D3.1: System Requirements Analysis and Specifications

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Authors	Alessandro Guidotti, Giulio Colavolpe, Tommaso Foggi, Alessandro Ugolini, Amina Piemontese, Armando Vannucci (CNIT) Benjamin Barth, Roshith Sebastian (DLR) Nadia Arago Higueras, Marc Porhel (TASF) Fanny Parzysz, David Arnaud (ORA) Nuria Candelaria Trujillo Quijada, Enrique MarinMatin (HSP) Marius Caus, Erislandy Mozo, Miguel Ángel Vázquez (CTTC) Marius Corici, Hemant Zope (FHG)
Reviewers	Marius Caus (CTTC)
Abstract	This document provides a detailed discussion on the NTN, TN, and 5GC architectures and interfaces. These are then evaluated and mapped onto the 5G-STARDUST Use Cases to identify a set of potential architectures to be developed in the Project. For each Use Case, the functional and system requirements are defined. Finally, an overview of NTN and TN spectrum is reported.
Keywords	3GPP, 5G-Advanced, Architecture, NTN, TN, Functional Split, Functional Requirements, Interface, Protocol, Spectrum

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EXECUTIVE SUMMARY

This document reports the outcomes of Task 3.1 “System Requirements Analysis and Specifications” and, based on the input from Task 2.1 “Use Cases and Scenarios Analysis and Selection” and Task 2.2 “Service and User Requirements Specification”, it defines the system architectures, interfaces, and functional requirements.

The objective of this document is that of providing a clear and common baseline for all subsequent tasks in WP3, as well as other WPs, in terms of system architectures and functional requirements. As such, several trade-offs are discussed and the possible options for each retained use case are identified. These will be further refined in the prosecution of the 5G-STARDUST Project.

More specifically, the document first reports a thorough and detailed revision of the architectures, User Plane (UP) and Control Plane (CP) protocol stacks, and interfaces for all network components, *i.e.*, including Non-Terrestrial Networks (NTN), Terrestrial Networks (TN), Open Radio Access Network (O-RAN), and the 5G Core network (5GC). While the TN, O-RAN, and 5GC review will be exploited when defining the end-to-end self-organised architecture in Task 3.2, the NTN architectures are then classified considering a few relevant Key Performance Indicators (KPIs) from a qualitative perspective (capacity, latency, payload complexity, adaptations to terrestrial handsets or satellite parabolic receivers).

For each use case identified as of interest in WP2, a potential set of architectures is identified based on a preliminary trade-off considering the above-mentioned KPIs. As extensively discussed in the document, the following NTN options will be prioritised: i) regenerative payloads for direct access (Vehicular-to-Network, Public Protection and Disaster Relief, Global Private Networks); ii) regenerative payloads for indirect access (Residential Broadband, Airway Communications, Public Protection and Disaster Relief, Global Private Networks). In addition, Multi-Connectivity (MC) is also considered as an optional feature for some of the identified Use Cases, to be evaluated in the upcoming tasks.

Based on the identified architecture options, for each Use Case the functional and mission requirements are identified, providing a detailed list of mandatory/optional operational concepts that shall be guaranteed to provide the considered service.

Finally, an overview of spectrum allocations is discussed. As extensively discussed below, based on 3GPP Rel. 17, NTN can already operate in Frequency Range 1 (FR1, S-band in particular) for handheld terminals; the extension of NTN to FR2 for Very Small Aperture Terminals (VSAT) is currently being investigated in Rel. 18 and no common agreement has already been achieved. In addition, spectrum coexistence in adjacent bands in Ka-band is also beginning to be assessed and the 3GPP studies will be monitored to be exploited as input for other tasks. For the TN component, a detailed overview of the potential allocations and market trends is reported, based on up-to-date information from both regulators and operators.

As previously mentioned, this document defines a detailed and common framework in terms of architectures, protocols, interfaces, and functional requirements that will be used as a baseline for all other tasks and WPs of the 5G-STARDUST Project. As such, no final decisions/agreements are reported, as further analyses and trade-offs will be needed and will be reported in D3.2.

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ABBREVIATIONS

5GC	5G Core network
A1AP	A1 Application Protocol
AI	Artificial Intelligence
AMF	Access and Mobility Function
BAP	Backhaul Adaptation Protocol
BH RLC	Backhaul RLC
CCC	Cell Configuration and Control
CP	Control Plane
E2AP	E2 Application Protocol
E2SM	E2 Service Model
EI	Enrichment Information
FH	Fronthaul
FR1	Frequency Range 1
GEO	Geostationary Earth Orbit
gNB-CU	gNB Centralised Unit
gNB-DU	gNB Distributed Unit
GPRS	General Packet Radio System
GTP	GPRS Tunnelling Protocol
GW	Gateway
HARQ	Hybrid Automatic Repeat request
IAB	Integrated Access and Backhaul
IETF	Internet Engineering Task Force
IP	Internet Protocol
ISL	Inter-Satellite Link
KPM	Key Performance Measurement
LEO	Low Earth Orbit
MAC	Medium Access Control

MC	Multi-Connectivity
MCG	Master Cell Group
MEO	Medium Earth Orbit
ML	Machine Learning
MN	Master Node
MnS	Management Service
MR-DC	Multi-Radio Dual-Connectivity
NAS	Non-Access Stratum
NAS-MM	NAS Mobility Management
NAS-SM	NAS Session Management
near-RT	near Real Time
NFV	Network Function Virtualisation
NGSO	Non-Geosynchronous Orbit
NI	Network Interface
non-RT	non Real Time
NR	New Radio
NT	Non-Terrestrial
NTN	Non-Terrestrial Network
O-CU	O-RAN Centralised Unit
O-DU	O-RAN Distributed Unit
O-RAN	Open Radio Access Network
O-RU	O-RAN Radio Unit
PCF	Policy Control Function
PDCP	Packet Data Convergence Protocol
PDU	Packed Data Unit
PHY	Physical Layer
PLFS	Physical Layer Frequency Signal
PSAP	Public Safety Answering Point

PTP	Precision Time Protocol
QoS	Quality of Service
RC	RAN Control
RDN	Radio Distribution Network
RF	Radio Frequency
RIC	RAN Intelligent Controller
RLC	Radio Link Control
RRC	Radio Resource Control
SAN	Satellite Access Node
SCG	Secondary Cell Group
SDAP	Service Data Adaptation Protocol
SDL	Shared Data Layer
SDN	Software Defined Network
SMF	Session Management Function
SMO	Service Management and Orchestration
SN	Secondary Node
SRI	Satellite Radio Interface
TA	Timing Advance
TN	Terrestrial Network
UDP	User Datagram Protocol
UE	User Equipment
UE-ID	UE identifier
UP	User Plane
UPF	User Plane Function
V2N	Vehicular-to-Network

1 NTN-TN SYSTEM ARCHITECTURES AND INTERFACES

In this Section, we provide an exhaustive overview of the architectures and interfaces for the Non-Terrestrial (NT) and terrestrial network components, as well as the 5G Core network (5GC). In addition, we also discuss the main characteristics of O-RAN solutions. These discussions provide a solid baseline for the identification of the most suitable system architectures and functional requirements, defined for each use case in Sections 2 and 3.

1.1 NR-NTN RADIO ACCESS NETWORK

In the following, we provide an overview of the 3GPP Non-Terrestrial Network (NTN) architecture options. Starting from the architectures and interfaces defined in Rel. 17, we then elaborate the possible evolutions towards 5G-Advanced, *i.e.*, Rel. 18+, which still have to be specified. For each architecture option, the Control Plane (CP) and User Plane (UP) protocol stacks are discussed, in particular identifying how the protocol layers are distributed across the network.

1.1.1 Rel. 17: 5G

In the recently finalised specifications for Rel. 17, the support of the New Radio (NR) standard via air-/space-borne platforms is provided through an NTN Satellite Access Node (SAN), [1]. Referring to Figure 1, the SAN is an element in the NR architecture providing UP/CP terminations towards the on-ground User Equipment (UE); it encompasses a transparent NTN payload, an on-ground gateway (GW), non-NTN (*i.e.*, elements/functions not included in or specified for the NTN component) infrastructure gNB functions, the feeder link, and the Radio Frequency (RF) functions of the NTN payload. The transparent NTN payload includes: i) a Transceiver Unit Array, containing an implementation-specific number of transmitter and receiver units; ii) a Radio Distribution Network (RDN), a passive linear network distributing the RF power generated by the transceiver unit array to the antenna array and/or distributing the radio signals collected by the antenna array to the transceiver unit array; and iii) an antenna array. The latter two elements (*i.e.*, the antenna array and the RDN) constitute the composite antenna and the details of the power/signal distribution operated by the RDN are implementation specific.

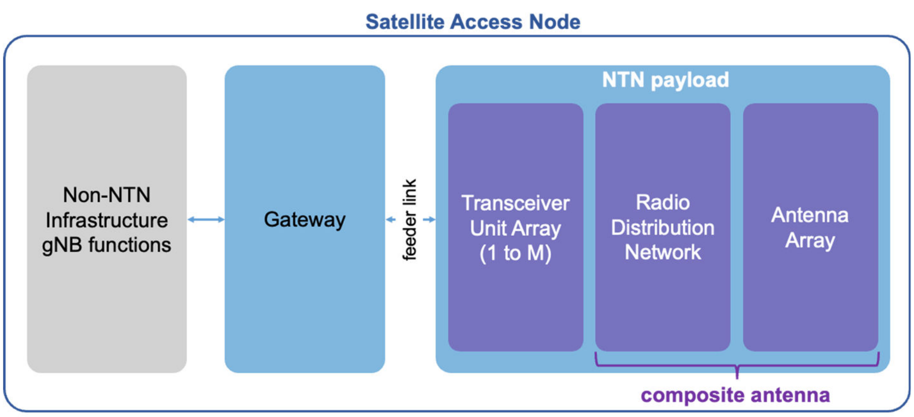


Figure 1: 3GPP NR Satellite Access Node (SAN).

The RF performance of the NTN payload has been defined on the service link for several frequency bands in Frequency Range 1 (FR1), *i.e.*, below 6 GHz, including S and L bands, based on adjacent channel co-existence studies between satellite and mobile networks; these details are not in the scope of this document and can be found in TS 38.108, [1], TR 38.863, [2], and TS 38.101-5, [3].

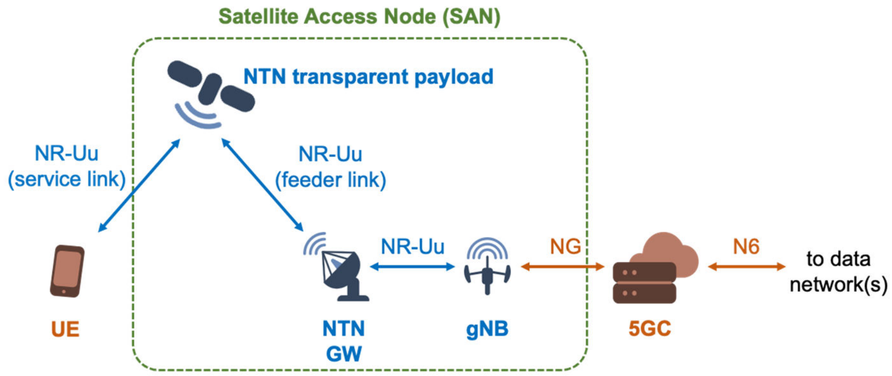


Figure 2: NTN architecture with transparent payload and direct access.

Based on the above-defined Rel. 17 SAN with transparent payload, Figure 2 shows the high-level system architecture for NTN-based NR direct access, as defined in 3GPP TR 38.821, [4]. In this architecture, the following aspects can be noticed:

- the transparent NTN payload implements only frequency conversion, filtering, and amplification, basically acting as an air-/space-borne RF repeater forwarding the radio protocols received by the UEs to the gNB and *vice versa*;

- the gNB serving the on-ground UEs is conceptually located at the NTN GW. Aiming at the full compatibility with the 3GPP NR standard, all CP and UP protocols are terminated at the on-ground gNB and, thus, both the feeder and the user service links shall be implemented by means of the NR-Uu Air Interface. The user service link can be implemented by means of: i) Earth-fixed beams, in which the on-ground beams continuously cover the same service area for the entire time, *e.g.*, Geostationary Earth Orbit (GEO) satellites; ii) Quasi-Earth-fixed beams, in which the on-ground beams cover the same service area for a time period limited to the visibility of the NTN payload, *e.g.*, Low Earth Orbit (LEO) or Medium Earth Orbit (MEO) satellites with steerable antennas; or iii) Earth-moving beams, in which the on-ground beams are non-steerable and continuously cover the area below the NTN payload, *i.e.*, they move on the surface of the Earth along with the satellite's movement on its orbit;

- the gNB is connected to the UP Function (UPF) and the Access and Mobility Management Function (AMF) in the 5GC by means of the terrestrial NG Air Interface.

It shall be noticed that, for the sake of clarity, the NTN architecture shown in Figure 2 shows a single gNB. However, each gNB can manage a few tens of beams and, thus, depending on the specific use case and mission design of the SAN, multiple NTN payloads can be connected to a single gNB or multiple gNBs can be connected to a single NTN payload. The NTN payload is capable of synthesising and managing multiple beams.

In terms of protocol stack, Figure 3 and Figure 4 show the UP and the CP, respectively. It can be noticed that the NTN payload (and the GW) indeed acts as a RF repeater, by only implementing RF processing and frequency switching in the transponders:

- on the UP, the Packet Data Unit (PDU) sessions, and the related Quality of Service (QoS) flows to adapt the network to the required service, are established between the UPF in the core network and the UE. To support the QoS flows via NTN, new QoS classes to support the extended latency on the NT access and backhaul were introduced. The QoS flows are carried over NG-U (NG-User Plane) tunnels between the 5GC and the gNB and through radio bearers from the gNB to the UEs. The N4 and N6 reference points in the UPF identify the conceptual points of interaction between the UPF and the Session Management Function (SMF) and data networks, respectively. Each UE's interaction with services is described as a session, and different sessions might have different QoS requirements. The SMF manages the sessions created for the users in the UPF, via policy rules obtained from the Policy Control Function (PCF) in the 5GC, and the exchange of information is performed through the N4 interface. Then, the UPF is connected to any other internal or external data network (or service platform) through the N6 interface;

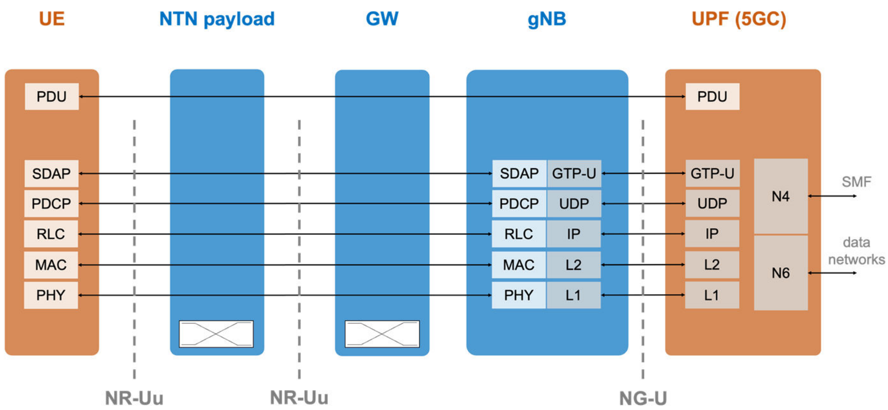


Figure 3: UP protocol stack: transparent payload and direct access.

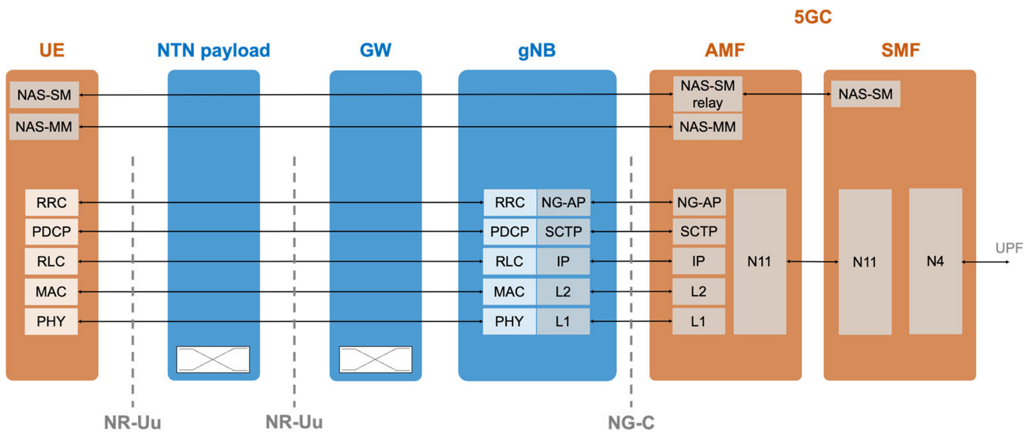


Figure 4: CP protocol stack: transparent payload and direct access.

- on the CP, the Non-Access Stratum (NAS) signalling between the AMF in the 5GC and the UE is transported through the transparent payload with RF processing only. Such signalling involves the Session Management (NAS-SS) and Mobility Management (NAS-MM) functionalities. In addition, N11 is the reference point for the interactions between the AMF and the SMF. It shall be noticed that the AMF and SMF in the CP have many other reference points with other elements in the 5GC. Further details can be found in TS 23.501, [5]. The N11 interface provides the connection between the AMF and the SMF to establish, coordinate, and terminate the different PDU session types. When a UE requests a session, the NG Application layer (NG-AP) protocols are used to provide NAS information to the AMF, which in turn passes the requests to the SMF through N11.

Table 1: Overview of the functions of UPF, AMF, and SMF.

UPF	AMF	SMF
Anchor point for intra-/inter-RAT mobility (when applicable) **External PDU Session point of interconnection to Data Network(s)** **Packet routing & forwarding** **Packet inspection** **UP part of the policy rule enforcement, *e.g.*, gating, redirection, traffic steering** **Lawful intercept (UP collection)** **Traffic usage reporting** **QoS handling for the UP, *e.g.*, UL/DL rate enforcement, reflective QoS marking in DL** **Uplink Traffic verification (SDF to QoS Flow mapping)** **Transport level packet marking in the uplink and downlink** **Downlink packet buffering and downlink data notification triggering** **Sending and forwarding of one or more "end marker" to the source NG-RAN node**	**Termination of RAN CP interface (N2)** **Termination of NAS (N1), NAS ciphering and integrity protection** **Registration management** **Connection management** **Reachability management** **Mobility Management** **Lawful intercept (for AMF events and interface to LI System)** **Provide transport for SM messages between UE and SMF** **Transparent proxy for routing SM messages** **Access Authentication and Access Authorization** **Provide transport for SMS messages between UE and SMSF** **Security Anchor Functionality (SEAF** **Security Context Management (SCM)** **Location Services management for regulatory services** **Provide transport for Location Services messages between UE and LMF as well as between RAN and LMF** **EPS Bearer ID allocation for interworking with EPS** **UE mobility event notification**	**Session Management** **UE IP address allocation and management** **Selection and control of UP functions** **Configuration of the traffic steering at the UPF to route traffic to the proper destination** **Control part of policy enforcement and QoS** **Downlink Data Notification**

The functions performed by the AMF, UPF, and SMF are summarised in Table 1, while more details on the functionalities provided by the N4, N6, and N11 interfaces are available in TS 23.501, [5]. To support NTN, the NR-Uu protocols have been enhanced in Rel. 17 with several fundamental features related to Timing Advance (TA), Random Access (RA), Hybrid Automatic Repeat request (HARQ), mobility management, and handover, including the extension of several timers to cope with the larger latency in NTN scenarios.

As reported in TS 38.410, [6], and TS 38.414, [7], the NG interface is an open interface that: i) supports the exchange of signalling information between the RAN and the 5GC; ii) defines the interconnection between the SAN(s) and the AMF(s), potentially supported by different manufacturers; and iii) specifies the separation of the radio network and transport network functionalities, facilitating the introduction of future technologies. The functions supported over the NG interfaces are provided in Section 1.4.1.2.

In terms of functional split, since the feeder and service links, as well as the functionalities of the NTN payload, are not impacted by the possible split in Centralised Unit (gNB-CU) and Distributed Unit (gNB-DU) in the on-ground gNB, without any loss of generality we assume that no functional split is implemented in the ground segment. The functional split options are shown in Figure 5.

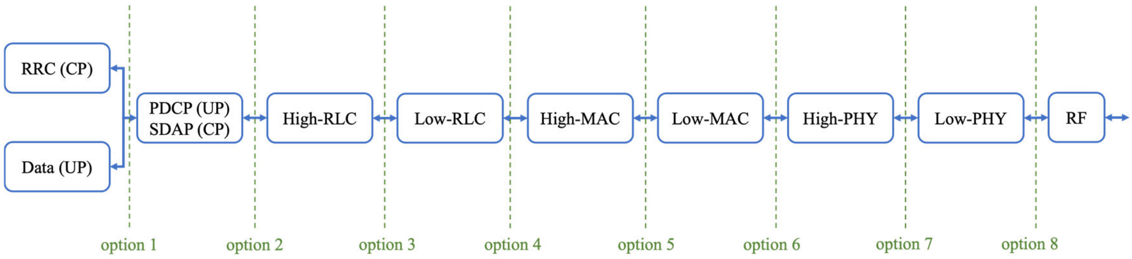


Figure 5: RAN split options.

1.1.2 Rel. 18-20: 5G-Advanced

In the framework of 5G-Advanced, covered in Rel.18 up to Rel. 20, there are three main evolutions in terms of architectures and the related interfaces: i) the use of regenerative payloads; ii) the use of Integrated Access and Backhaul (IAB) nodes for indirect access; and iii) the implementation of Multi-Connectivity (MC) solutions. In addition, it is worthwhile highlighting that, in the framework of Rel. 18 and 19, UE-to-UE communications for users under the same satellite footprint will also be addressed.

1.1.2.1 Regenerative payloads

A regenerative NTN payload in the SAN allows to bring on-board the entire protocol stack of the gNB or part of it, depending on the selected functional split option. The exploitation of regenerative payloads also allows the introduction of Inter-Satellite Links (ISLs), operating in RF or optical frequency bands, which can be either 3GPP or non-3GPP defined. Today, ISLs constitute a pre-requisite for satellite constellations as, without ISLs, a huge number of gateways would be required to manage the system, leading to unfeasible costs and complexity. In addition, regenerative payloads also allow to lower the required bandwidth for in-space routing. It is worthwhile highlighting that regenerative payloads might also be exploited on GEO platforms to reduce the required bandwidth on the feeder link, in case a massive number of beams in Very High Throughput Satellite (VHTS) systems is generated. Finally, another potential application for regenerative payloads is related to their support for direct UE-to-UE connectivity for users served by the same satellite, *i.e.*, without letting the traffic flow through the gateway.

Figure 6 shows the system architecture with a regenerative NTN payload implementing the full gNB, *i.e.*, no functional split. In this scenario, all of the NR-Uu protocols are terminated on-board and, thus, only the user service link requires this Air Interface. Consequently, the same adjustments introduced in Rel. 17 to support this interface on the NTN links apply. In this case, the GW is basically operating as a Transport Network layer node, as it terminates all transport protocols and connects the gNB to the 5GC through the NG Air Interface. Since the gNB is on-board, the feeder link requires the implementation of the NG interface over a Satellite Radio Interface (NG-SRI), *i.e.*, a transport link as, for instance, DVB-S2, DVB-S2X, or DVB-RCS2.

