to be performed from scratch

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THE EAGER PROJECT

This document summarises the initial outcomes of the **EAGER (tEchnologies And techniques for satcom beyond 5G nEtwoRks)** Project, funded by the European Space Agency (ESA). This Study is coordinated by the University of Bologna and the Partners are: Thales Alenia Space Italia, Thales Alenia Space France, Magister Solutions, and Martel Innovate.

Leveraging the soon to be finalized Rel. 17 Non-Terrestrial Network (NTN) standardization framework, the EAGER project aims at **researching innovative technologies and techniques targeting highly efficient and deeply integrated satellite networks in beyond 5G cellular systems**. The objectives are:

- To **evaluate and adopt discarded solutions** or use cases, including, *e.g.*, MIMO techniques, advanced payload with digital beamforming and active antennas, AI/ML techniques, low PAPR waveforms, handheld direct access for broadband communications with VLEO constellations, mMTC, self-driving car services and V2X applications, etc.
- To **identify and evaluate novel concepts** (both in the waveform and in the network domain, as well as in the space and ground segment technologies).
- To **develop the necessary software or analytical tools** in order to properly assess the performance of the most promising techniques and technologies.

Both **mid- and long-term satellite network solutions are being targeted** with a focus on solutions providing **mobile broadband** services as follows:

- **Mid-term**: the Study will select and evaluate the most relevant candidate features that were de prioritized from Rel. 18, such as the support of UEs without GNSS, beam management and bandwidth part (BWP) association enhancements, carrier aggregation, coordinated transmission, asynchronous multi connectivity etc.
- **Long-term**: the Study will
  - Undertake some preliminary studies on versatile radio protocols able to cope with terrestrial and satellite propagation channel impairments and constraints thanks to low PAPR, as well as AI/ML techniques.
  - Carry out some feasibility study and trade-offs on a novel VLEO-based network infrastructure providing mobile broadband services to small terminals.

To this aim, the project will also **develop some NTN link/capacity/system level simulation tools** and use them to assess the performance gain of the considered techniques.

More information can be found on the project website (https://www.eagerproject.eu) and on the following social media channels:

- LinkedIn: https://www.linkedin.com/company/eager-project/
- Twitter: https://twitter.com/eagersatcom

Stay tuned!