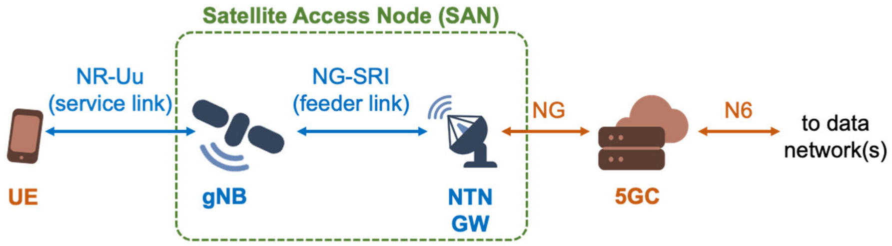


Figure 6: NTN architecture with regenerative payload and direct access: full gNB on-board.

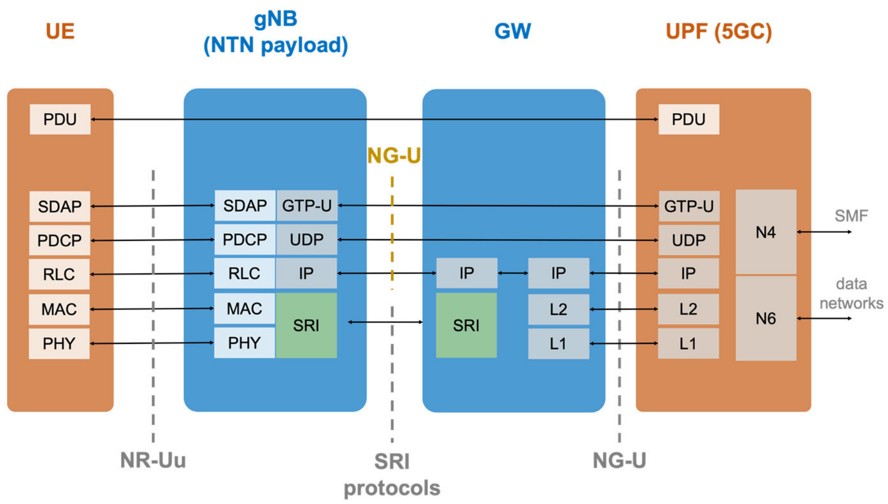


Figure 7: UP protocol stack: regenerative payload and direct access with full gNB on-board.

Figure 7 and Figure 8 show the UP and CP protocol stacks with a full gNB on-board. It is worthwhile highlighting that multiple gNBs, each on-board a dedicated NTN payload, can be connected to the same 5GC. Moreover, a single NTN payload might host multiple gNBs; in this case, the same NG-SRI interface on the feeder link shall carry the transport layer traffic of all the on-board gNBs, which might make this solution unfeasible in the near future due to the large capacity requirements.

Compared to the transparent payload architecture introduced above, it can be noticed that:

- all protocols up to the Service Data Adaptation Protocol (SDAP) on the UP and the Radio Resource Control (RRC) on the CP are terminated on-board, thus allowing to reduce the overall latency;
- the GW and the satellite shall implement the protocol stack of the SRI that is used to transport the UP and CP on the feeder link, in particular to carry the upper layers of the NG interface (this is left for implementation);

- the user's PDUs are transported again over GTP-U tunnels and radio bearers, but in this case the GTP-U tunnels are established between the UPF and the NTN payload (*i.e.*, they now involve also the feeder link), while the radio bearers are established between the NTN payload and the UE (*i.e.*, they only involve the user service link);
- routing schemes and algorithms now also involve the GW and the NTN payload as nodes to be exploited for more efficient networking solutions;
- the NG-AP protocol timers might need to be extended to deal with the extended latencies in the NTN scenario on the feeder link, while the latency on the NR-Uu interface is significantly reduced compared to the transparent payload scenario.

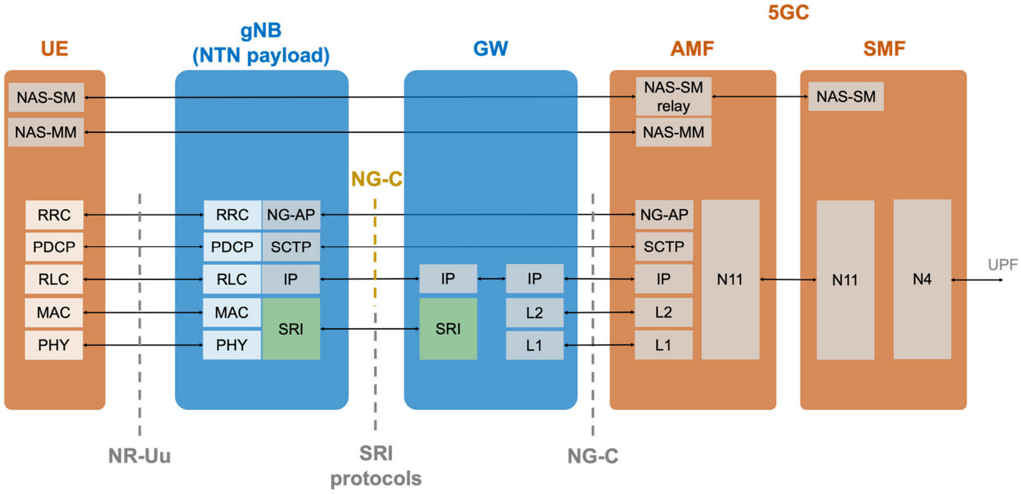


Figure 8: CP protocol stack: regenerative payload and direct access with full gNB on-board.

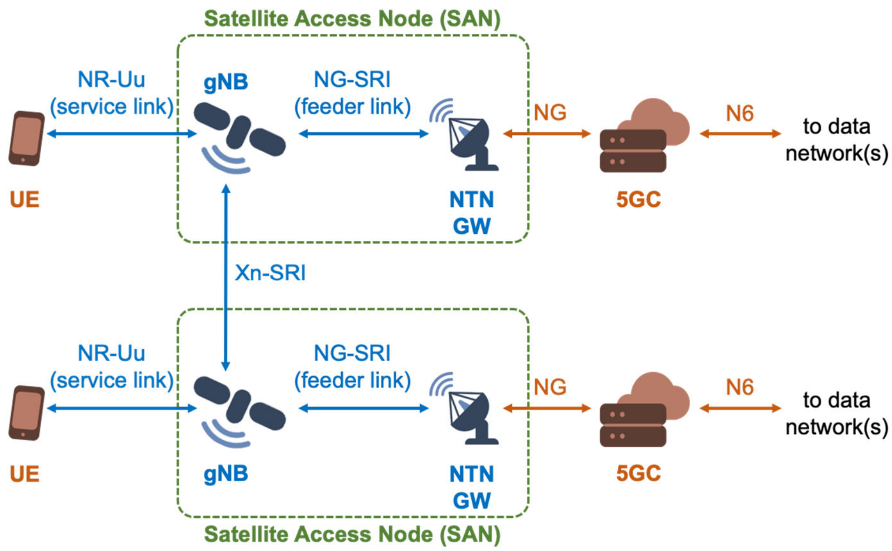


Figure 9: NTN architecture with regenerative payload and direct access: full gNB on-board with ISL.

Figure 9 shows the system architecture in the presence of multiple NTN payloads and ISLs among them. It shall be noticed that in this representation we are considering two 5GCs, one per payload; however, they can also be connected to the same 5GC without any loss of generality. The functions handled by the Xn interface are listed in Section 1.4.1.1.

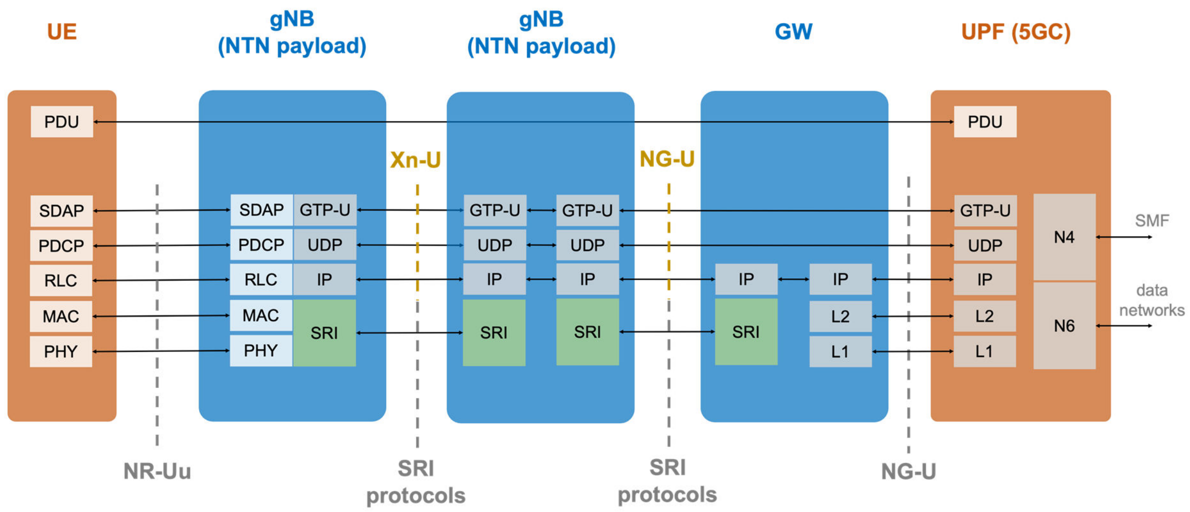


Figure 10: UP protocol stack: regenerative payload and direct access with full gNB on-board and ISL.

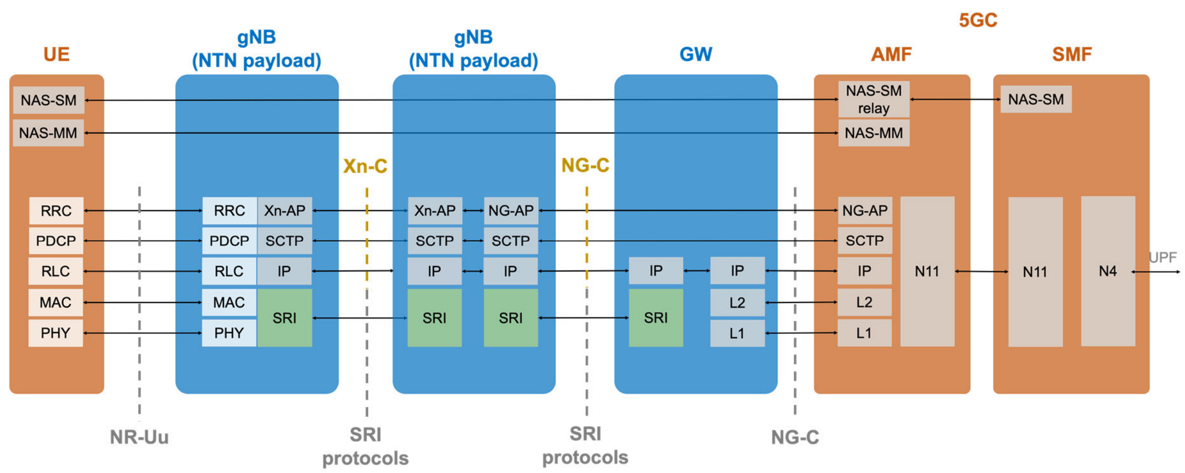


Figure 11: CP protocol stack: regenerative payload and direct access with full gNB on-board and ISL.

Xn is a logical interface, *i.e.*, it can be implemented by means of any SRI as long as the above functionalities are guaranteed. Figure 10 and Figure 11 show the UP and CP protocol stacks, respectively, in which the Xn-U and Xn-C interfaces between the involved payloads are highlighted and shall be carried over SRI. The NG interface on the feeder link has the same functions as in the previous case and it is carried over SRI between the GW and the first NTN payload in the multi-hop architecture. In this case, the PDU sessions are established between the UPF on the 5GC and the UE, over radio bearers between the UE and the serving NTN payload and NG-U tunnels between the UPF and the serving NTN payload. More details on the Xn interface are available in 3GPP TS 38.420, [8].

Finally, it is worthwhile to highlight that the protocol stacks involving regenerative payloads and ISLs are not specified yet and they will be targeted in the framework of Rel. 9. The proposed architectures are based on the NR protocol stacks and on 3GPP TR 38.821.

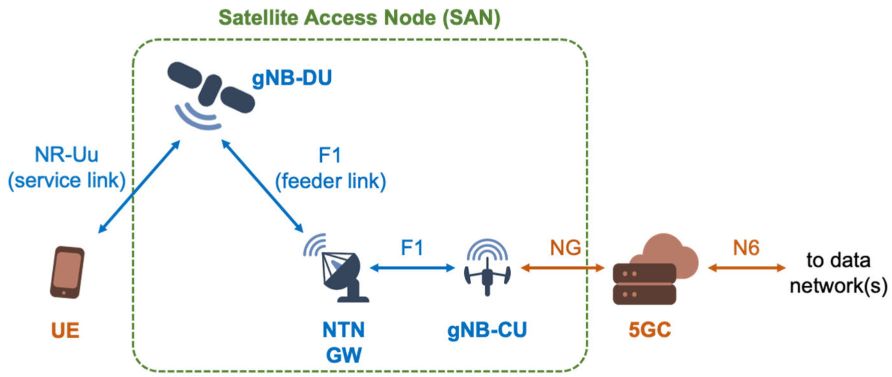


Figure 12: NTN architecture for direct access with regenerative payload and functional split.

When functional split is implemented, the gNB-DU is implemented on-board while the gNB-CU is implemented on-ground, as shown in Figure 12. This solution allows scalable network implementations based on Network Function Virtualisation (NFV) and Software Defined Network (SDN) principles, aimed at tailoring the system to the requested use cases and vertical services in addition to a more efficient network management. However, it shall also be mentioned that the overall system cost and complexity are increased. Moreover, two disadvantages arise:

- the RLC and PDCP layer processing might involve links with delays above 10 ms, depending on the NTN system. As such, the RLC would acknowledge packets and then forward them to the PDCP for decryption and reordering with more than a 10 ms latency, which would make the split not feasible;
- the split requires additional encoding and decoding on the F1 interface, thus requiring more processing time and, ultimately, increasing the latency.

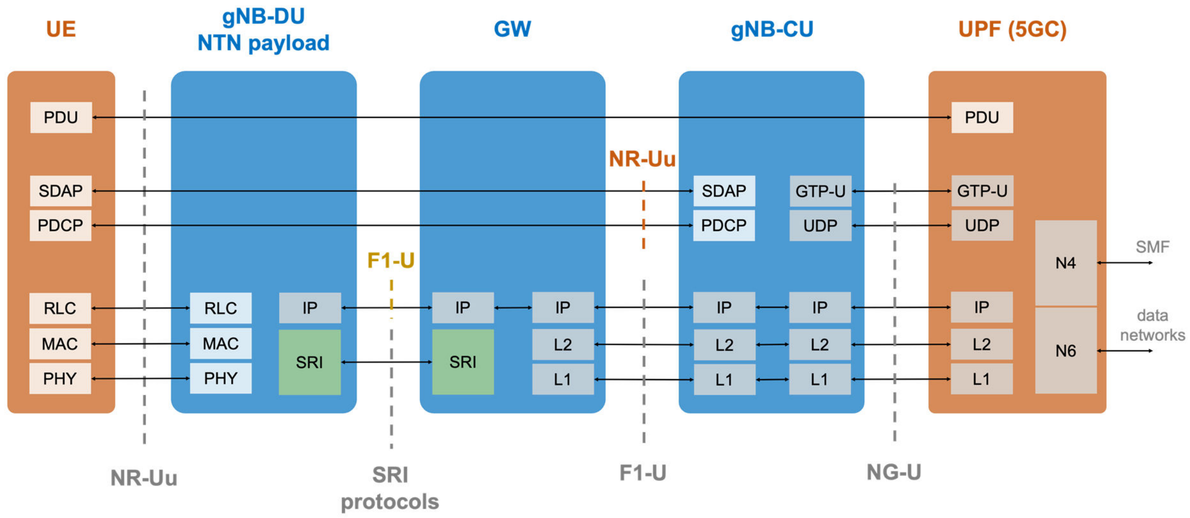


Figure 13: UP protocol stack: regenerative payload with functional split for direct access.

With functional split, 3GPP TS 38.401 clarifies that:

- a gNB can be split into one gNB-CU and one or more gNB-DUs;

- each gNB-DU can be connected to a single gNB-CU and a single gNB-CU can manage multiple gNB-DUs;
- the gNB-CU and gNB DU are connected through the logical F1 interface, specified in TS 38.470, [9], TS 38.471, [10], TS 38.472, [11], TS 38.473, [12], and TS 38.474, [13].

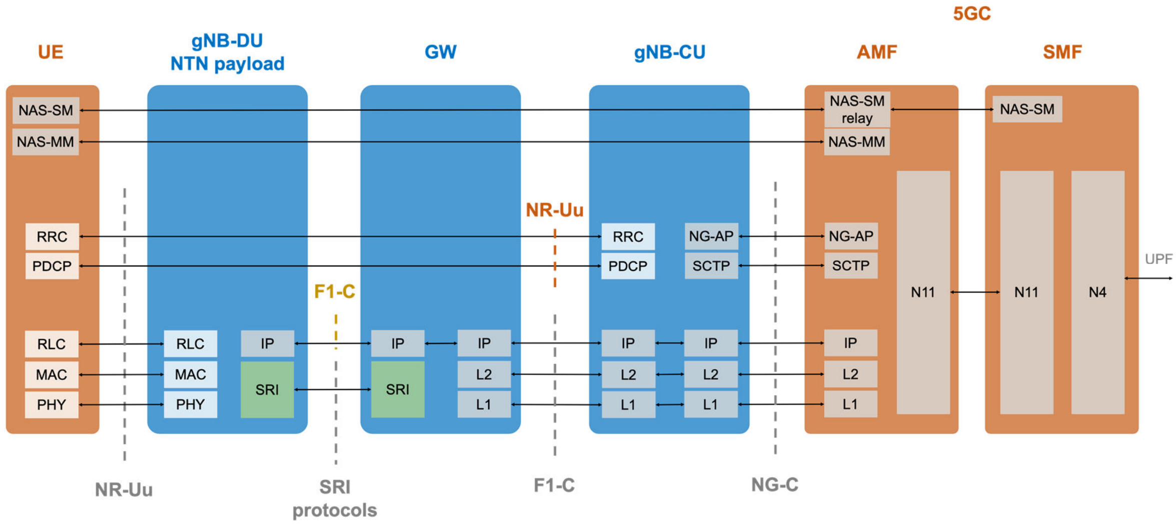


Figure 14: CP protocol stack: regenerative payload with functional split for direct access.

Figure 13 and Figure 14 show the UP and CP protocol stacks for the above architecture. In this case, the PDU sessions are established between the UPF in the 5GC and the UE, as in all architectures. Then, such sessions are carried over NG-U (GTP-U) tunnels between the UPF and the gNB-CU and over radio bearers between the gNB-CU and the UE, carried over the NR-Uu interface. It shall be noticed that this architecture poses a challenge related to the implementation of the F1 interface over SRI. In fact, this interface requires a persistent connection between the gNB-CU and the gNB-DU, which cannot be closed and re-activated on-demand. Thus, when considering Non-Geosynchronous Orbit (NGSO) scenarios, all of the connections towards the UEs would be dropped once the satellite is out of the visibility of the current GW. Smart implementations of the F1 interface and/or the functional split options shall thus be designed. In general, to allow basic services in the (temporary) absence of a feeder link, the RAN and some of the 5GC functions shall be embedded on-board.

In addition, as shown in Figure 5, there are several options for the implementation of functional split solutions. Currently, only Option 2 (RRC/PDCP split) is fully supported by 3GPP Rel. 17, as shown in Figure 13 and Figure 14. The other options, in particular Options 6 (MAC/PHY split) and Option 7 (Low PHY/High PHY) are possible, but they are not yet 3GPP-compliant and they shall be implemented by means of O-RAN solutions, discussed in Section 1.3. It shall be noticed that, as of today, the O-RAN approach for network disaggregation does not support NTN and, thus, proper solutions shall be designed.

Finally, it is worthwhile highlighting that this type of architecture also supports ISLs. In fact, with an on-ground gNB-CU, routing and PHY/MAC operations are performed on-board each payload, with the PDU sessions still established between the UE and the UPF. It might also be possible to have an on-board gNB-CU managing a set of nearby payloads equipped with the corresponding gNB-DUs; however, this type of solution has not yet been considered in 3GPP.

1.1.2.2 Indirect access through IAB nodes

An IAB node is a network element introduced in Rel. 16 specifications to provide flexible and scalable multi-hop backhauling solutions for ultra-dense scenarios, while minimising the impact on the core network, [14]-[15]; in general, the only limitation to the number of hops is posed by the network capacity. Below, we report some considerations on potential implementation of the IAB protocol stack via NTN. However, it shall be noticed that these are still to be developed within 3GPP and, thus, not yet standardised. Therefore, depending on how such specifications will evolve, there might be adjustments to be made in later phases of the project, in case IAB solutions will be retained in other WPs.

An IAB-Donor basically acts as a gNB and it is connected to the 5GC through the NG Air Interface; as shown in Figure 15, it includes a CU (CP and UP) that interacts with the 5GC and then one or more DUs that manage other IAB nodes in a hierarchical structure. The DU of each IAB-node or IAB-Donor can either provide backhaul connectivity to other child IAB-nodes (through the corresponding Mobile Termination, MT) or indirect connectivity to UEs. When introduced in Rel. 16, one of the requirements for IABs was that of allowing connectivity to legacy NR UEs; as such, the UEs connected to an IAB-node/Donor do not experience any difference compared to connecting to a regular gNB. Thus, all the access related protocols (*i.e.*, up to RLC) were retained in the IAB protocol stack. The F1 interface supports the multi-hop backhaul between the IAB-node DU and the IAB-Donor CU, while communications on the upper layers (PDCP and above) are established between the IAB-Donor CU and the UE.

It is worthwhile highlighting that each IAB DU: i) can be connected to multiple IAB-nodes, in particular to their MT; and/or ii) can be connected to UEs via the NR-Uu Air Interface.

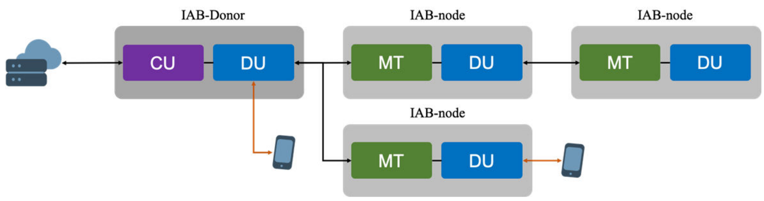


Figure 15: Hierarchical RAN structure based on IAB nodes.

Based on the above observations, and considering both transparent and regenerative payloads, there are several implementations of IAB-based NTN networks. When assuming a transparent NTN payload, there are two possible applications: i) the NTN payload connects the IAB-Donor and its child IAB-nodes; and ii) the NTN payload connects the 5GC and one or more IAB-Donors. Figure 16 shows the former scenario, *i.e.*, the NTN payload provides connectivity between IAB-Donors and child IAB-nodes. One of the most interesting benefits to the system flexibility brought by the implementation of IAB-based access via NTN is that the NTN payload can both provide connectivity to the UEs and provide backhaul connectivity between the IAB-Donor and the IAB-nodes. The former case has been addressed in the above discussions /with the only exception being the need for the Backhaul Adaptation Protocol on-board, discussed below) and, thus, in the following we focus on indirect access, if not otherwise specified. It is worthwhile mentioning that access solutions based on IAB nodes have not yet been addressed in 3GPP; as such, the possibility to have both direct and indirect access through the IAB might be deprioritised, while considering only indirect options. Such 3GPP standardisation aspects will be monitored during the lifetime of 5G-STARDUST.

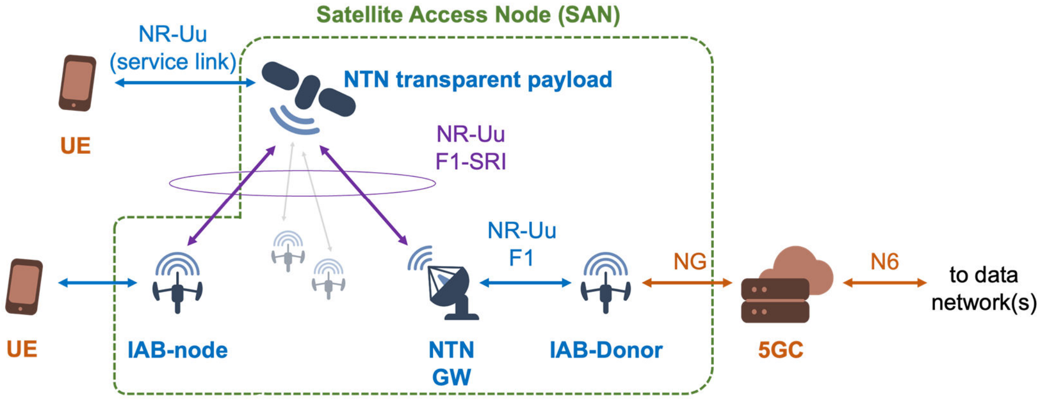


Figure 16: NTN architecture for indirect access with transparent payload: backhaul to the IAB-Donor.

It shall be noticed, as also reported in the protocol stacks in Figure 17 and Figure 18, that the IAB-node provides RLC connectivity for UE access in the DU, while also implementing backhaul RLC channels (BH RLC) over NR-Uu interfaces that support full RLC functionalities on each hop in the MT. In particular, in addition to PHY, MAC, and RLC, these channels also carry the Backhaul Adaptation Protocol (BAP), which enables efficient IP forwarding across the multi-hop topology. The BAP supports the F1 protocol stack on both the CP and the UP. The BAP is specified in 3GPP TS 38.340, [16].

Figure 19 shows an architecture with a transparent NTN payload providing backhaul connectivity between the IAB-Donor and the 5GC. In this case, both the feeder and user links shall implement the NG Air Interface to support the connectivity between the IAB-Donor and the UPF (AMF) on the UP (CP). It is also worthwhile highlighting that, in this case, no direct access can be provided via NTN and only the backhaul implementation is possible.

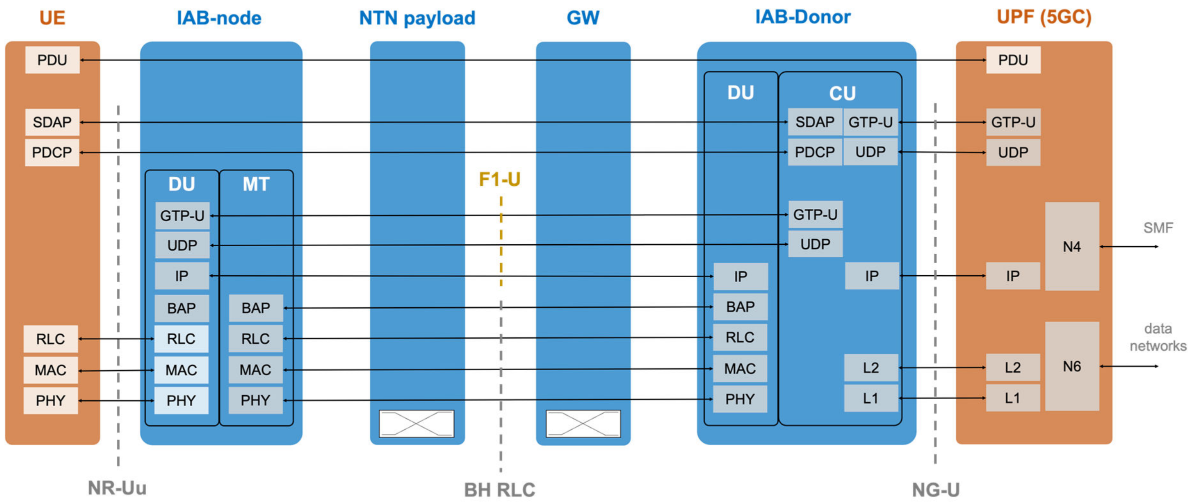


Figure 17: UP protocol stack: NTN architecture for indirect access with transparent payload, with backhaul to the IAB-Donor.

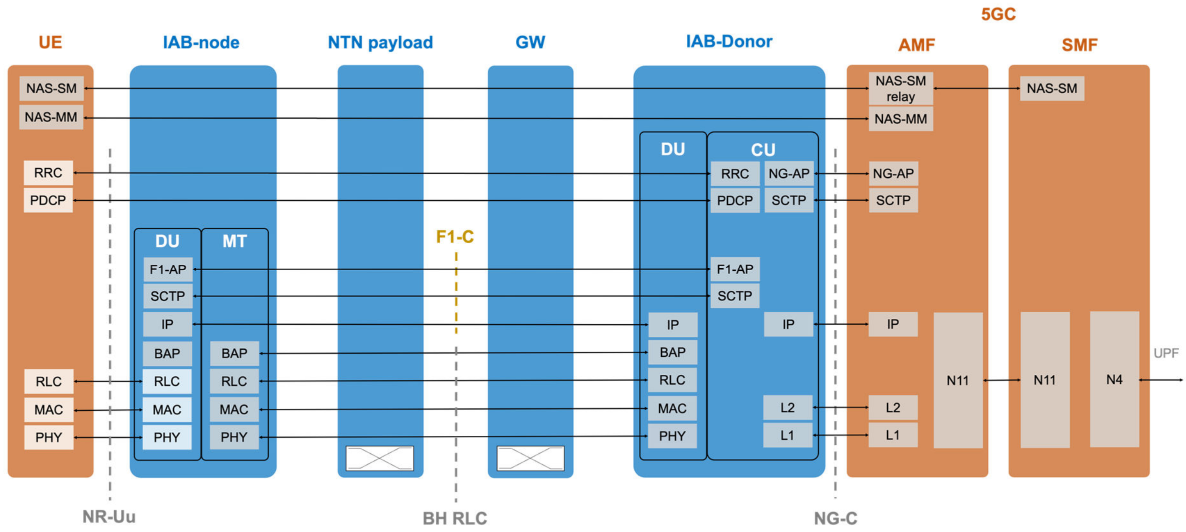


Figure 18: CP protocol stack: NTN architecture for indirect access with transparent payload, with backhaul to the IAB-Donor.

Figure 19 shows the architecture with the transparent NTN payload providing backhaul connectivity between the IAB-Donor and the 5GC, which thus requires the NG interface on both the user and feeder links.

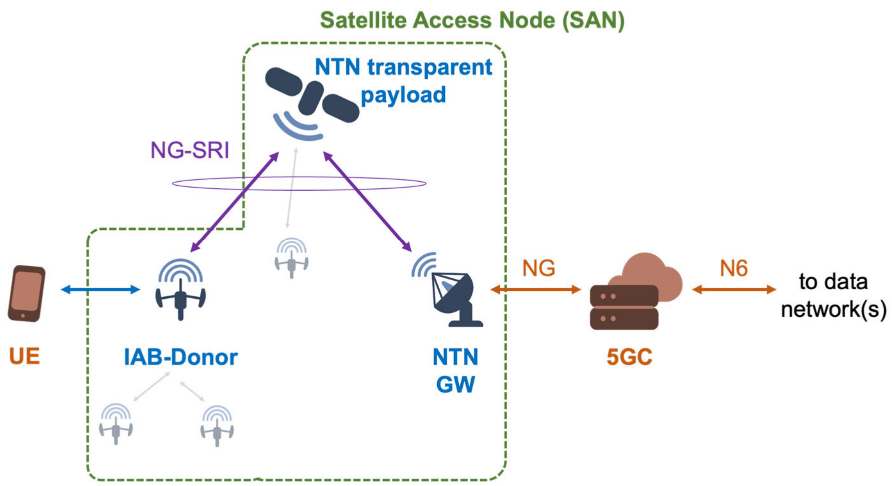


Figure 19: NTN architecture for indirect access with transparent payload: backhaul to the 5GC.

When considering regenerative NTN payloads, either an IAB-node or an IAB-Donor can be implemented on-board; moreover, if functional split is implemented at the IAB-Donor, it is also possible to only implement the IAB-Donor DU on the payload, while leaving the CU on-ground. These two scenarios are reported in Figure 20 and Figure 23, respectively. It shall be noticed that, when considering functional split at the IAB-Donor, the CP and UP connections are implemented over the N2 and N3 interfaces, respectively.

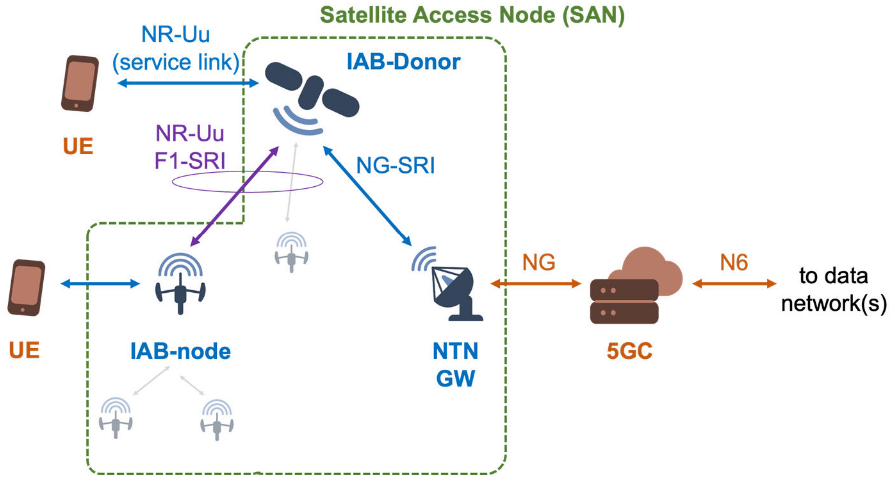


Figure 20: NTN architecture for indirect access with regenerative payload: full IAB-Donor on-board.

When the full IAB-Donor is implemented on-board, SRIs shall support both the BAP and RLC communications between the IAB-Donor and the IAB-nodes on the user link and the NG interface on the feeder link. All layers and interfaces carried over SRI shall be not impacted by the NTN links, apart from the possible need to extend the timers of specific procedures to accommodate the extended latencies. The UP and CP protocol stacks in this scenario are reported in Figure 21 and Figure 22, respectively.

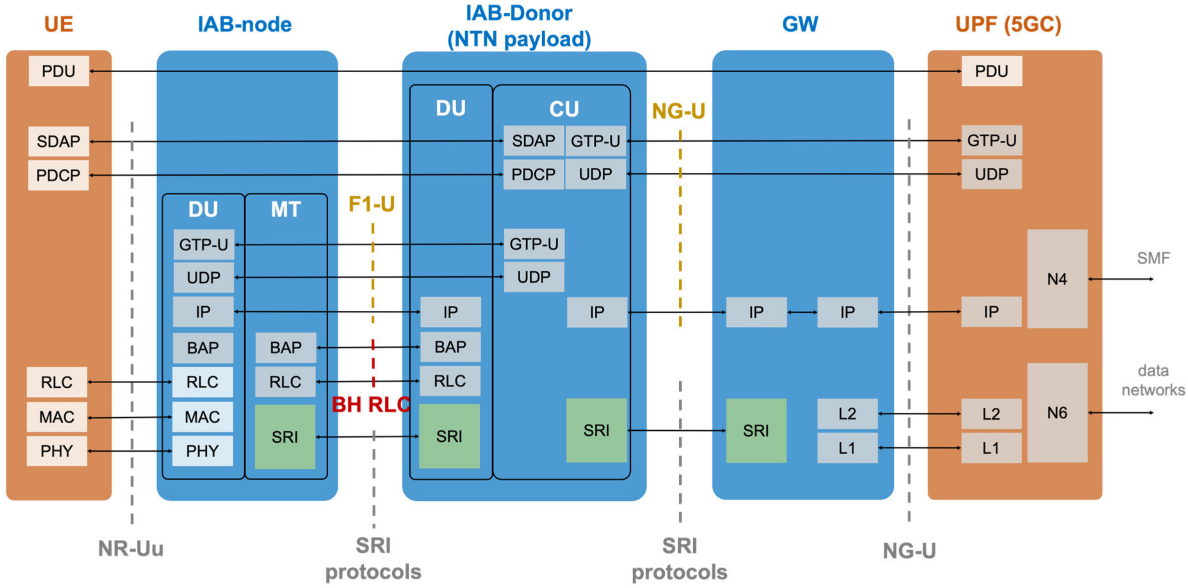


Figure 21: UP protocol stack: NTN architecture for indirect access with regenerative payload, with full IAB-Donor on-board.

When considering the IAB-Donor DU on-board, for which the protocol stack is shown in Figure 24 and Figure 25, respectively, the considerations and interfaces on the user link are the same. The only difference is on the feeder link, where the communications between the IAB-Donor DU and CU on the CP/UP shall be supported through the F1-C/F1-U interfaces.

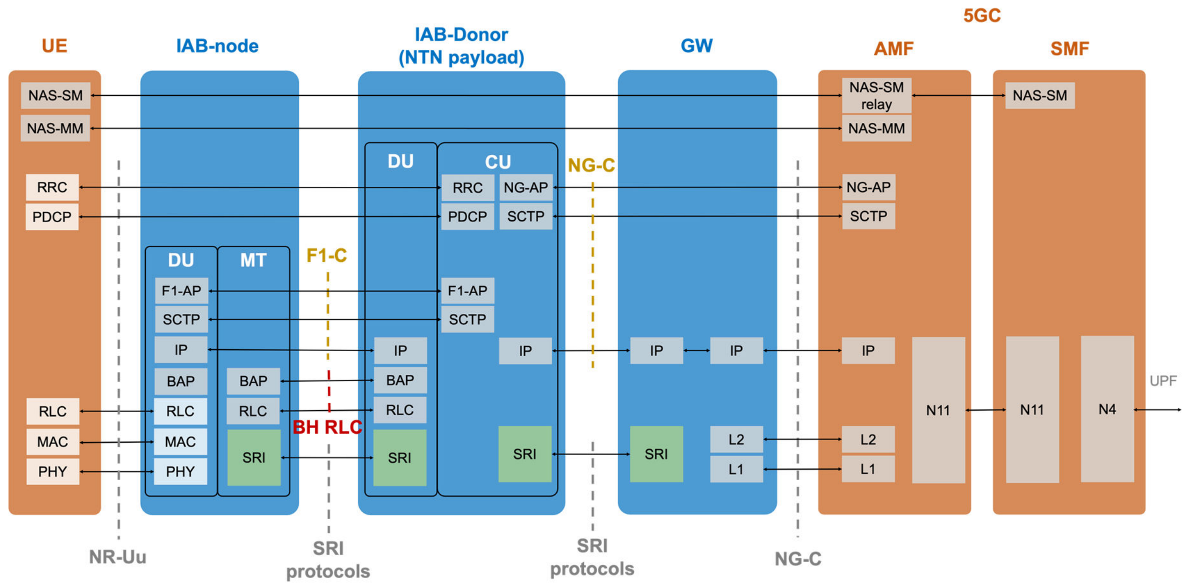


Figure 22: CP protocol stack: NTN architecture for indirect access with regenerative payload, with full IAB-Donor on-board.

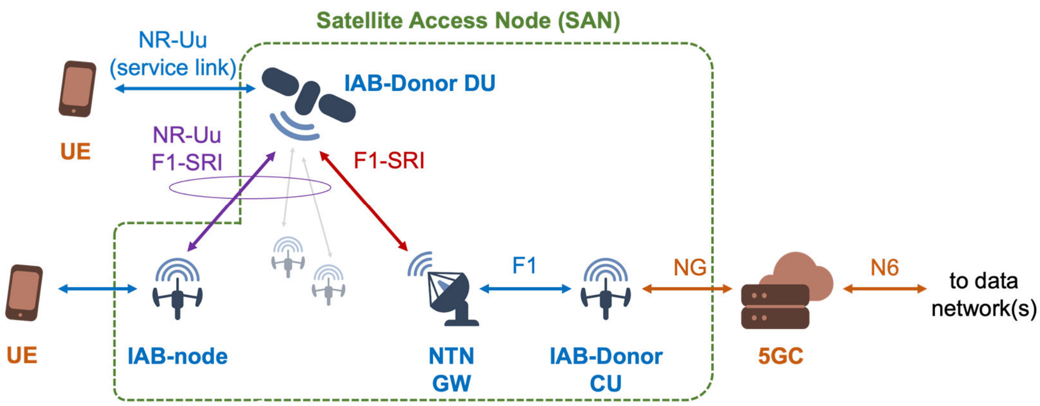


Figure 23: NTN architecture for indirect access with regenerative payload: IAB-Donor DU on-board.

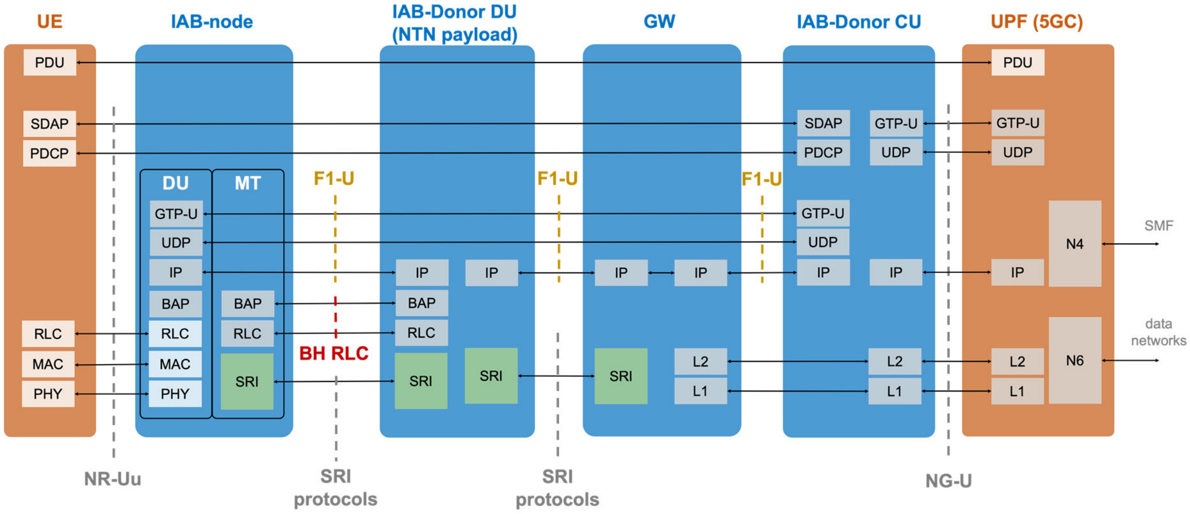


Figure 24: UP protocol stack: NTN architecture for indirect access with regenerative payload, with IAB-Donor DU on-board.

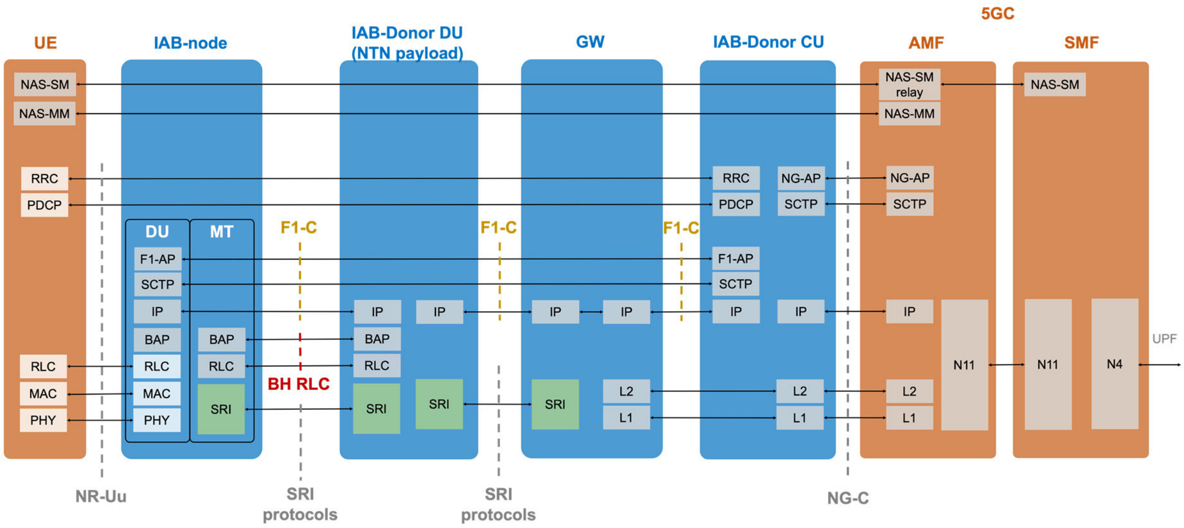


Figure 25: CP protocol stack: NTN architecture for indirect access with regenerative payload, with IAB-Donor DU on-board.

With respect to the indirect access solutions discussed above, the possibility of exploiting ISLs between the IAB-Donor and the IAB-nodes has not been addressed. However, considering that the F1 interface is open and logical, it can be expected that no major challenge prevents such applications. The functions handled by the F1 interface are reported in Section 1.4.1.3.

1.1.2.3 Multi-Connectivity solutions

3GPP analysed the implementation of Multi-Connectivity, and in particular Dual Connectivity, to simultaneously transmit PDU sessions to the same UE over multiple SAN/RAN nodes, but it was decided to not include it in Rel. 17. Further analyses are being carried out in the framework of Rel. 18 and it is expected that at most by Rel. 19 (*i.e.*, in any case for 5G-Advanced) this technology will be allowed.

In principle, MC including a NT component can be implemented between TN and NTN or between NTN and NTN nodes; moreover, considering NTN nodes, they can be either transparent (*i.e.*, MC operations managed between on-ground gNBs) or regenerative (*i.e.*, MC operations managed between on-board gNBs).

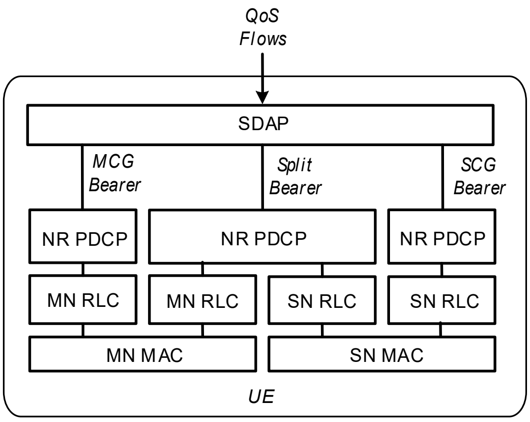


Figure 26: Radio protocol architecture for MCG, SCG, and split bearers for the UE in NR-MC, [17].

Figure 26 shows the UE radio protocol architecture for Master Cell Group (MCG), Secondary Cell Group (SCG), and split bearers; Figure 27 reports the protocol terminations at the network side for the same bearers. In principle, with MSG (SCG) bearers, the RLC bearers are located exclusively in the MSG (SCG); in this case, from the SCG (MCG), the Xn interface allows to interact with the MCG (SCG) RLC protocol. With split bearers, the RLC bearer for the UE is located in both the Master Node (MN) and Secondary Node (SN). From a network architecture point of view, it shall be noticed that: i) MN terminated bearers refer to implementations in which the UP protocols are terminated in the MN; and ii) SN terminated bearers refer to implementations in which the UP protocols are terminated in the SN. However, for both MN and SN terminated bearers, all three split options (MCG, SCG, split bearers) are possible, as they indicate which resources are involved to carry the UP data over the NR-Uu interface, *i.e.*, MN only, SN only, or both MN and SN, respectively. From a control plane perspective:

- one of the two network nodes serving the UE acts as MN, *i.e.*, the access node that terminates the CP connection with the 5GC and provides primary radio resources via the MCG under its control;
- the other node acts as SN, *i.e.*, an access node with no CP connection to the 5GC (and with or without a UP connection to the 5GC) providing additional radio resources to the UE via the SCG.

It is also worthwhile highlighting that the MN and SN are logical network nodes, *i.e.*, they can be located in different entities or in separate ones, and they exchange CP/UP information through the Xn interface.

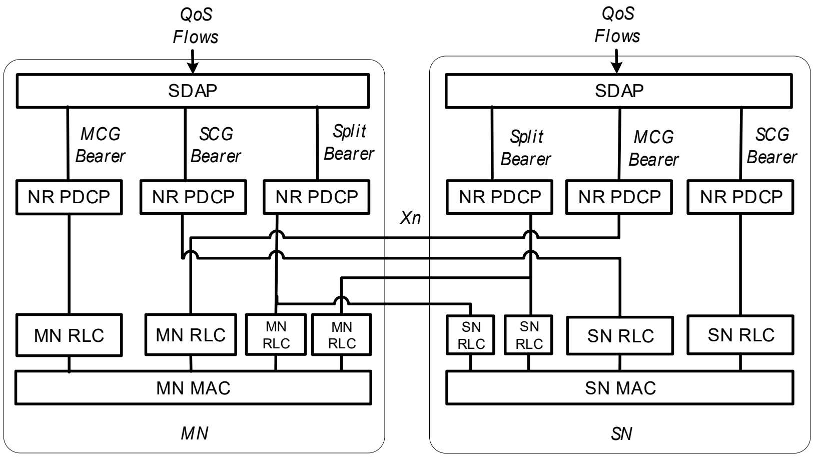


Figure 27: Network side protocol termination options for MCG, SCG and split bearers in NR-MC, [17].

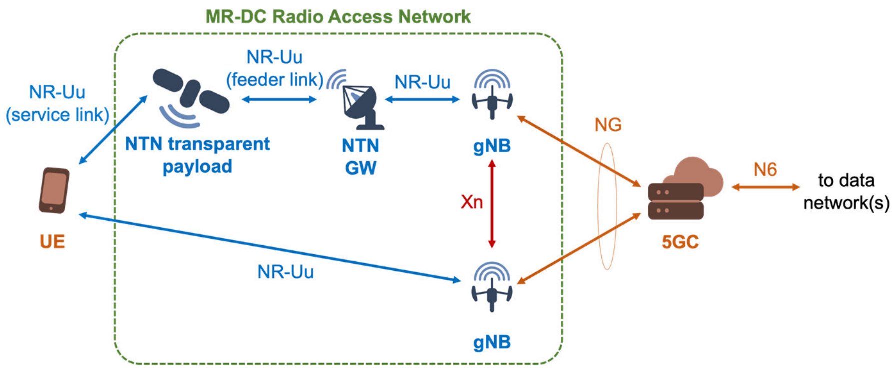


Figure 28: MR-DC architecture between TN and NTN with transparent payload.

Figures from Figure 28 to Figure 33 show the various architecture options for MC in 5G involving at least one NTN node, which have been initially introduced in TR 38.821, [4]. When considering two nodes, it is referred to as Multi-Radio Dual Connectivity (MR-DC). The following aspects are worth mentioning:

- with TN-NTN MC, both the NTN and the TN gNB (gNB-CU) can be elected as MN;
- with NTN-NTN MC, the two satellites do not necessarily need to belong to the same orbit, *i.e.*, one can be a GEO satellite and the other can be a LEO or HAPS. This application can be of interest to provide latency-sensitive services through the lower orbit node and large throughput service through GEO;
- the scenario with TN-NTN MC and full gNB on-board is particularly challenging and, for the moment being, not yet addressed within 3GPP. This is motivated by the need to transport the Xn protocols over the feeder link;
- scenarios involving TN-NTN MC typically require smart adjustments of the F1 and/or NG timers, in order to compensate the (significantly) different latencies on the terrestrial and non-terrestrial links.

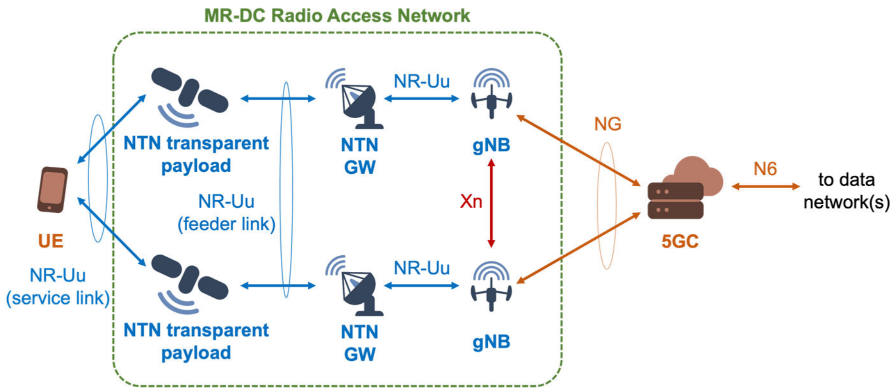


Figure 29: MR-DC architecture between NTN and NTN with transparent payload.

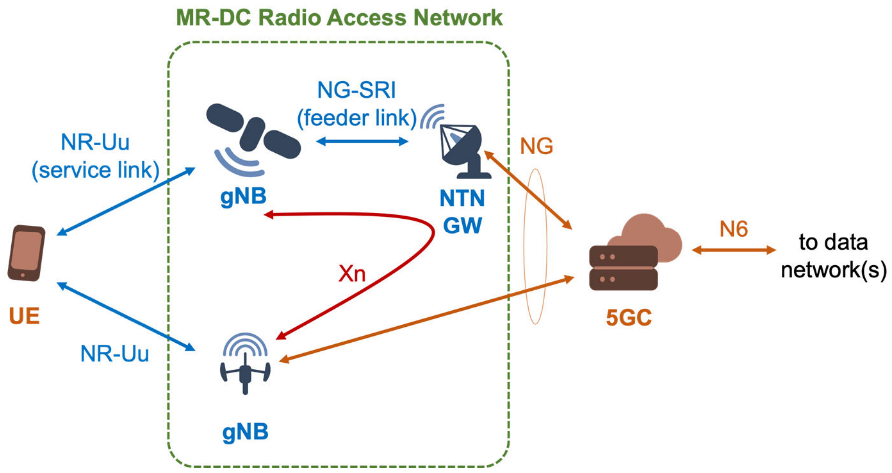


Figure 30: MR-DC architecture between TN and NTN with regenerative payload: full gNB on-board.

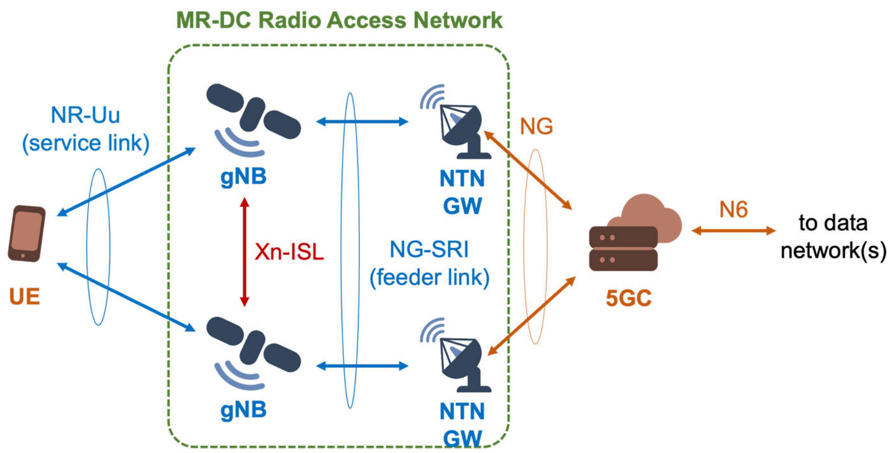


Figure 31: MR-DC architecture between NTN and NTN with regenerative payload: full gNB on-board.

It is worthwhile highlighting that, with MC, we are denoting the interface between gNBs as Xn-ISL, while previously we indicated an Xn-SRI for scenarios involving ISLs. While the interface is always the same, it was deemed useful to differentiate the two cases. On the one hand, with ISLs, the SRI shall support the first 3 layers in the protocol architecture; on the other hand, with MC (see Table 2) there might be need to implement more functionalities, depending on the specific type of multi-connectivity to be implemented.

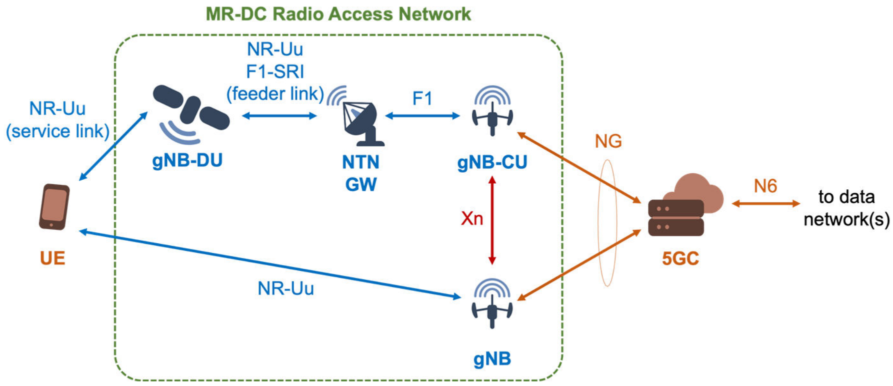


Figure 32: MR-DC architecture between TN and NTN with regenerative payload: gNB-DU on-board.

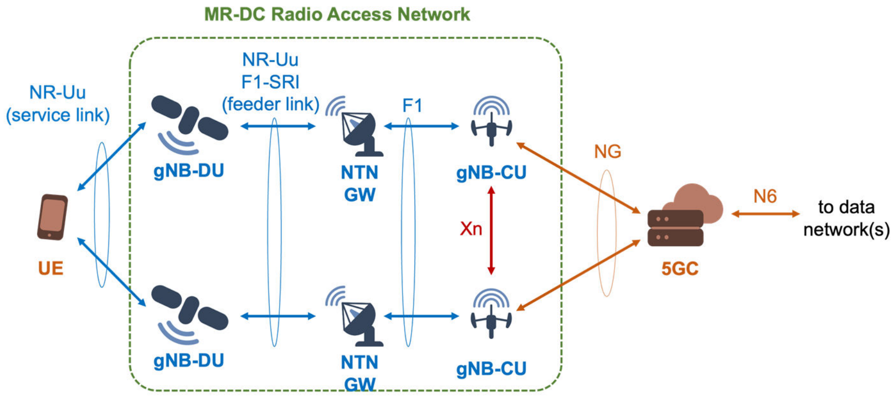


Figure 33: MR-DC architecture between NTN and NTN with regenerative payload: gNB-DU on-board.

Finally, it is worthwhile highlighting that TS 37.340 clearly states that all functions that are specified for a UE can be also used for the MT of an IAB, *i.e.*, the IAB-MT can access the node exploiting MC principles and architectures.

Table 2 provides a comprehensive overview of the different MC options based on the anchor layer, *i.e.*, the layer at which the information flows are aggregated, and the related technical specifications, main objectives, and limitations. In general, the solutions described above can be classified as Dual Connectivity (DC) and Multi-Radio DC (MR-DC) when involving two NTN nodes and one NTN and one TN node, respectively. Please note that this table refers to MC in general, *i.e.*, not only for NTN.

Table 2. Summary of MC options, specifications, objectives, and limitations.

Anchor layer	Standardised solution	Technical specification	Objective	Main limitations
PHY	CoMP	TS 36.300	SINR improvement	Tight coordination between the transmission points, leading to difficulties in achieving coherent signal reception
	Multi-TRP	TS 38.300		
MAC	NR-U CA	TS 38.331	Fast system adaptation in case of link failures	Complex packet scheduler
PDCP	DC	TS 36.300	Higher data reliability Higher throughput	Requires additional hardware and software capabilities at the UE
	MR-DC	TS 37.340		
	LWA	TS 36.300	Higher throughput	Aggregation limited to LTE and Wi-Fi controlled by the MNO
	NR-U DC	TS 38.331	Higher throughput	Requires additional hardware and software capabilities at the
	DAPS	TS 38.300	Mobility robustness	Currently available between 5G BSs
Network	LWIP	TS 36.300	Deployment affordability	Traffic offload limited to LTE and Wi-Fi
Transport (E2E)	MPTCP	RFC 8684	Higher throughput Deployment affordability	MC operations are not in the control of the MNO MC operations limited to TCP-based traffic
Transport (5GC)	ATSSS	TS 24.193	Higher throughput Higher data reliability	MC operations limited to TCP-based traffic
Other	**DSDS / DSDA (Dual SIM Dual Standby / Active)**	**TR 22.834 TR 23.761 GSMA requirements for Multi SIM Devices**	**Higher flexibility for the user Redundancy through Back-up Network Controlled roaming costs Professional / Private usage with the same smartphone**	**3GPP mostly covers paging issues. Network switching is mostly proprietary, implying lack of interoperability, performance depends of smartphone, etc. Optimized network switching possible on a case-by-case basis (ex: geolocalization / geofencing, sharing network information on neighboring cells, info from external sensors, etc. Manual or Automated switching, and its triggering generally depends on spectrum scanning (proprietary procedure, +/- every 6min), quite long service interruption (5-**

				10sec to some minutes) **2IMSI with 2 different security keys**

1.1.2.4 NTN architecture summary

In Table 3, we summarise the architectures discussed above and classify them based on the potential benefits in terms of latency reduction, capacity enhancement, support of legacy (pre-Rel. 17) UE terminals, and payload complexity. In addition, we also report the expected 3GPP Release in which the specifications supporting the considered architecture might be finalised. Such classification is based on the following observations:

- in terms of latency, the best solutions are those in which the termination of the communication protocols is closer to the users. Thus, solutions with full gNB (or IAB-Donor) on-board are the best option, followed by architectures in which only the DU is on-board. Notably, depending on the functional split, there might be more protocols terminated on-board, which make this solution more similar to the full gNB on-board case. With respect to transparent payloads, everything is operated and terminated on-ground and, thus, they lead to the largest latency. It shall be noticed that, clearly, latency is also impacted by the NTN node altitude and the number, if any, of ISL hops (*e.g.*, a transparent LEO payload has a reduced latency compared to a regenerative GEO payload). The above observations hold for NTN nodes at the same altitude and without ISL links and the objective is that of understanding how a specific architecture might be able to contribute to a latency reduction: the actual reduction, if any, can be defined only based on the thorough design of the system architecture;

- in terms of capacity, MC solutions are the best option with both regenerative and transparent payloads; then, regenerative payloads can support the implementation of further advanced technologies (*e.g.*, Cell-Free MIMO) that shall be designed to improve the overall capacity. A transparent payload without MC solutions is not expected to yield any potential improvement to the system capacity compared to terrestrial NR systems. With respect to legacy NTN systems, the comparison with NR-NTN is currently ongoing in the framework of the ETSI SES-SCN Work Item on "Comparison of DVB-S2X/RCS2 and 3GPP 5G-NR NTN-based systems for broadband satellite communication systems";

- from a terminal perspective, two aspects shall be considered: i) adaptations to legacy TN handsets; and ii) adaptations to legacy NTN VSAT terminals. With respect to the former, the only possibility to use existing handset terminals is provided by indirect access through IAB nodes (*i.e.*, IAB-based architectures in which the on-board IAB, if any, does not directly serve UEs); all other options require some adaptations to the terminals so as to connect to the NTN node(s). With respect to VSATs: i) the use of regenerative payloads does not impact the terminal (some of the protocols are terminated on-board, but this is transparent to the terminal); ii) when providing connectivity to IAB nodes, a regular VSAT can also be considered as it will connect either to a regenerative or a transparent payload, but no additional capabilities are foreseen at this stage; iii) when considering MC solutions, the terminal needs to be capable of generating at least two beams by means of antenna arrays. With MC, it shall also be mentioned that different frequency bands might be required for the MC signals, adding computational complexity in the terminal;

- finally, in terms of payload complexity, regenerative solutions with the full gNB on-board are the most demanding. Partially regenerative solutions, which include the gNB-DU or IAB (node or Donor) on-board pose intermediate challenges, while transparent payloads clearly are the less demanding for the payload. The on-board IAB node or Donor is not considered as demanding as a full gNB on-board since their complexity is lower.

Table 3: Summary of the main characteristics of the considered NTN architectures (green: high; yellow: medium; red: low).

Category	#	Payload	Connectivity *(D: direct; I: indirect)*	Served entity	ISL	Latency	Capacity	Adaptations to handset	Adaptations to VSATs	Payload complexity	Expected Release
Regenerative	1a	gNB	D	UE	Y						Rel. 19
	1b	gNB-DU	D	UE	Y						Rel. 19
IAB	2a	T	I	IAB-node	N						Rel. 19-20
	2b	T	I	IAB-Donor	N						Rel. 19-20
	2c	IAB-Donor	I	IAB-node	Y						Rel. 19-20
	2d	IAB-Donor DU	I	IAB-node	Y						Rel. 19-20
MC	3a (NTN-TN)	gNB	D	UE	Y						Rel. 19
	3b (NTN-NTN)	gNB	D	UE	Y						Rel. 19
	3c (NTN-NT)	gNB-DU	D	UE	Y						Rel. 19
	3d (NTN-NTN)	gNB-DU	D	UE	Y						Rel. 19
	3e (NTN-TN)	T	D	UE	N						Rel. 18
	3f (NTN-NTN)	**T**	**D**	**UE**	**N**						**Rel. 18**

1.2 5G CORE NETWORK

In the following section, we will provide an overview of 5G Core Networks. This will cover 5G Core architecture, inter-component communication interfaces, protocol stacks for control and data plane.

1.1.1 5G Service-Based Architecture

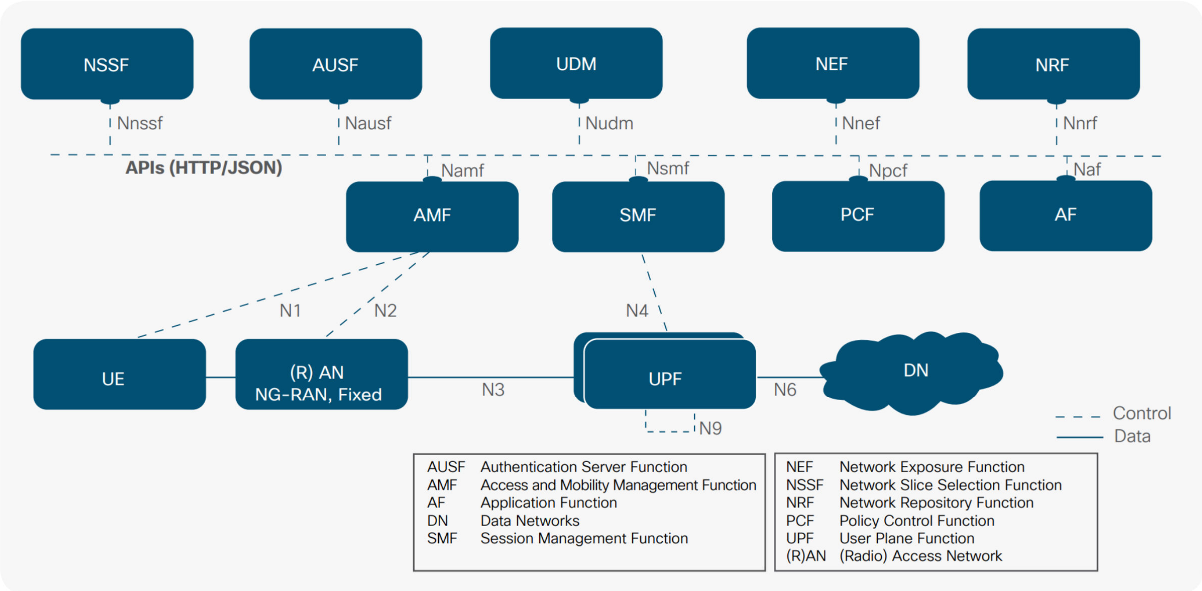


Figure 34: 5G Service-Based Architecture.

The 5G network is implemented based on the concept of NFV and SDN. NFV helps in decoupling the software from the hardware by replacing NF (it is a functional block within a network infrastructure having well-defined external interfaces and functional behaviour) with virtualised software instances. The advantages of virtualising network services by NFV are- cost for purchasing purpose-built hardware can be reduced, flexibility can be delivered by scaling network services up and down based on the demand. SDN is related to NFV conceptually, but they refer to different domains. SDN technology enables dynamic, programmability features in the network configuration for improved network performance. SDN provides on demand network resource allocation and it separates control plane management from the underlying data plane for the network devices. 3GPP defines all the procedures like registration, authentication, security, session management, traffic handling between end devices for 5G core and it also utilizes service-based-architecture for all interactions. Service-based interfaces in 5G will use HTTP/2 over Transmission Control Protocol (TCP). Figure 34, shows service-based 5G architecture.

Service-Oriented Architecture (SOA) is a style of software design where services are provided to the other components by application components, through a communication protocol over a network. A service is a discrete unit of functionality which is accessed remotely and can be used or updated independently, [20]. SOA allows to break down functions of different components in services and because of modularity, the management of services becomes more flexible. Service-oriented architecture works in two ways mentioned below, which is also shown in Figure 35.

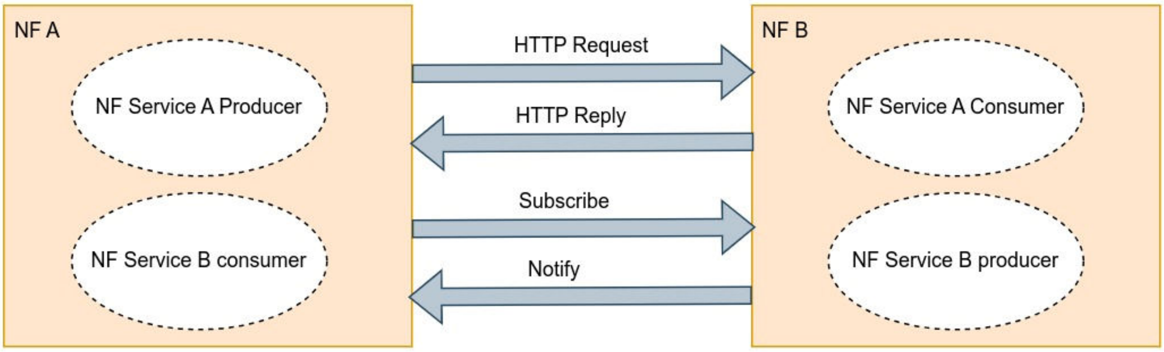


Figure 35: Service-Based Interface

- Request-Reply: This is typically used when a consumer of a service wants to interact with the producer of the service.
- Subscriber-Notify: This is used when a service consumer wants to get notification about changes or events happening asynchronously at the producer's service.

The 3GPP 5G system consists of the 5G Access Network (AN), which comprising of a Next Generation-RAN (NG-RAN) and/or non-3GPP AN that connects to a 5G Core Network. The 5G core network connects to access network and the UE. The core network has different network functions. A brief about few of the core components which are directly connected to the thesis, NG-RAN and about the protocols used in 5G architecture will be discussed here in the next subsections.

1.1.2 5G Core

It is the implementation of new 5G components evolved from the Evolved Packet Core (EPC). Classic 5G architecture with the interfaces between the components is shown in Figure 36. The functionalities of the components are discussed below.

AMF: In 5G, the 4G Mobility Management Entity (MME) is decomposed into two network functions. The Access and Mobility Management Function receives all connection and session related information from the UE, but it handles only connection and mobility management tasks for the UEs. Whereas the messages regarding the session management are forwarded to the Session Management Function over N11 interface. The primary tasks for AMF are Registration Management, Connection Management, Reachability Management, Mobility Management, Transport for Session Management messages to SMF, Access Authentication, Access Authorization, handling AMF events and various functions related to security management, [5].

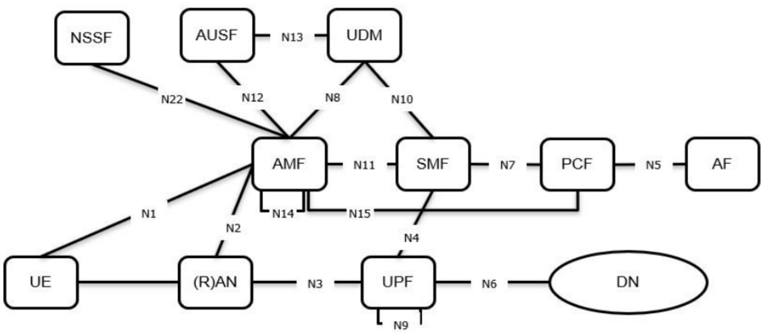


Figure 36: The 5G Classic Architecture.

During the Registration, Protocol Data Unit (PDU) Session Establishment, De-registration procedures the UE sends a Non-Access Stratum (NAS) message (containing the encrypted identifier, protocol discriminator, registration type etc) to the gNB (RAN). The RAN encapsulates the NAS message in Next Generation Application Protocol (NGAP) to send to the AMF over N2 interface and AMF takes care of further actions based on the events. It also stores the MM-state for the UE. In Xn (handover initiated from source to target NG-RAN using Xn interface, core network does not take part in handover preparation phase) and N2 (source NG-RAN initiates handover using N2 interface, core network takes part starting from the preparation phase) based handover also, AMF takes an integral part. In a network, handover is the most frequent operation among all, which keeps the network busy and increase the load in the network. Another important event in the core network is paging. If the UE is in IDLE state due to no ongoing data transmissions and if new data comes into one of the data bearers, the network initiates the paging message for the device. AMF determines the whole policy for the paging and takes necessary actions. SMF Session Management Function is an important part of 5G service-based architecture. It interacts with the decoupled data plane, by managing all the PDU sessions related functionalities like establishment, modifications, release in association with UPF, [5]. The connectivity service in 5G is named as PDU Session. A PDU session is made by a sequence of Next Generation (NG) tunnels in 5GC, and of one or more radio bearers on the radio interface. A sequence of NG tunnels in 5G core and multiple radio bearers on the radio interface, together makes a PDU session. PDU is very similar to Evolved Packet System (EPS) bearer in LTE.

AMF sends messages over the N11 interface to SMF. Based on the message, SMF takes action to add, modify or delete a PDU session across the user plane. The SMF uses Packet Forwarding Control Protocol (PFCP) to interact with the UPF over the N4 interface. SMF also interacts with the UDM over N10 interface (which is the replacement of Home Subscriber Server (HSS) in 4G EPC) and allocates IP (Internet Protocol) addresses to the UEs for PDU sessions. It also maintains the SM state of the PDU sessions with their PDU session IDs. User plane functions are also selected and controlled by the SMF. It configures traffic steering parameters for UPF and handles the routing of packets ensuring the incoming packets delivery through Downlink data notification (same as message from SGW to MME in 4G EPC). SMF also interacts with the Policy Control Function over the N7 interface while creating and modifying the PDU sessions.

AUSF: Authentication Server Function works as the front-end for the UDM to execute the authentication properly. For the UE registration, AMF sends authentication request message to the AUSF over N12 interface. The AUSF then talks to UDM over N13 interface and obtains UE authentication information from UDM. Based on the type of the authentication whether it is 5G-AKA (Authentication and Key Agreement) or EAP-AKA’ (Extensible Authentication Protocol-AKA’), AUSF generates the challenge message and send back to AMF as response. It also generates master keys which are used by the AMF to derive subsequent keys for the authentication procedure. The authentication procedure can also be used to recover from synchronization failure situations.

UDM: Unified Data Management in 5G has a front end, which is AUSF and a User Data Repository. UDR stores subscriber information and also policy profiles for PCF. The main functionalities of UDM are Authentication credential processing, User identification handling, Access Authorization, Registration/mobility management, Subscription management. For the authentication procedure AUSF uses the user profiles stored in the UDM.

UPF: User Plane Functions are responsible for data plane functionalities of 5G system, [5]. PFCP protocol is used for communication between the control and user plane functions. UPF handles the routing and forwarding of packets coming from UEs to the data network or to another UPF (in case, it is in chained topology). It works as the interconnect point between the core and the data network. It also performs packet inspection and enforce user plane policies like Gating (restricting traffic), Redirection (directing to some default route), Traffic steering (sorting network traffic based on predefined match conditions and steers them as per defined traffic steering behaviour). UPF acts as the anchor point for PDU session to provide mobility within and between RATs. It also acts as the lawful intercept collector interface in the network for subscribers, [21].

UPF also takes care of the QoS handling for user plane, which includes Uplink (UL)/Downlink (DL) rate enforcement, rate limiting, reflective QoS marking in DL and also transport level packet marking in the uplink and downlink traffic. UPF detects user plane traffic flow depending on the information indicated by the SMF, *e.g.*, for IPv4 (Internet Protocol Version 4) or IPv6 (Internet Protocol Version 6) PDU Session type information are PDU session, QoS Flow ID (QFI) and Application Identifier, which is an index to a set of application detection rules configured in UPF.

NRF: Network Repository Function (NRF) in the 5G Core Network (5GC) maintains the profiles of all available NF instances and their supported services. All the NF instances register their NF profiles in the NRF. The NRF makes them available to be discovered by other NFs. If it receives NF discovery requests from NF instances, NRF replies with the information of the NF instances based on the criteria. NF instances can subscribe to the NRF so that they can be notified against registration of new NF instances for a given type, [22].

PCF: Policy Control Function (PCF) in 5G has the same functionalities as PCRF in LTE network. It enforces policy rules for control plane functions which includes mobility and roaming management, network slicing. PCF accesses subscriber information from the UDR to take policy decisions.

1.1.3 Protocols in 5G

The protocols that are used for the communication between the components in 5G core are as follows.

NAS-5G: The Non-Access Stratum is a set of protocols used for EPS. For 5G also NAS is used as the highest stratum in the control plane. Messages for procedures initiated by the UE, like registration, PDU connection, deregistration are encoded as per the NAS specification defined by 3GPP and transferred to RAN(gNodeB). NAS messages are then encapsulated in NG messages and relayed by the gNodeB to the AMF. NAS procedures in 5G are grouped into two categories- 5G Mobility Management (5GMM) and 5G Session Management (5GSM), [23]. UE can initiate the 5GMM procedures. The registration, authentication, deregistration for all these MM procedures, the message format is defined by the NAS. It also defines state machine for the subscriber. UE can initiate the 5GSM procedures, only if there is a 5GMM context established at the UE. The core can only send the 5GSM message to UE if there is 5GMM context already established in the core. In case of procedures like registration and PDU connection for the UE, where 5GSM message is piggybacked to 5GMM message, the success of the 5GMM procedure is not dependant on the 5GSM procedure. During PDU connection default bearer is set up, with service request multiple dedicated bearers can also be setup for the UE.

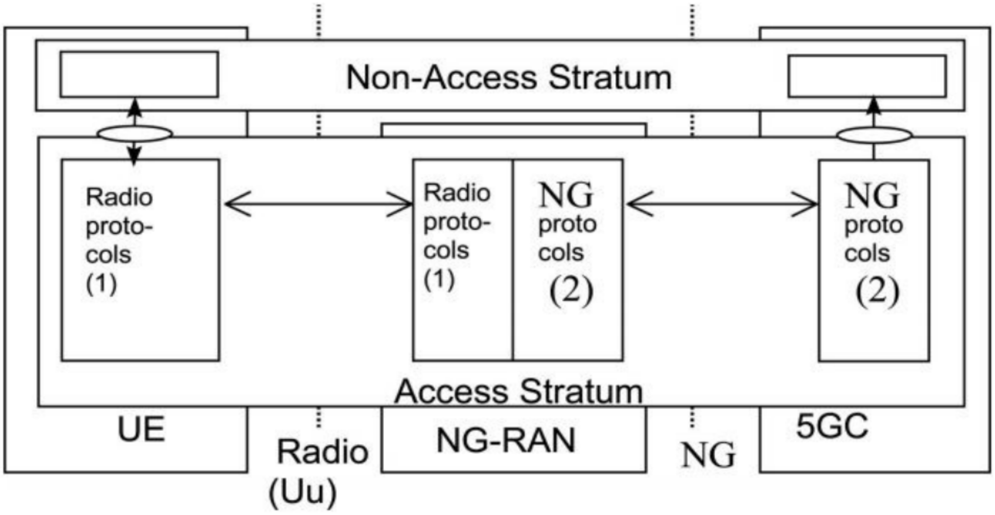


Figure 37: NAS and NGAP in 5G, [25].

NGAP: NGAP consists of Elementary Procedures like interaction between the NG-RAN node and the AMF, [24]. NGAP messages for the procedures are exchanged via SCTP on transport layer. For control plane NG-C is used as the NGAP interface and for user plane the corresponding interface is NG-U. The relation between UE, NG-RAN, 5G core with respect to NAS and NGAP is shown in Figure 37.

NGAP is found in the N2 interface between the gNodeB and AMF to provide signalling services for both UE and non-UE related services. UE-associated services are related to a single UE. Here UE-associated signalling connection is maintained for the UE with the NGAP functions, which are required for the services. This includes operations such as, UE context transfer, PDU session resource management and also support for mobility procedures. Non UE-associated services are related to non UE-associated signalling connection between the NG-RAN node and the AMF. This includes operations as configuration updates for the NG-RAN. Uplink and downlink NAS messages can also be transferred as payloads by NGAP. It also supports CM-IDLE and CM-Connected procedures initiated by the core, such as UE context release and Paging.

PFCP: Packet Forwarding Control Protocol is the standard protocol defined by 3GPP for 4G and 5G for communication between the control and user plane functions. PFCP ensures reliable message delivery. PFCP is similar as OpenFlow, which is a communication protocol to handle the network packets routing across network switch or router over the network. But unlike OpenFlow, PFCP is designed only for the functionalities required to support mobile core networks. PFCP needs association, which is a channel between a Control Plane (CP) and a User Plane (UP) component for communication. With the help of the associations the CP function (like SMF for 5G) and UP functions (*e.g.*, UPF) connected with the CP function, can identify each other. The creation and management of the association and also the communication over it, are handled by PFCP-defined messages. Connected CP and UP nodes are also responsible for Heartbeat procedure to check PFCP peer is alive or not.

PFCP defined sessions are established in the UP function, to provision the UP function how to process a certain traffic. The UPF stores the session information received from the CPF and uses it to make forwarding and tunnelling decisions. The rules used for packet matching, header manipulation, buffering, QoS enforcement and packet forwarding are included in the session. PFCP session can correspond to a single PDU session. From the 5G perspective a PDU-session for a UE (from UE to internet gateway) is translated to a set of PFCP sessions, one per UPF on the path from UE to internet gateway.

HTTP/2: IETF has released HTTP/2 which is an extension of HTTP/1.1. HTTP/1.1 protocol costs too much CPU resources and internet connection capacity. On the other hand, HTTP/2 enables use of network resources more efficiently and also reduces latency, by enabling full request and response multiplexing and minimizing protocol overhead by introducing header field compression. It also supports request prioritization that helps more important requests to complete more quickly, thus improving overall performance. HTTP/2 uses fewer TCP connections compared to HTTP/1.x, that results in less congestion with other flows. Long-lived connection of HTTP/2 leads to better utilization of available network capacity and it also enables more efficient message processing through use of binary message framing. HTTP/2 is more secured and has improved page load times.

The application semantics of HTTP is not modified for HTTP/2. Also, the core concepts like HTTP methods, status codes, header fields all are same. However, the data frame and transportation between the client and server is modified in HTTP/2. The modification takes care of the entire process and hides the complexity from the application with the help of the new framing layer, so existing applications are not affected. It is able to send multiple requests in parallel over a single TCP connection, this is the most advanced and useful feature of HTTP/2, which enhances the overall performance of the procedures.

HTTP/3: is a new update from 2022 of the HTTP protocol which replaces the TCP connectivity with QUIC/UDP enabling a more flexible connectivity at transport layer.

1.3 O-RAN SOLUTIONS

In this section, we review the Open Radio Access Network (O-RAN) specification. The O-RAN architectural concepts, defined embracing and extending 3GPP specifications about NR RAN, are discussed.

1.3.1 Architectural concepts

The O-RAN architecture is based on the principles of: i) disaggregation; ii) virtualization; iii) data-driven RAN control; and iv) open interfaces. These are presented below.

1.3.1.1 Disaggregation

The disaggregation principle extends the functional disaggregation paradigm proposed by 3GPP for the New Radio (NR) gNB, [18], effectively splitting base stations into different functional units. Referring to Figure 34, the gNB is split into a Central Unit (O-CU), a Distributed Unit (O-DU), and a Radio Unit (O-RU), with the CU divided also in the CP and UP.

Thanks to this logical split, different functionalities can be deployed at different network elements and on specialized or general-purpose hardware platforms. Which functionalities are implemented in the different gNB units defines the type of functional split. In O-RAN the selected split is 7.2x. In this case, the RU takes care of the Fast Fourier Transform (FFT) and of the cyclic prefix addition/removal operations. The remaining functions of the physical link are then implemented in the DU, together with the MAC and RLC layers. Finally, all the remaining functions of the 3GPP protocol stack are centralized in the CU, *i.e.*, the RRC, SDAP, and the PDCP.

1.3.1.2 Virtualization

As defined in [19], all the O-RAN architecture components shown in Figure 34 can be deployed as virtualized components on a hybrid cloud computing platform called O-Cloud. This platform specialises the virtualization paradigm of O-RAN combining physical nodes, software components, and management and orchestration functionalities. The virtualization concept enables: i) the decoupling between software and hardware components; ii) the definition of standardized hardware capabilities to use in the O-RAN infrastructure; iii) sharing of the computational capabilities of the hardware; and iv) the automated deployment of the RAN functions on the hardware platforms.

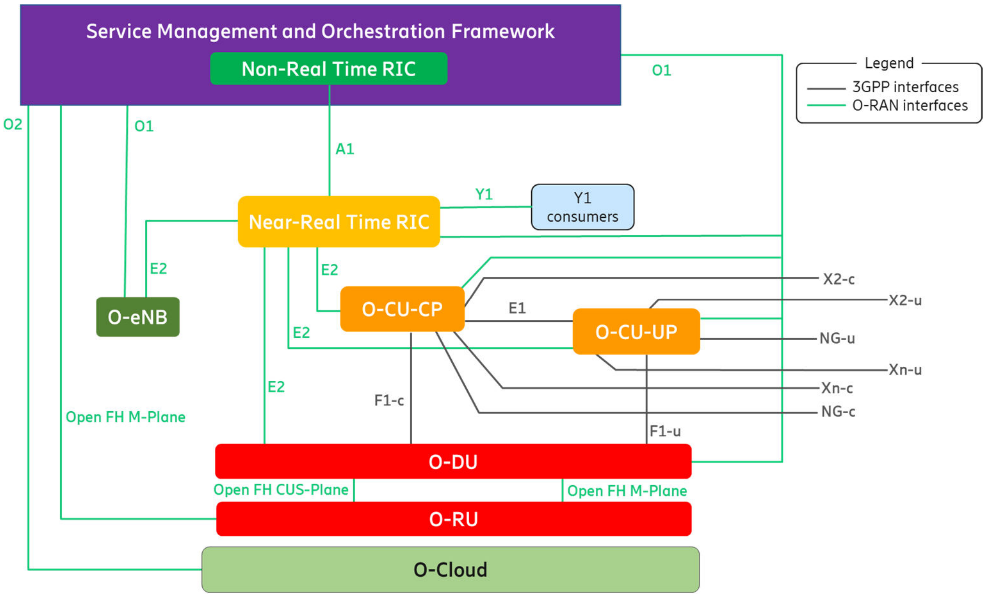


Figure 34: O-RAN architecture (components and interfaces).

1.3.1.3 Open Interfaces

O-RAN introduces technical specifications describing open interfaces connecting different components of the architecture. Figure 34 shows the O-RAN open interfaces interconnecting the architecture components along with the 3GPP defined interfaces. Indeed, O-RAN includes and leverages 3GPP defined interfaces to additionally foster the disaggregation of the RAN. Leveraging open interfaces is possible to deploy the O-RAN architecture described in Figure 34 selecting different network locations for the virtualized components, with multiple possible configurations. An additional benefit of open interfaces is to break the vendor lock-in inside the RAN, fostering market competitiveness, faster components upgrade, and facilitating the introduction of additional virtualized components in the RAN. We will provide a description of each interface in section 1.3.2.

1.3.1.4 Closed-Loop Control

In order to orchestrate the RAN, O-RAN introduces the RAN Intelligent Controllers (RICs). These, thanks to data pipelines that stream the Key Performance Indicators (KPI) of system nodes, have an abstract and centralized point of view on the network. By processing this data and exploiting Artificial Intelligence (AI) and Machine Learning (ML) algorithms, the RICs can optimize and apply the control policies of the RAN in a closed loop. With reference to Figure 35, O-RAN foresees the non Real Time (non-RT) RIC and the near Real Time (near-RT) RIC, differentiated on the role and on the timescale of intervention. The former operates on a time scale longer than 1 s and provides guidance, enrichment information, and management of ML models for the near-RT RIC. The latter consists of multiple applications supporting custom ML models deployed at the edge and operating on a time scale between 10 ms and 1 s. In Figure 35 are highlighted the closed-loop controls on the disaggregated O-RAN infrastructure enabled by the different RICs. Control loops that operate in the real-time domain (below 10 ms) are also included, even if they are not yet included in the current O-RAN architecture and are mentioned for further study. These could be used for Radio Resource Management, beam management, or detection of physical layer parameters.

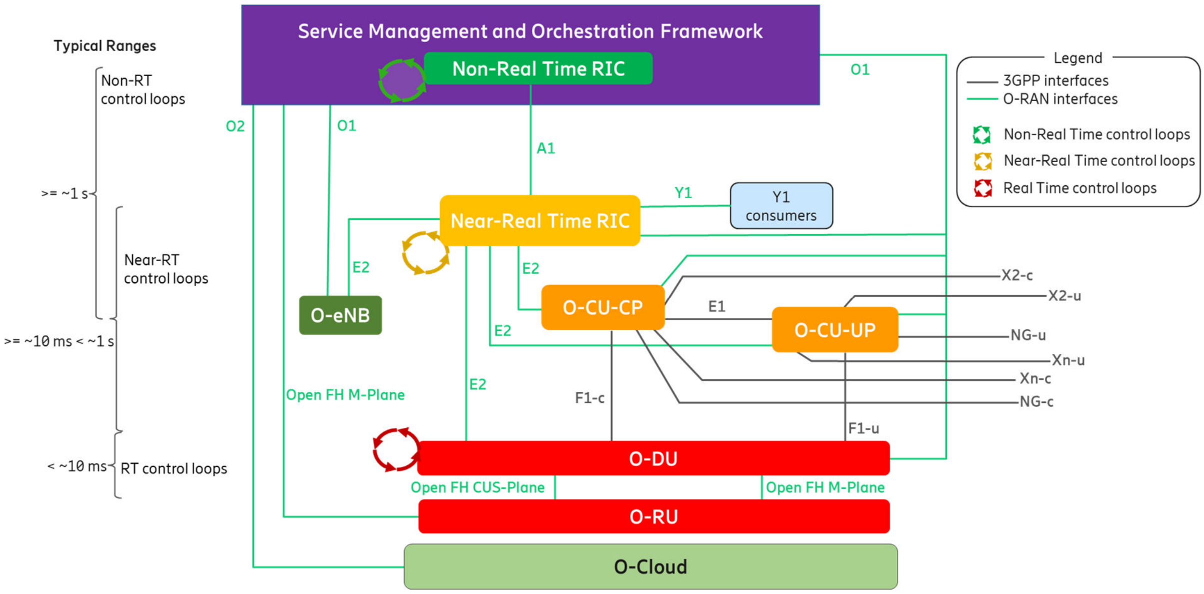


Figure 35: O-RAN Control loops.

1.3.2 O-RAN Open Interfaces

In this section we review the interfaces standardized by the O-RAN Alliance so far, detailing their logical abstractions and procedures. More specifically, the E2, O1, A1, and Fronthaul interfaces are detailed below, together with other O-RAN and 3GPP defined interfaces.

1.3.2.1 E2 Interface

The E2 interface is an open interface interconnecting the near-RT RIC with the E2 nodes, *i.e.*, CUs, DUs, and LTE eNBs designed to be O-RAN compliant. This interface enables the RIC to collect metrics from the RAN components periodically or after trigger events. The metrics can then be used by the RIC to control functionalities and procedures of the E2 nodes. The data collection and control services can have different granularities, *i.e.*, specific UEs, one cell, multiple cells, or QoS classes. The single UE and groups of UEs are identified by the O-RAN Alliance using a variety of unique identifiers. To identify the gNBs, QoS classes, and slices, O-RAN relies on identifiers based on 3GPP specifications, while specific UEs are identified relying on O-RAN introduced user identifier (UE-ID). Each E2 node exposes different capabilities and the services it supports, *i.e.*, different DUs can expose different parameters to be tuned, along with their capability collect specific network metrics. Additionally, the capabilities of each node are clearly separate, and the RIC-RAN interaction is clearly defined relying on a publish-subscribe mechanics.

- E2 Application Protocol (E2AP), [26]. It coordinates the communication between the near-RT RIC and the E2 nodes, and provides a set of services:
  - E2 Setup: is used to establish the E2 interface between the Near-RT RIC and an E2 Node.
  - E2 Reset: is used by either the E2 Node or Near-RT RIC to reset the E2 interface.

- Near-RT RIC Service Update: is used by the E2 Node to inform the Near-RT RIC of any change to the list of supported RIC services and mapping of services to functions within the E2 Node.

- E2 Node configuration update: is used by the E2 Node to inform the Near-RT RIC of any change to the list of supported RIC services and mapping of services to functions within the E2 Node;

- E2 Removal: is used by either the E2 Node or Near-RT RIC to release the E2 signalling connection.

After the connection is established, the following E2AP services can be exploited to implement the E2 service models.

- Report: Near-RT RIC uses a RIC Subscription and/or RIC Subscription Modification procedures to request that E2 Node sends a report message to Near-RT RIC and the associated procedure continues in the E2 Node after each occurrence of a defined RIC Subscription procedure Event Trigger.

- Insert: Near-RT RIC uses a RIC Subscription and/or RIC Subscription Modification procedures to request that E2 Node sends an insert message to Near-RT RIC and suspends the associated procedure in the E2 Node after each occurrence of a defined RIC Subscription procedure Event Trigger.

- Control: Near-RT RIC sends a control message to E2 Node to initiate a new associated procedure or resume a previously suspended associated procedure in the E2 Node.

- Policy: Near-RT RIC uses a RIC Subscription and/or RIC Subscription Modification procedures to request that E2 Node executes a specific policy during functioning of the E2 Node after each occurrence of a defined RIC Subscription procedure Event Trigger.

- Query: Near-RT RIC sends a query message to the E2 node to retrieve RAN-related and/or UE-related information from the E2 Node.

- E2 Service Model (E2SM), [27]: The E2SM is inserted as payload in one of the E2AP messages. The O-RAN Alliance has standardized three service models:

  - E2SM Key Performance Measurement (KPM), [28], reports the RAN performance metrics, exploiting E2 report messages. Precisely, the procedure is as follows: i) in the E2 setup procedures, the metrics exposed by the E2 nodes are advertised; ii) an xApp in the RIC sends a subscription message indicating which KPMs are of interest; iii) the E2 node streams the selected KPMs trough Indication messages of type Report.

  - E2SM Network Interface (NI), [29], takes the messages received by the E2 node on the network interfaces and delivers them to the near-RT RIC exploiting the E2 report messages. The E2 node advertises which interfaces it supports during the subscription procedure, and they include X2 (which connects LTE eNBs), Xn (which connects different NR gNBs), and F1, which connects DUs and CUs).

  - E2SM Cell Configuration and Control (CCC), [30], controls and re-configure the E2 nodes at a cell or node level, *e.g.*, for the bandwidth part configuration. It relies primarily on E2 report and control messages. The technical specification for CCC, in its current version, specifies the control of the selection of X2 and Xn neighbours, RAN slicing, and parameters related to the bandwidth part and the synchronization signals of a cell.

- E2SM RAN Control (RC) implements control functionalities through E2 control services. Compared to E2SM CCC, it focuses on more granular control (up to the UE or bearer level). It also provides capabilities for UE identification and UE information reporting.

1.3.2.2 O1 Interface

O1, [31], is an open interface that standardizes operations and maintenance practices. It interconnects the O-RAN managed elements (including the near-RT RIC, RAN nodes) to the SMO and the non-RT RIC. O1 interface uses a combination of REST/HTTPS APIs and NETCONF, [32], which is a protocol standardized by the Internet Engineering Task Force (IETF) for the lifecycle management of networked functions.

The O1 interface enables Management Services (MnS) including: i) O-RAN components' life-cycle management; ii) trace collection trough KPI reports and performance assurance; and iii) software and file management. To this aim, this interface connects a MnS provider, *i.e.*, the node managed by the SMO to one MnS consumer, *i.e.*, the SMO.

The defined management services are described below:

- Provisioning Management services: they allow a Provisioning MnS Consumer to configure attributes of managed objects on the Provisioning MnS Provider that modify the Provisioning MnS Provider's capabilities in its role in end-to-end network services and allows a Provisioning MnS Provider to report configuration changes to the Provisioning MnS Consumer. NETCONF is used for the Provisioning Management Services to Create Managed Object Instance, Delete Managed Object Instance, Modify Managed Object Instance Attributes and Read Managed Object Instance Attributes. A REST/HTTPS event is used to notify the Provisioning MnS subscribed Consumers when a configuration change occurs.

- Fault Supervision Management Services: they allow a Fault Supervision MnS Provider to report errors and events to a Fault Supervision MnS Consumer and allows a Fault Supervision MnS Consumer to perform fault supervision operations on the Fault Supervision MnS Provider, such as get alarm list.

- Performance Assurance Management Services: they allow a Performance Assurance MnS Provider to report file-based (bulk) and/or streaming (real time) performance data to a Performance Assurance MnS Consumer and allows a Performance Assurance MnS Consumer to perform performance assurance operations on the Performance Assurance MnS Provider, such as selecting the measurements to be reported and setting the frequency of reporting.

- Trace Management Services: they allow a Trace MnS Provider to report file-based or streaming trace records to the Trace MnS Consumer. Trace Control provides the ability for the Trace Consumer to start a trace session by configuring a Trace Job via the Trace Control IOC or by establishing a trace session that will propagate trace parameters to other trace management providers via signalling. There are multiple levels of trace that can be supported on the provider. The Trace Provider may be configured to support file-based trace reporting or streaming trace reporting.

- File Management Services: they allow a File Management MnS Consumer to request the transfer of files between the File Management MnS Provider and the File Management MnS Consumer.

- Heartbeat Management Services: they allow a Heartbeat MnS Provider to send heartbeats to the Heartbeat MnS Consumer and allow the Heartbeat MnS Consumer to configure the heartbeat services on the Heartbeat MnS Provider.

- PNF Startup and Registration Management Services: they allow a physical PNF Startup and Registration MnS Provider to acquire its network layer parameters either via static procedures (pre-configured in the element) or via dynamic procedures (Plug-n-Play) during startup. During this process, the PNF Startup and Registration MnS Provider also acquires the IP address of the PNF Startup and Registration MnS Consumer for PNF Startup and Registration MnS Provider registration. Once the PNF Startup and Registration MnS Provider registers, the PNF Startup and Registration MnS Consumer can then bring the PNF Startup and Registration MnS Provider to an operational state.

- PNF Software Management Services: they allow a PNF Software MnS Consumer to request a physical PNF Software MnS Provider to download, install, validate and activate a new software package and allow a physical PNF Software MnS Provider to report its software versions. O-RAN will utilize the liaison to 3GPP to initiate enhancements to the 3GPP specifications for PNF Software Management. Until those enhancements are put in place, O-RAN PNF Software Management will be described in this specification. Software management described in this document is modelled on the O-RAN Fronthaul Management Plane Specification.

1.3.2.3 A1 Interface

The A1 is an open interface interconnecting the two O-RAN specific components (the non-RT RIC and the near-RT RIC), [32]. Exploiting the A1 interface, the non-RT RIC is able to:

- deploy policy-based guidance to the near-RT RIC, *e.g.*, to set optimization goals;

- manage ML models used in xApps;

- orchestrate and negotiate the collection of enrichment information from the network to the near-RT RIC.

The network policies, ML models, and enrichment information can be applied at different levels in order to refer a group of UEs or to a single UE. A1 interface relies on the A1 Application Protocol (A1AP), designed for policy deployment and network functions combining REST APIs over HTTP for the transfer of JSON objects.

As the A1-based ML model management is still considered for further studies, [33], the A1 interface functions are:

- **Policy Management**: the purpose of A1 policies is to enable the Non-RT RIC function in the SMO to guide the Near-RT RIC function, and hence the RAN, towards a better fulfilment of the RAN intent. By utilising the observability over O1, and the A1 policy feedback, the Non-RT RIC can conclude that the RAN intent is not achieved. The Non-RT RIC can then decide to use A1 policies that enable the Near-RT RIC to, *e.g.*, optimize RRM for a single UEs or for group of UEs. There are different types of A1 policies referred to as A1 policy types. A Non-RT RIC need not use all A1 policy types, and a specific function in the Near-RT RIC may only support one specific A1 policy type. Non-RT RIC can discover available A1 policy types over the A1 interface. An A1 policy type is identified by the policy type identifier (PolicyTypeId). Different policy types have different PolicyTypeIds. Based on the PolicyTypeId, schemas are identified and used for creation, validation, and formulation, and for query of the status, of A1 policies of that type. An A1 policy is identified by a policy identifier (PolicyId) that shall be assigned by Non-RT RIC. The PolicyId shall be locally unique within Non-RT RIC and sent in the policy request operations that carry representations of A1 policies. A1 policies consist of a scope identifier and one or more policy statements. The scope identifier represents what the policy statements are to be applied on (*e.g.*, UEs, QoS flows, or cells). The policy statements represent the goals to the Near-RT RIC and covers policy objectives and policy resources.

- **Enrichment Information (EI)**: the purpose of A1 enrichment information is to enable the Near-RT RIC to improve its RAN optimization performance by utilising information that is not available within the RAN. The information sources can be O-RAN internal and O-RAN external, and the derived A1 enrichment information can be provided by the Non-RT RIC over the A1 interface. There are different types of A1 enrichment information referred to as EI types. A Near-RT RIC may not need to use all EI types, and a specific function in the Near-RT RIC may only need one specific type of A1 enrichment information. An EI type is identified by the EI type identifier (EiTypeId). Based on the EiTypeId, information can be provided about the A1 enrichment information properties and how to request delivery of the A1 enrichment information. The Near-RT RIC can discover available EiTypeIds over A1 and request delivery of A1 enrichment information related to an available EiTypeId. The Non-RT RIC controls the access to A1 enrichment information and how the connection for delivery of the enrichment information can be made. The enrichment information function is used by the Non-RT RIC to produce and make A1 enrichment information available to the Near-RT RIC. The Non-RT RIC is responsible for exposure and secure delivery of A1 enrichment information.

1.3.2.4 O-RAN Fronthaul

The O-RAN Fronthaul (FH) interface connects a DU to one or multiple RUs inside the same gNB, [34], and enables the distribution of the physical layer functionalities between the RU and the DU, and to control RU operations from the DU.

When considering the functional split defining a fronthaul interface there are two competing interests: the simplicity of the interface and of the RU design, and the data rate required for fronthaul transport. To resolve this, O-RAN has selected a single split point, known as "7-2x" but allows a variation, with the precoding function to be located either "above" the interface in the O-DU or "below" the interface in the O-RU. For the most part the interface is not affected by this decision, but there are some impacts namely to provide the necessary information to the O-RU to execute the precoding operation. O-RUs within which the precoding is not done (therefore of lower complexity) are called "Category A" O-RUs while O-RUs within which the precoding is done are called "Category B" O-RUs. See Figure 36 for a depiction of this dual O-RU concept.

The FH interface can be based on Ethernet or UPD/IP encapsulation, carrying either an eCPRI, [35], or an IEEE 1914.3, [36], payload. Since one DU can support multiple Rus, the FH specification introduces and additional component with the aim to multiples the fronthaul stream to multiple RUs. As an alternative, the RUs can be connected in a chain.

The O-RAN FH specification foresees four different communication planes detailed below.

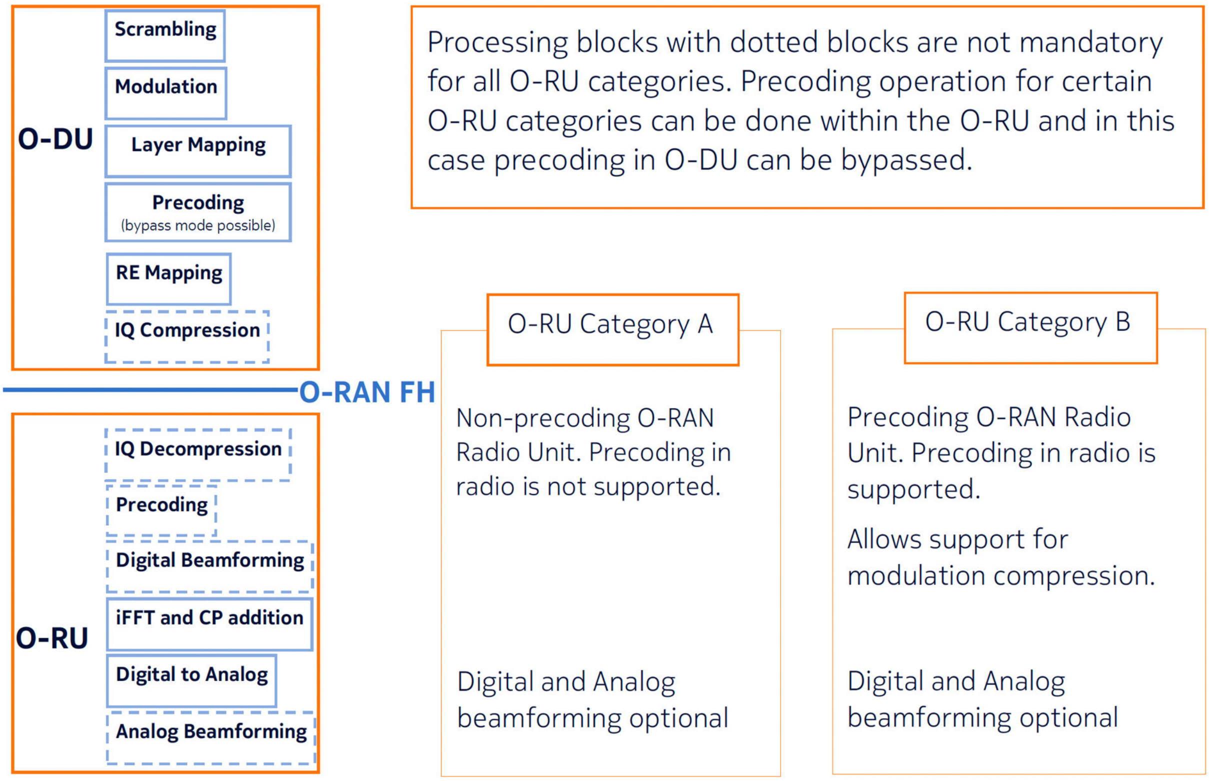


Figure 36: Split Point and Category A and Category B O-RAN Radio Units.

C-plane: this plane transfers commands from the DU and the RU, *i.e.*, from the high-PHY to the low-PHY, including:

- scheduling and beamforming configurations;
- management of different NR numerologies in different subframes;
- downlink precoding configuration;
- spectrum sharing control.

The C-plane messages are encapsulated in eCPRI or IEEE 1914.3 protocols, with specific fields and commands for different control procedures.

U-plane: This communication plane is mainly used to transfer I/Q samples in the frequency domain between the DU and the RU. Typically, the U-plane messages follow a C-plane one that specifies scheduling and beamforming configurations, so that the I/Q samples can be transmitted in the corresponding transmission opportunities.

An additional functionality of the U-plane is to take care of the transmission timing of the packets so that the RU has enough time for processing before transmission. Additionally, the U-plane specifies the digital gain of the samples and, for more efficient transfer, it can compress them.

S-plane: this communication plane takes care of synchronization between the DU and RU in terms of time, frequency, and Phase between the clocks. Having a shared clock reference enable the DU and RU to properly align time and frequency resources for the transmission of data and control channels. This is of paramount importance in a slotted distributed system.

The topologies foreseen by the O-RAN specification differ on the type of interconnection between the DU and RU that can be either a direct link or an indirect link trough a fabric of ethernet switches. Additionally, the synchronization can be based in different protocol with different precisions: i) Physical Layer Frequency Signals (PLFS) or Precision Time Protocol (PTP), with sub-microsecond accuracy.

M-plane: This protocol enables the initialization of the DU and RU, and the management of their interconnection. It is also in charge of the configuration of the RU, [37]. Specifically, it takes care of:

- managing the RU start-up, during which the RU establishes the management with the DU and/or the SMO;
- enabling software updates, configuration management, performance and fault monitoring, and file management for bulk transfer of data;
- managing the registration of the RU as PNF, the parameters of the RU-to-DU link, and the update of beamforming vectors.

M-plane relies on a IPv4 or IPv6 tunnel with dedicated endpoints in the DU and RU, and runs in parallel to the C-, U-, and S-planes. The specification foresees two architectural options for the M-plane implementation:

- Hierarchical: the SMO manages the DU and the DU manages the RU;
- Hybrid: the SMO manages the DU and can also interact directly with the RU.

Contrary to the C-/U-/S-planes, the M-plane is end-to-end encrypted through SSH and/or TLS.

1.3.3 Orchestration Framework and Non-RT RIC

Non-Real Time RAN Intelligent Controller (Non-RT RIC) is the intelligent RAN operation and optimization functionality internal to the Service Management and Orchestration (SMO) framework in O-RAN overall architecture. Indeed, it represents a subset of functionality of the SMO framework. Non-RT RIC logically terminates the A1 interface, and it provides policy-based guidance, enrichment information, and AI/ML model management to the Near-RT RICs. It can also access other SMO framework functionalities, for example influencing what is carried across the O1 and O2 interface.

Non-RT RIC is comprised of:

- Non-RT RIC Framework – Functionality internal to the SMO Framework that logically terminates the A1 interface to 1 the Near-RT RIC and exposes set of R1 services to Non-RT RIC Applications (rApps);
- rApps: Applications that leverage the functionalities available in the Non-RT RIC Framework / SMO Framework to provide value added services related to RAN operation and optimization. The scope of rApps includes, but is not limited to, radio resource management, data analytics, and providing enrichment information.

In Figure 37 is shown the high-level architecture of the SMO. The O-RAN specification do not set a strict boundary between the SMO and non-RT RIC functionalities but group them into three distinct sets:

- functions anchored inside the non-RT RIC (in blue);
- functions anchored outside the non-RT RIC (in orange);
- functions not anchored to any SMO component or spanning multiple components (in white).

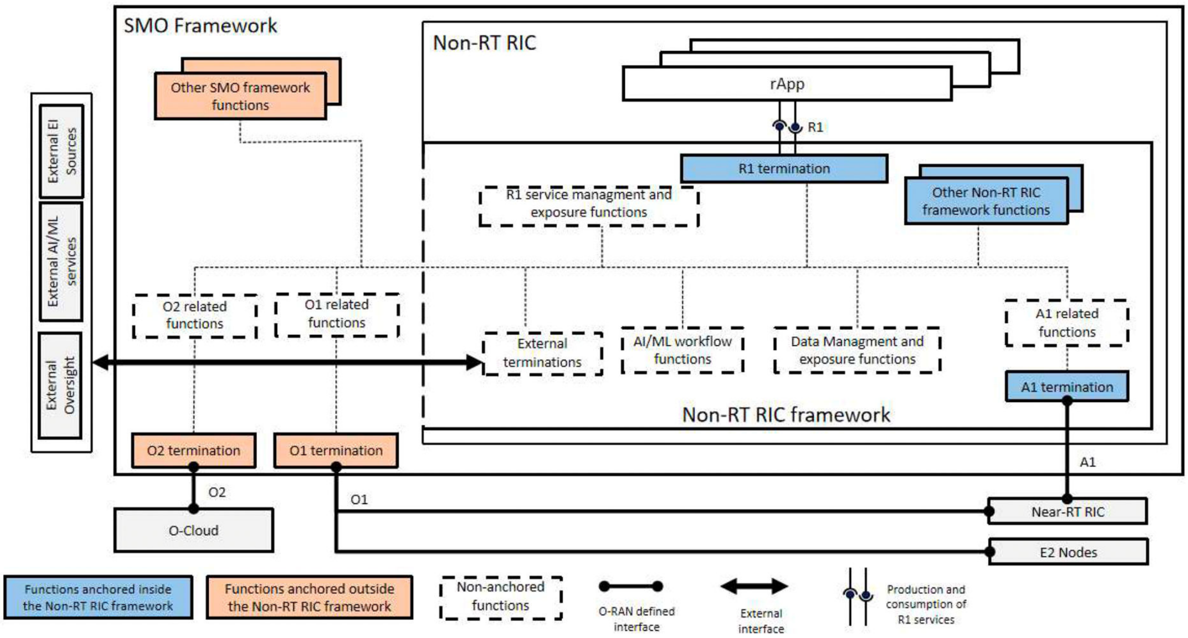


Figure 37: non-RT RIC Reference Architecture.

In this section we describe the SMO framework functionalities and interfaces.

1.3.3.1 Non-RT RIC

The non-RT RIC enables closed-loop control of the RAN (with time scales larger then 1 s) supporting the execution of third-party applications, the rApps. These are used to enable value added services to support RAN optimization and RAN operations, including: i) policy guidance; ii) enrichment information; iii) configuration management; and iv) data analytics.

Inside the non-RT RIC is defined the R1 termination, shown in Figure 37, which interfaces rApps with the non-RT RIC and allows them to obtain access to: i) data management and exposure services; ii) AI/ML functionalities; and iii) A1, O1 and O2 interfaces through the internal messaging infrastructure. Although rApps are very similar to xApps in the control functionalities they can provide, they have been designed to provide control policies that operate at a larger scale, such as RAN sharing, performance diagnostics, frequency and interference management, and network slicing.

1.3.3.2 Near-RT RIC

The Near-RT RIC is deployed at the edge of the network to operate control-loops over the CUs and DUs in the RAN, as well as over O-RAN compliant eNBs. Usually, the near-RT RIC controls multiple RAN nodes, so its closed-loop control function is associated with the UEs of several cells.

The control functionality of the near-RT RIC is delegated to the xApps, multiple application deployed inside the RIC that support custom logic. The xApps receive KPIs data from the RAN at all different layers, *i.e.*, user, cell, or slice, and computes and applies control policies. Near-RT RIC shall consist of multiple xApps and a set of platform functions that are commonly used to support the specific functions hosted by xApps.

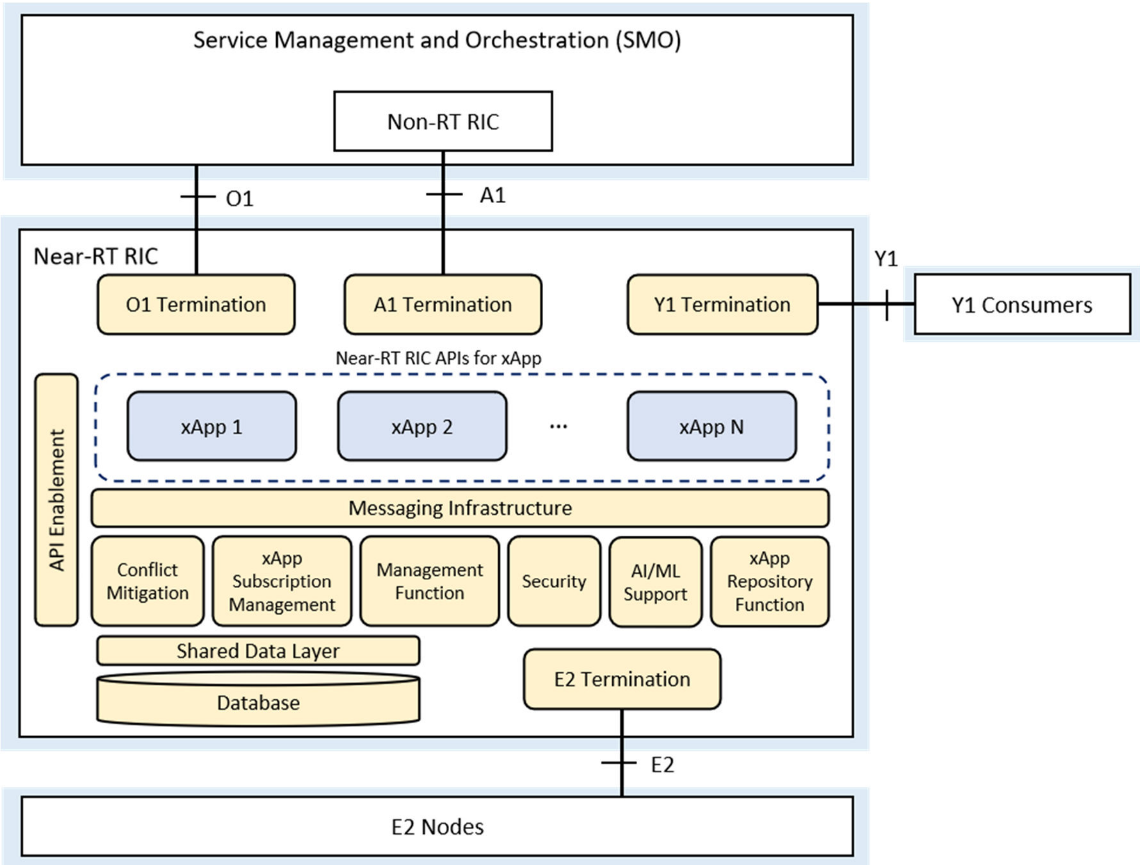


Figure 38: Near-RT RIC Internal Architecture.

An overview of the architecture of the O-RAN standardized near-RT RIC is provided in Figure 38. The architecture includes:

- **Conflict mitigation**: in the context of Near-RT RIC, Conflict Mitigation is about addressing conflicting interactions between different xApps. An application will typically change one or more parameters with the objective of optimizing a specific metric. Conflict Mitigation is necessary because xApps objectives may be chosen/configured such that they result in conflicting actions. The control target of the radio resource management can be a cell, a UE or a bearer, etc. The control contents of the radio resource management can cover access control, bearer control, handover control, QoS control, resource assignment and so on. The control time span indicates the valid control duration which is expected by the control request. The conflicts of control can be illustrated as: i) Direct Conflicts, that can be observed directly by Conflict Mitigation; and ii) Indirect Conflicts, that cannot be observed directly, nevertheless, some dependence among the parameters and resources that the xApps target can be observed. Conflict Mitigation may anticipate the possible conflicts and take actions to mitigate them.

- **Internal messaging infrastructure**: it provides low-latency message delivery service between Near-RT RIC internal endpoints. It needs to support: i) registration message used from endpoints to register themselves to the messaging infrastructure; ii) discovery message used to discover endpoints by the messaging infrastructure initially and registered to the messaging infrastructure; and iii) deletion message to delete endpoints one they are not used anymore. It also provides APIs to send and receive messages from the xApps. This APIs can rely on point-to-point communications or publish/subscribe mechanisms.

- **Subscription manager**: the subscription management functionality manages subscriptions from xApps to E2 Nodes and enforces authorization of policies controlling xApp access to messages. It also enables merging of identical subscriptions from different xApps into a single subscription toward an E2 Node.

- **Security**: to prevent malicious xApps from leaking sensitive RAN data or from affecting the RAN performance. The details of this component are still left for further studies;

- **Network Information Based (NIB) Database and Shared Data Layer API**: the RAN NIB contains information about the E2 nodes and the UE-NIB contains the identification of the UEs and their entries. The SDL (Shared Data Layer) is used by xApps to subscribe to database notification services and to read, write and modify information stored on the database. UE-NIB, R-NIB and other use case specific information may be exposed using the SDL services.

- **xApp management**: this service features automated life-cycle management of the xApps. It accounts for onboarding, deployment, termination, and tracing and logging of Fault, Configuration, Accounting, Performance, Security (FCAPS).

- **AI/ML support**: the AI/ML data pipeline in Near-RT RIC offers data ingestion and preparation for applications (xApps). The input to the AI/ML data pipeline may include E2 node data collected over E2 interface, enrichment information over A1 interface, information from applications, and data retrieved from the Near-RT RIC database through the messaging infrastructure. The output of the AI/ML data pipeline may be provided to the AI/ML training capability in Near-RT RIC. The AI/ML training in Near-RT RIC offers training of applications (xApps) within Near-RT RIC, [19]. The AI/ML training provides generic and use case-independent capabilities to AI/ML-based applications that may be useful to multiple use cases.

1.3.3.3 xApps

The Near-RT xApp platform allows the roll-out of smart apps for management and optimisation of the RAN. These applications can have access to the RAN data as never before. They can use this to feed near-real time control functions, leveraging the benefits of AI and Big Data. This open platform allows third-party apps to complement the RAN vendors portfolio.

It can implement functions such as the following:

- **Intelligent and autonomous Neighbour Manager:** Manage frequency planning or force handover to another cell when two UEs are close to the cell boundary and close to each other to avoid interference in MuMIMO network.

- **Radio resource management:** xApps can be used to optimize the use of radio resources in the O-RAN architecture, such as by allocating frequency bands or scheduling transmissions.

- **Mobility management:** xApps can be used to manage the movement of devices within the O-RAN architecture, such as by providing handover support or tracking device location.

- **Quality of Service (QoS):** xApps can be used to implement QoS control functions, such as traffic management or congestion control, to optimize the performance of the O-RAN architecture.

- **Near zero-touch network provisioning:** Adding new sites, CU, DU or RU will automatically provision the network to integrate it and optimise their use.

- **Smarter Handover manager:** Manage handover not only on radio quality but from past handovers using machine learning algorithms, using knowledge of success of failure of past handovers

- **Automated PCI Allocation:** Avoid and learning from past PCI collisions by a smart allocation and re-allocation

- **Security:** xApps can be used to implement security functions, such as authentication and encryption

1.4 NR-TN RADIO ACCESS NETWORK

1.4.1 Backhaul/Fronthaul interfaces

This section presents the different interfaces in a standard TN, as specified in 3GPP Rel. 17.

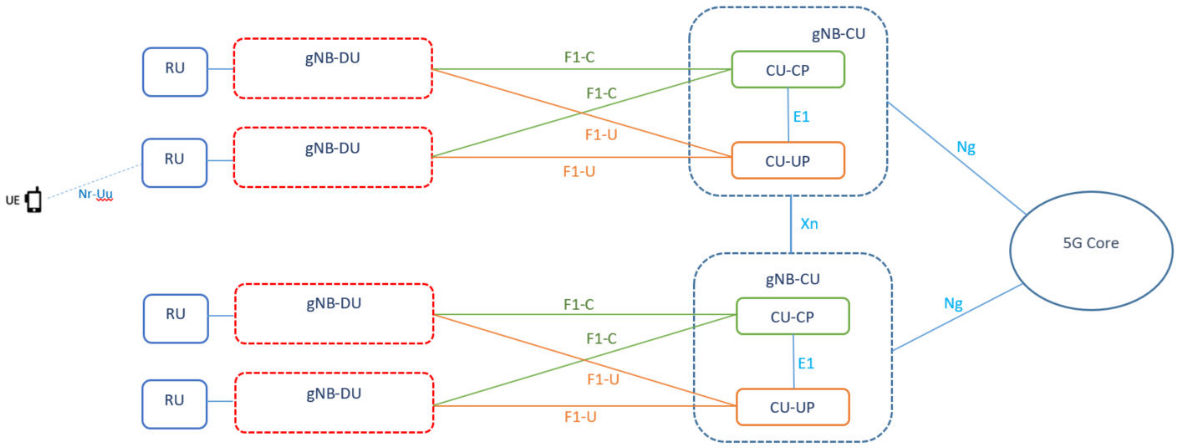


Figure 39: High-level architecture of a standard TN.

1.4.1.1 Xn interface

Xn is a point to point interface between 2 gNB. The functions handled by its CP part, **Xn-C**, are the following:

- Xn-C interface management and error handling functions
- UE mobility management functions
- Dual connectivity function
- Energy saving function
- Resource coordination function
- Secondary RAT Data Volume Report function
- Trace function
- Load management function
- Data exchange for self-optimisation function
- IAB support function
- Small data transmission function
- QMC support function
- MBS management support function

The functions handled by the UP part, **Xn-U**, are the following:

- Data transfer function
- Flow control function
- Assistance information function
- Fast retransmission function

More details on the Xn interface are available in 3GPP TS 38.420, [8].

The Xn interface will be the most important one if we consider a Multi-Connectivity solution with both TN and NTN nodes, as it is the main interface for intra NG-RAN Handover and Dual Connectivity (DC).

The procedures for DC, such as S-NG-RAN Node Addition Preparation, S-NG-RAN node Reconfiguration Completion, M-NG-RAN node initiated S-NG-RAN node are already defined in 3GPP 38.423 for the TN, [40]. Some modifications of these procedures might be necessary in case of TN/NTN Multi-Connectivity, adding for example an IE indicating if M-NG-RAN/S-NG-RAN are TN or NTN. Some timers might need to be incremented in case of TN/NTN cohabitation.

1.4.1.2 NG interface

The NG interface connects the NG RAN and the 5GC. The functions supported over the NG interfaces are the following:

- Procedures to establish, maintain and release NG-RAN part of PDU sessions;
- Procedures to perform intra-RAT handover and inter-RAT handover
- The separation of each UE on the protocol level for user specific signalling management;
- The transfer of NAS signalling messages between UE and AMF;
- Mechanisms for resource reservation for packet data streams;
- Procedures to establish, maintain and release NG-RAN part of MBS sessions.

For more details refer to 3GPP TS 38.410 [6]. The procedures/functions from NG link will remain the same in case of TN/NTN cohabitation. Some timers might need to be incremented.

1.4.1.3 F1 interface

F1 is the interface between gNB-CU and gNB-DU. The F1 interface supports:

- Procedures to establish, maintain and release radio bearers for the NG-RAN part of PDU sessions and MBS Sessions, and for E-UTRAN Radio Access Bearers;
- Procedures to establish, maintain and release BH RLC channels;
- The separation of each UE on the protocol level for user specific signalling management;
- The separation of each IAB-MT on the protocol level for IAB-MT specific signalling management;

- The transfer of RRC signalling messages between the UE and the gNB-CU.
- Procedures to establish, maintain and release Uu Relay RLC channels and PC5 Relay RLC channels.

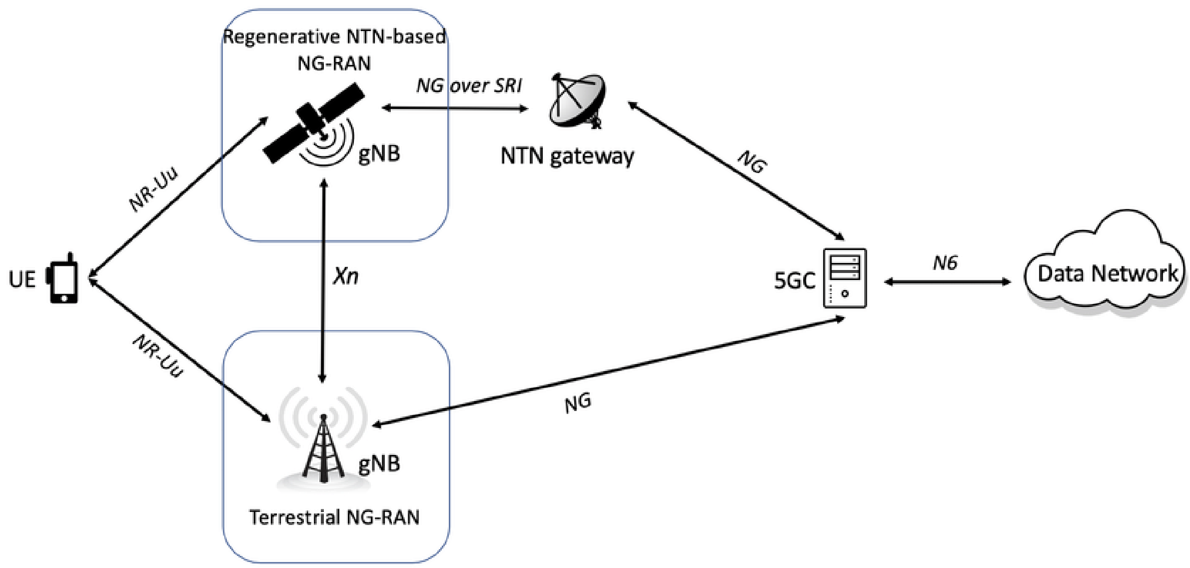
For more details regarding F1 interface please refer to 3GPP TS 38.470, [9]. Procedures/functions from F1 link will remain the same in case of TN/NTN cohabitation. Some timers might need to be incremented.

1.4.1.4 E1 interface

E1 is a point-to-point interface between a gNB-CU-CP and a gNB-CU-UP. The functions supported over the E1 interfaces are the following:

- E1 Interface Management function
- E1 Bearer Context Management function
- Trace function
- Load Management function
- Measurements Result Transfer function
- Support for IAB

For more details regarding E1 interface, please refer to TS 38.463, .



1.4.2 Radio

The Radio is an interface in itself as TN are designed for its large near far effect constraints, that can be relaxed for NTN network as they are already at less few hundreds of km from ground. However, some parameters need to be aligned between the two usage for cohabitation of the networks.

1.4.2.1 Transmitter

Table 4 lists some key parameters for transmitter characteristic.

Table 4: Key parameters for the transmitter characteristics.

Parameters	TN WA (TS 138.104)	NTN LEO (TS138.108)	NTN GEO (TS138.108)
Frequency Error	+/-0.05ppm	Not yet specified	Not yet specified
Time Alignment (min. between gNodeB)	<3µs	Not yet specified	Not yet specified
EVM (64QAM)	8%	8%	8%
ACLR	45dBc	24dBc	14dBc
Spurious Emissions	-36dBm/100KHz	-13dBm/4Khz	-13dBm/4Khz

It shall be noticed that some parameters not yet fully specified as frequency errors and time alignment would need to be very precise if soft handovers or even carrier aggregation are envisaged between TN and NTN network.

The ACLR relaxation would certainly give such huge design constraint relaxation as the most stringent parameter will become the EVM target not relaxed.

1.4.2.2 Receiver

Table 5 provides a list of some key parameters for receiver characteristics.

Table 5: Key parameters for the receiver characteristics.

Parameters	TN WA (TS 138.104)	NTN LEO (TS138.108)	NTN GEO (TS138.108)
Static Sensitivity 5MHz/SCS 15KHz	-101.7dBm	-102.4dBm	-99.3dBm
ACS	-52dBm	-60dBm	-57dBm
Blocker	-15dBm	-44dBm	-44dBm
ICS – Blocking signal 5MHz/SCS 15KHz	-81.4dBm	-83.1dBm	-92dBm

Even if here as well some parameters can be relaxed, for NTN some parameters, such as TX/RX isolation, would make this relaxation not so useful for the product design.

2 TRADE-OFF ANALYSIS AND ARCHITECTURE DEFINITION

In this Section, for each use case defined in D2.1and based on the extensive review of the architectures in Section 1, we identify the most suitable solutions for the NTN component. For each use case, we identify at least one potential NTN architecture, which will then be refined in the following tasks of WP3 in order to define a single end-to-end system capable of providing all of the selected use cases by means of proper orchestration and reconfiguration.

In this context, it shall be noticed that we consider the regenerative or IAB architecture categories as the baseline for each use case. With respect to MC, it is considered as an optional architecture solution when required by the use case and feasible from a system perspective, to be added on top of the baseline.

Finally, with respect to spectrum: i) we provide an overview of the current allocations for NTN based on Rel. 17; ii) we report information on the currently on-going activities for FR2 allocations in Rel. 18 and on the spectrum coexistence analyses that are required; and iii) report some considerations on the allocation of mmWave spectrum to TN.

It shall be noticed that, as also reported in D2.1, we consider the airway scenario (Use Case 1.2c) as representative also for 1.1a and 1.1b.

2.1 ARCHITECTURE/INTERFACE MAPPING PER USE CASE

2.1.1 Use Case 1.1c: Airway scenario

To provide fast and reliable global in-flight connectivity, regenerative payloads are the most suitable option, as they allow to significantly reduce the communication latency and to implement advanced technologies for capacity enhancement (such as user-centric beamforming and MEC).

Thus, architecture options 1 (regenerative with and without functional split) and 2b/2c (IAB-based access with regenerative payload) shall be considered. In this context, it shall be noticed that:

- as already discussed in the previous sections, having the full gNB or IAB-Donor on-board allows to limit the overall latency compared to solutions involving the node split;
- the connectivity is provided for all passengers on-board by means of an IAB-node that relays all communications to/from the UEs from/to the flying platform(s).

Thus, the most suitable architecture options for this use case is option 2c, with IAB-based access and a full IAB-Donor on-board the NTN node.

As previously mentioned, to further enhance the capacity provided to the users, MC solutions can be envisaged. In this framework, it is worthwhile highlighting that 3GPP specifications on IAB (TS 37.340, in particular) indicate that all functions that are specified for a UE can be used also for the MT component of an IAB. As such, an IAB-MT can exploit MC capabilities. Consequently, option 3b for NTN-NTN MC can be implemented as well[1]. Also option 3d allows

[1] It shall be noticed that the implementation of MC solutions for the IAB-MT might have some differences compared to the MC options for full on-board gNBs. Such differences will be evaluated and assessed in the next Tasks.

NTN-NTN MC, but due to the presence of the DU-CU split of the gNB, it typically involves larger latencies and, thus, is not considered as a prioritised solution for this use case.

2.1.2 Use Case 1.2a: Residential broadband – LEO or GEO depending on QoS

This use case belongs to the “Residential Broadband” service category, aimed at bridging the Digital Divide in scarcely populated areas where the deployment of TNs is not economically viable. For all these use cases, the objective is that of providing low-latency broadband connectivity to users in residential buildings.

In use case 1.2a, the NTN system can provide connectivity to a user inside the house through GEO or LEO satellites based on the requested QoS. Since the UE is in indoor conditions, connectivity can be provided either through direct access to a VSAT terminal, which then provides Wi-Fi connectivity to all terminals, or indirect-access through IAB, *i.e.*, option 2c. As already discussed for use case 1.1c:

- it is also possible to implement split options, thus moving to option 2d with an IAB-Donor DU on-board while the CU would be on-ground at the GW. However, in this case the latency is increased and, thus, it shall not be prioritised;
- NTN-NTN MC solutions to further boost the capacity to the IAB, which might serve multiple UEs in the household or perhaps also provide connectivity to a limited area in its surrounding, can be considered.

Direct access from a regenerative payload is also a possibility, with lower priority due to the building penetration loss. 3GPP currently foresees omni-directional handheld terminals in S-band with a null limited antenna gain (actually, only 3 dB gain through receiver diversity that are needed to compensate the depolarisation loss).

2.1.3 Use Case 1.2b: Residential broadband – IAB for residential broadband

This second “Residential Broadband” is specifically aimed at providing remote connection to the users to monitor and control their domestic automation system, which include both sensors (*e.g.*, home camera with movement detection, intrusion detection sensor) and actuators (*e.g.*, set of wireless smart plugs to remotely switch on/off equipment and a tele-operated automatic watering system).

This use case is thus similar to the previous one, with the exception of the required capacity. In fact, in this case the user does not need broadband connectivity but at most the capacity to receive a live feed from the home cameras backhauled through the IAB-node. Consequently, the most viable architecture option is again 2c (IAB-Donor on-board) and, with lower priority, 2d (IAB-Donor DU on-board) due to the larger latency.

In principle, also in this case it might be possible to consider MC solutions. However, it is not expected that the capacity requests from the users would require such advanced solution and, thus, option 3b for NTN-NTN MC can be considered with a lower priority.

2.1.4 Use Case 1.2c: Residential broadband – TN to NTN backup for energy saving purpose

This last use case related to “Residential Broadband” is aimed at providing connectivity via NTN when the TN is switched off for energy saving purposes.

As such, from an architecture perspective it is quite similar to use case 1.2a and, thus, we can consider architecture options 1a (on-board gNB for direct access) and 2c (IAB-Donor on-board) as the prioritised solution, with the possibility to further enhance the capacity via NTN-NTN MC (option 3b).

In addition, it is worthwhile mentioning that to support a smoother handover from the TN to the NTN component, also options 3a (full stack on-board) and 3c (functional split) for TN-NTN MC might be considered, with a lower priority. In fact, this would allow to implement soft handover when moving from TN to NTN and *vice versa*.

2.1.5 Use Case 2.1: Vehicle connected

To integrate satellite communications into the automotive context, it is of paramount importance to reduce the latency to the highest possible extent. The accomplishment of delay-sensitive tasks is crucial to support this use case, such as real-time video. The deployment of LEO satellites equipped with regenerative payloads arises as the most suitable option to satisfy stringent latency requirements, as it allows satellites to embed some gNB functions or even act as a full gNB.

Attention must be drawn to the architecture where a full gNB is placed onboard the satellite. This architecture opens a wide range of usages that go beyond the RAN. For instance, it enables benefiting from the MEC framework. Endowing LEO satellites with MEC could be of particular interest to rapidly processing data. In this regard, when the eCall is triggered in the event of a serious accident, space edge computing capabilities can be harnessed to implement a call session control function to find the appropriate Public Safety Answering Point (PSAP), To make MEC possible the UPF shall be moved to the edge. On the one hand, satellite edge servers allow moving the services close to the user, which is crucial to reduce the latency. On the other hand, the computation and storage resources are scarcer in the satellites than in the ground segment. There is a trade-off between the latency reduction and the complexity of the computing task that is diverted to the satellite.

It is important to remark that the use of IAB technology is not envisaged in this use case. The reason stems from the fact that vehicles connect directly to the satellite over the NR-Uu interface. IAB comes into play essentially when indirect satellite connectivity is needed. The immediate consequence is that in the proposed deployment the terminals do not need any terrestrial infrastructure to communicate with the satellite. In the light of this discussion, the most suitable architecture to provision the services specified in this use case corresponds to the Option 1a in Table 3.

2.1.6 Use Case 2.2: PPDR communications

Public Protection and Disaster Relief (PPDR) scenarios are characterised by the abrupt unavailability of a terrestrial infrastructure due to natural or man-made disasters. In such conditions, access via NTN is fundamental for both the first responders and the users in the area. Once the TN is progressively restored, both access options can be used (perhaps even exploiting MC).

In general, the service provided via NTN should be characterised by low latency and a potentially large capacity, to support both the first responders and the affected population. Moreover, in the former case there might even be need for Augmented Reality (AR) headsets to support the rescue operations.

Taking the above aspects into account, and based on the observations previously reported for the other use cases, the use of regenerative payloads with full gNB (option 1a) or full IAB-Donor (option 2c) on-board shall be prioritised. Solutions including functional split might be feasible, but the larger latencies lead to a lower prioritisation.

Finally, NTN-NTN MC solutions (option 3b) might be implemented to further boost the capacity in the disaster area.

2.1.7 Use Case 2.3: Global private networks

To be able to provide a global private network for static, nomadic, and mobile terminals alike, it is highly important to have a reduced end-to-end delay, while at the same time to simplify the space-based architecture as much as possible, *i.e.*, not to add additional protocols due to the functionality split.

As such, the low delay should be achieved at the core network level by establishing specific data paths between the UE gNBs as short as possible through the space links, by proper selection of the UPF functionality. Similar considerations could be made for the control plane links.

It is less important to be able to split the gNB functionality between multiple space or ground nodes. Specifically, for this use case, an optimized data path would not return to ground the data packets before the destination, so all alternatives with ground gNB or ground gNB CU would not reduce enough the end-to-end delay. Furthermore, a split of the gNB functionality in space, albeit possible would only introduce additional overhead due to the encode-exchange-decode operations which would have to be executed in the F1 interface. This could be motivated only when a single space node would not be able to process the complete gNB functionality and would have to offload the compute of PDCP for example to another node.

As such, the best alternatives would be to have either the full gNB in space (option 1a) or to have an IAB (option 2c) to interconnect the common, off-the shelf devices to the network with a gNB in space backend. An additional alternative with gNB at the edge could be also considered depending on the deployment type, however this being considered already State-of-the-Art.

2.1.8 Selected architecture options

Table 6 summarises the selected architecture options per use case. As already mentioned, it shall be noticed that MC is considered as an additional architecture feature that can be added on top of the baseline architecture. The need for this additional solution is related to the potential request for larger capacities and its feasibility shall be evaluated on a use case basis.

In general, TN-NTN MC solutions are more complex due to the different link characteristics and are considered as less feasible for 5G-Advanced services. MC options including two NTN nodes are a viable option for some use cases and they will be considered in the following WP3 tasks.

Table 6: Architecture options per use case. Green: best solution; yellow: applicable with medium modifications; red: needs major modifications/adjustments.

Category	#	Payload	Connectivity	UC1.1c	UC1.2a	UC1.2b	UC1.2c	UC2.1	UC2.2	UC2.3
Regenerative	1a	gNB	D	Yellow	Green	Red	Green	Green	Green	Green
	1b	gNB-DU	D	Yellow	Yellow	Red	Yellow	Yellow	Yellow	Yellow
IAB	2a	T	I	Red	Red	Red	Red	Red	Red	Red
	2b	T	I	Red	Red	Red	Red	Red	Red	Red
	2c	IAB-Donor	I	Green	Green	Green	Green	Red	Green	Green
	2d	IAB-Donor DU	I	Yellow	Yellow	Yellow	Yellow	Red	Yellow	Yellow
MC	3a (NTN-TN)	gNB	D	Red	Red	Red	Yellow	Red	Red	Yellow
	3b (NTN-NTN)	gNB	D	Green	Green	Yellow	Green	Yellow	Green	Green
	3c (NTN-NT)	gNB-DU	D	Red	Red	Red	Yellow	Red	Red	Yellow
	3d (NTN-NTN)	gNB-DU	D	Yellow	Yellow	Red	Yellow	Yellow	Yellow	Yellow
	3e (NTN-TN)	T	D	Red	Red	Red	Red	Red	Red	Red
	3f (NTN-NTN)	**T**	**D**	Red	Red	Red	Red	Red	Red	Red

2.2 REVIEW OF NTN AND TN SPECTRUM ALLOCATIONS

In this Section, we provide an overview of the current spectrum allocations for NTN and TN systems. This information will serve as a basis for the subsequent WP3 tasks to define the operating frequencies and bandwidths to be exploited for the identified use cases.

Remark: The context of spectrum sharing is still awaiting new rulemaking. On the one hand, the sharing of spectrum between the different satellite constellation operators begins to be regulated. The US Federal Communications Commission (FCC) has recently adopted new rules for Satellite System Spectrum Sharing, [42], which clarify how the operators that have been awarded fixed-satellite service NGSO licenses in different FCC application processing rounds must avoid interfering with each other. On the other hand, the sharing of spectrum between 5G TN and NTN services remains essentially addressed through experimental licences for exclusive and temporary usage of MNO spectrum for NTN direct-to-device scenario, but strictly speaking, it is not spectrum sharing. Moreover, it shall be noticed that spectrum sharing was deprioritised in 3GPP NTN in Rel. 19; it might be addressed in Rel. 20+, but probably for C-band, which is not considered in 5G-STARDUST.

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In this deliverable, only exclusive usage of spectrum is analysed. In terms of co-existence, an overview of the on-going activities in 3GPP is provided. The content reported below will be used as a baseline for future 5G-STARDUST activities and designs.

2.2.1 NTN spectrum

In the framework of Rel. 17 specifications, the RF performance on the user service link has been evaluated in L and S bands (*i.e.*, FR1) through adjacent channel coexistence studies between NTN and TN nodes and reported in 3GPP TS 38.104, [43]. This document also captures the RF requirements for HAPS.

Table 7: NTN operating bands and duplexing as per 3GPP Rel. 17.

Band	UL (UE-to-SAN)	DL (SAN-to-UE)	Duplexing
n256	1980-2010 MHz	2170-2200 MHz	FDD
n255	1626.5-1660.5 MHz	1525-1559 MHz	FDD

The NTN bands and the related duplexing modes are summarised in Table 7. It shall be noticed that band n256 is adjacent to the TN NR bands n1 (operating in FDD) and n34 (operating in TDD), while band n255 is not adjacent to any current TN band. The RF requirements in FR1 for UEs supporting NTN access are reported in TR 38.863 for NTN nodes compliant with the specifications in TS 38.101-5, [3], and TS 38.108, [1]. According to these specifications, **Rel. 17 already allows, from a spectrum perspective, to provide NTN connectivity to handheld terminals in the above-mentioned chunks of S-band**. Based on TR 38.821, NTN operations in these bands assume: i) a maximum of 30 MHz per beam in downlink and uplink, but for a single handheld terminal in uplink the maximum allocation is 360 kHz; and ii) a Sub-Carrier Spacing (SCS) equal to 15 kHz or 30 kHz.

Table 8: Summary of the currently considered NTN Ka-band allocations.

<table>
<tr><td>NTN Ka-band DL</td><td>17.7-20.2 GHz
(n512, n511, n510)</td><td>For the Ka-band Downlink NTN band definition, define one NTN band covering the full harmonized Ka-band space-to-earth range of 17.7-20.2 GHz for Regions 1, 2 and 3.</td></tr>
<tr><td>NTN Ka-band UL</td><td>27.5-30.0 GHz
(n512)
28.35-30.0 GHz
(n511)
27.5-28.35 GHz
(n510)</td><td>Define 3 NTN bands for Ka-band UL
• one band covering the full harmonized Ka-band Earth-to-space range of 27.5-30.0 GHz applicable for Region 1, Region 3, and Region 2 countries except the US
• additional two bands for the US/FCC market and countries deploying the same assignments:
  • 27.5-28.35 GHz range
  • 28.35-30.0 GHz range</td></tr>
<tr><td colspan="3">Note 1: the above NTN Ka-bands definition is based on the preliminary discussions at RAN4#105 (Held in November 2022). Further updates on NTN Ka-bands definition will be provided following 3GPP progress during Rel. 18 course.
Note 2:
• n511 with consideration of US/FCC regulations;
• n512 with consideration of CEPT regulations: impacts of latest revision of ECC Decision(05)01 on ECC Decision(13)01 need to be checked;
• n510 with consideration of US/FCC regulation: need to provide the 3GPP definition that specifies the prevention of the use of a fixed terminal in the FSS and provide information of a movable NTN user terminal in FSS spectrum in the US.</td></tr>
</table>

NTN deployments above 10 GHz, *i.e.*, FR2, are being addressed in the framework of Rel. 18, [45], and some aspects are likely to be finalised in Rel. 19. The terminals allowed in this range are only VSAT devices with directive antennas, which include fixed terminals and devices mounted on moving platforms. In Rel. 18, the analyses are being carried out based on the transparent payload architecture specified in Rel. 17, with other architecture options (*e.g.*, IAB or regenerative) to be addressed in future releases. Table 8 and Figure 40 summarise the current Ka-band allocations considered for NTN.

In addition, the following configurations are allowed: i) at least 50, 100, and 200 MHz channel bandwidths shall be supported, with 400 MHz channels to be optionally available for FR2; ii) rhe SCS values for FR2 are 60 kHz and 120 kHz; and iii) FDD mode is considered.

The analyses related to NTN deployments in FR2 are being performed within RAN4 based on the following steps:

- study and identification of an NTN example band, including the analysis of available regulations and the definition of an adjacent channel co-existence scenario;
- specification of TX/RX requirements for the SAN and various VSATs (*i.e.*, including antennas with additional apertures with respect to the 60 cm one specified in 38.821) for the identified example band;
- identification of the PHY parameters.

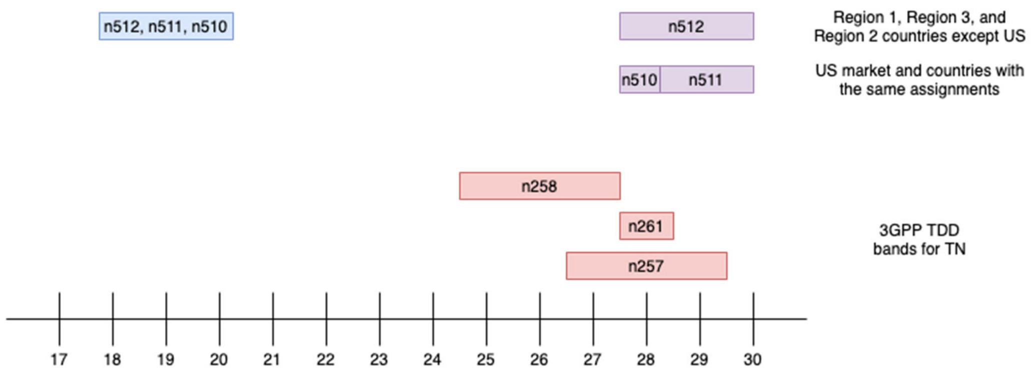


Figure 40: Representation of the currently considered NTN Ka-band allocations in Table 8.

As reported in R4-2308414, [44], the following assumptions are taken as a baseline for this study led by RAN4:

- GSO and NGSO (*e.g.*, LEO, MEO, HEO) based satellite access is considered;
  - Earth Station In Motion (ESIM) scenarios for NGSO in Ka-band are not considered in this WI for the moment being;
- targeted UE types: fixed and mobile VSAT. The characteristics of the VSAT UE are those available TR 38.821 with priority, but additional NTN UE classes may be considered if properly justified
  - with respect to mobile VSAT, three types of terminals and scenarios exist: airborne, maritime, and land ESIM. Which type(s) shall be specified depends on the outcome of the regulation analysis and co-existence study;

- FDD mode is assumed for satellite operation above 10 GHz, while TDD mode is assumed for terrestrial operation in FR2;
- the ITU-R harmonized Ka-band will serve as reference;
- co-existence between overlapping (*i.e.*, co-channel) NTN and TN band portions is out of scope of this activity in 3GPP. This aspect will be captured in the specification reporting the outcomes of this study.

For the co-existence analysis, it is clearly stated that relevant co-existence scenarios and analysis shall be considered in RAN4, if and where applicable, to ensure that satellite bands introduced in 3GPP for NTN do not impact the existing specifications and do not cause degradation (in the sense of RAN4 co-existence studies) to TN networks in 3GPP specified bands adjacent to the NTN band. To this aim, it is assumed that the NTN-TN adjacent band co-existence analysis will be performed in the harmonized Ka-band edges, also in line with the above-listed assumptions. The outcome of such analyses is expected to be applicable to all NTN-TN adjacent band scenarios (if any) in the whole Ka-band range, where applicable and allowed by regulations.

In general, the same RAN4 agreed procedure exploited for FR1 analyses will be implemented also for the co-existence analyses in FR2. Tdoc R4-2308414 also reports a detailed list of simulation assumptions, including the network layout, parameters (including the antenna model and configuration), and evaluation methodology. Initial simulation results are available in R4-2308417,[46] , R4-2309768, [47], and R4-2305929, [48].

Table 9: Use cases for co-existence analyses in RAN4, [49].

No.	Combination	Aggressor	Victim	Objective	NTN band
1	TN with NTN	NTN UL	TN UL	ACLR NTN UE to be varied/defined ACS TN gNB fixed	27 GHz
2	TN with NTN	TN UL	NTN UL	ACLR TN UE fixed ACS NTN SAN to be varied/defined	27 GHz
3	TN with NTN	NTN UL	TN DL	ACLR NTN UE to be varied/defined ACS TN UE fixed	27 GHz
4	TN with NTN	TN DL	NTN UL	ACLR TN gNB fixed ACS NTN SAN to be varied/defined	27 GHz
5	TN with NTN	TN DL	NTN DL	ACLR TN gNB fixed ACS NTN UE to be varied/defined	17 GHz
6	TN with NTN	NTN DL	TN DL	ACLR NTN SAN to be varied/defined ACS TN UE fixed	17 GHz
7	TN with NTN	NTN DL	TN UL	ACLR NTN SAN to be varied/defined ACS TN gNB fixed	17 GHz

8	TN with NTN	TN UL	NTN DL	ACLR TN UE fixed ACS NTN UE to be varied/defined	17 GHz
NOTE 1: For coexistence between Ka-Band DL and adjacent TN bands, there are no 3GPP defined/specified TN bands.					

Tdoc R4-2302878, [49], provides a detailed way forward for the co-existence analyses in FR2. In particular, the NTN-TN coexistence shall be studied by assuming a reference frequency of 17 GHz for NTN DL cases and 27 GHz NTN UL case as reported in Table 9; this table also reports the assumptions related to Adjacent Channel Selectivity (ACS) and Adjacent Channel Leakage Ratio (ACLR). These scenarios are also represented in Figure 41 and Figure 42.

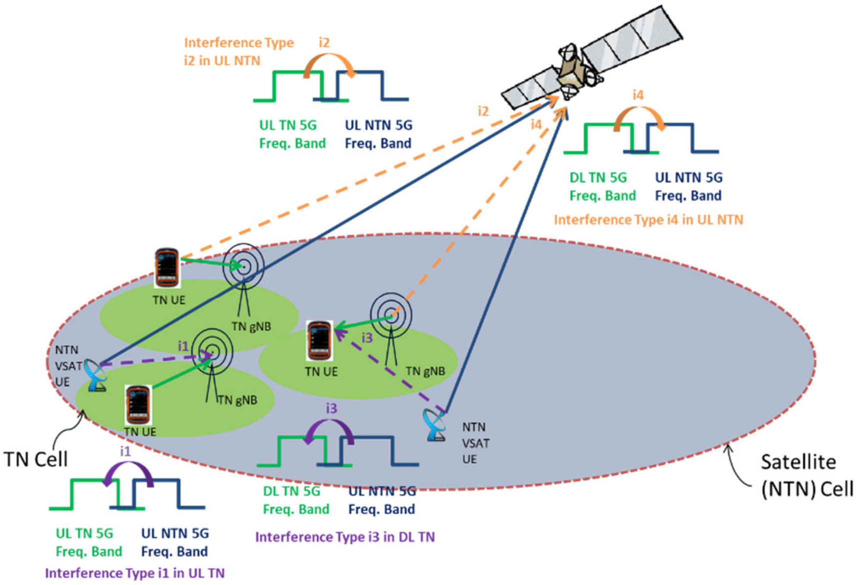


Figure 41: Co-existence scenarios with NTN UL at 27 GHz, [49].

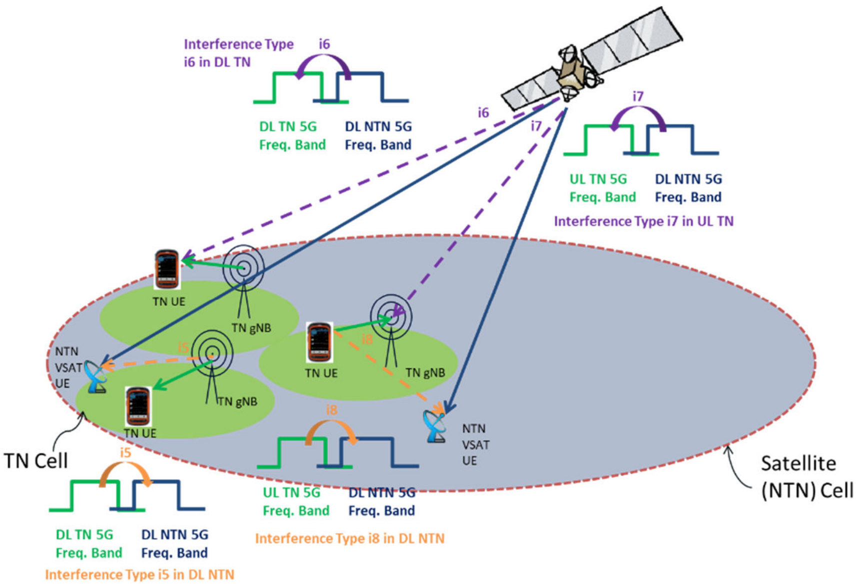


Figure 42: Co-existence scenarios with NTN DL at 17 GHz, [49].

▪ TN spectrum in FR2 bands

Next, from a TN perspective, millimetre-wave (mmWave) spectrum is often seen as a valuable resource to meet 5G TN coverage obligations and enable specific use cases, including:

- Fixed Wireless Access (FWA), as an alternative to optical fibre
- Customers "hot zones", for high capacity and high quality of experience, for example in commercial centres, public areas, stadium, train stations, airports, etc.
- Private / Local 5G networks.

In general, the market demand is still relatively low and very few commercial networks have been deployed so far as illustrated in Figure 43, [50]. The number of available devices is increasing but remains rather limited.

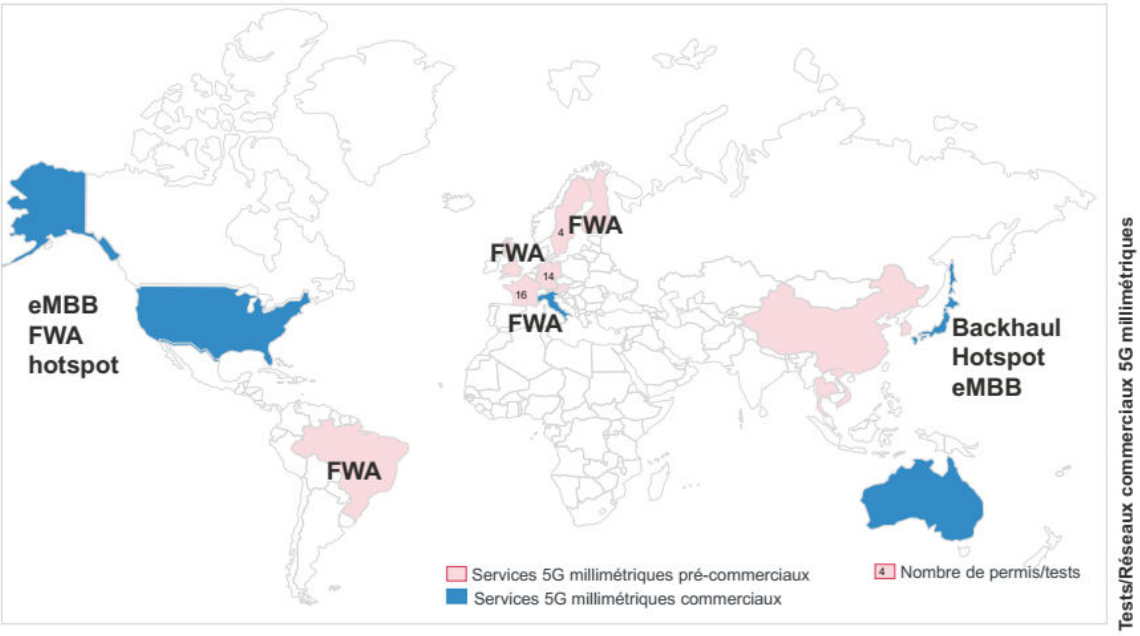


Figure 43: Commercial and pre-commercial services worldwide, [50].

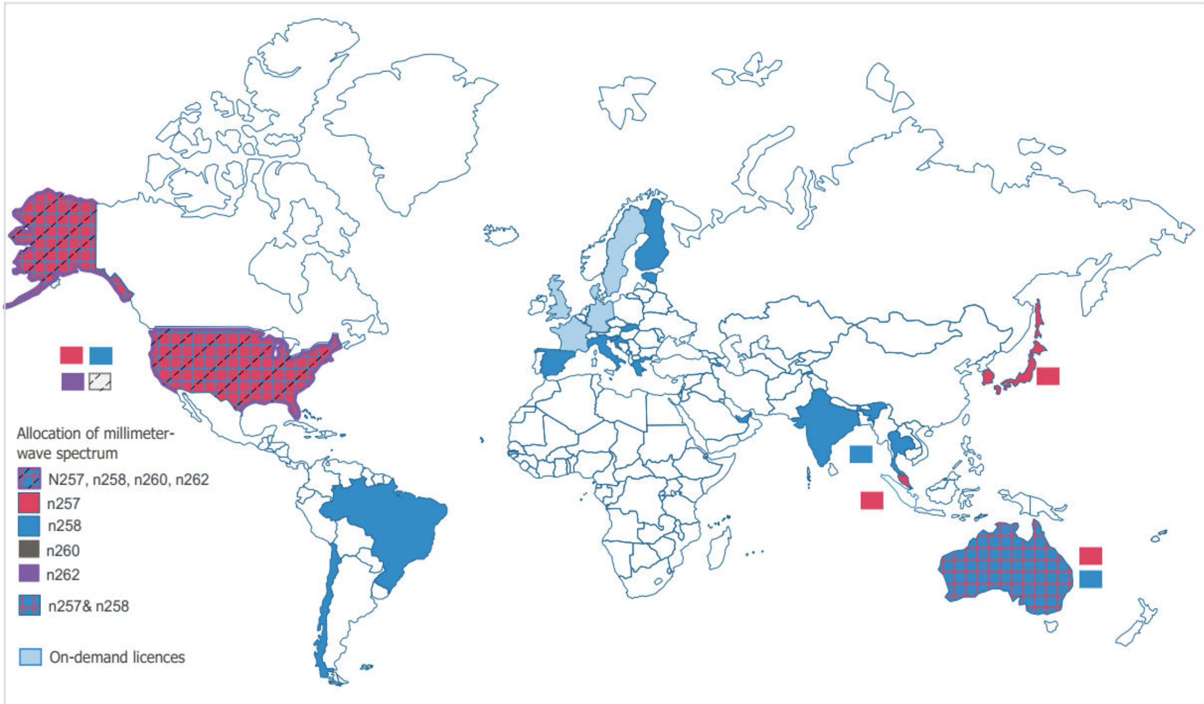
However, millimetre-wave spectrum offers some key opportunities. According to Nokia, [51], the cost per gigabyte in hot zones can be reduced by up to 75%, compared to sub-6 GHz spectrum and, on average, a four-year payback period is expected, with an internal rate of return estimated to 20 – 30% after the fourth year. While only 7% of 5G FWA initiatives have been in the mmWave spectrum so far, interest seems to grow and recently, 35% of trials are using 5G mmWave bands, [52].

In Europe, Deutsche Telekom (Germany), Elisa (Finland), FastWeb (Italy) and TIM (Italy) are in the early stages of commercialization of millimeter wave, with a main focus on FWA, smartphones and industrial applications, [53]. But other initiatives can be cited so as the experimental deployment of healthcare services in France, through the European project 5G-TOURS, or the demonstration of a 5G mmWave base station at the MWC 2023 by Telefonica, Ericsson and Qualcomm.

The following 5G NR FR2 bands, all TDD, are targeted for current and future deployments:

- n257: 26,5 GHZ - 29,5 GHZ
- n258: 24,25 GHZ - 27,5 GHZ
- n259: 39,5 GHZ - 43,5 GHZ
- n260: 37,0 GHZ - 40,0 GHZ
- n261: 27,5 GHZ - 28,25 GHZ
- n62: 47,2 GHZ - 48,2 GHZ

with a strong interest in Europe for bands 26 and 28GHz, and in the USA, for bands 37, 39 and 47GHz. The allocation of millimeter-wave spectrum around the word is presented in Figure 44 and across Europe in Figure 45. In EU, most countries have yet to auction off the 26 GHz or 28 GHz band.



Source : IDATE, *Cas d'usage 5G millimétriques*, Nov. 2022

Figure 44: Millimeter-wave spectrum allocation across the world, [50].

The use of such spectrum has rapidly become quite intricate, especially around the 28GHz band, [54]. The challenges around co-existence scenarios are indeed manyfold. From a technical perspective, interference can spoil the quality of satellite broadband (*e.g.*, as highlighted by OneWeb about the services offered in India) as well as can prevent the successful deployment of terrestrial 5G mmWave services (*e.g.*, as highlighted by T-Mobile and Verizon in the US). From a non-technical perspective, such co-existence scenarios are also about the efficiency of spectrum utilization and the adaptation to different national regulations for both satellite and terrestrial 5G mmWave services.

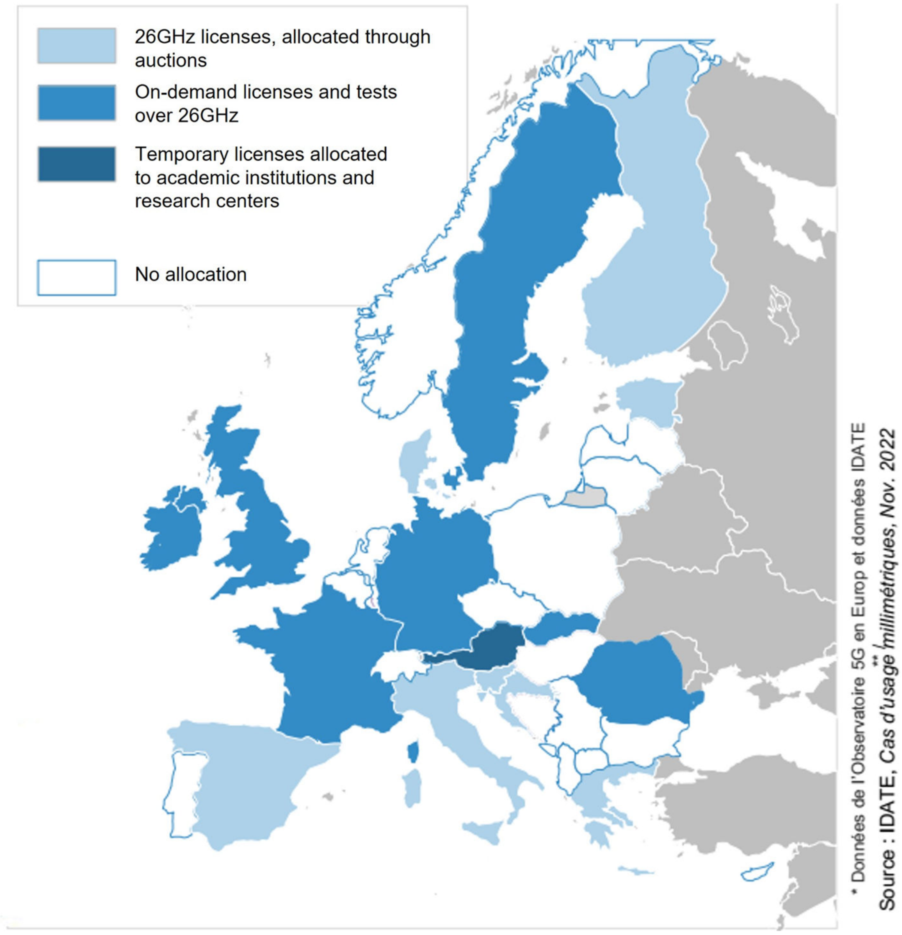


Figure 45: Millimeter-wave spectrum allocation across Europe, [50].

3 FUNCTIONAL REQUIREMENTS

In this Section, we report the functional (FCN) and system (SYS) requirements identified for each of the selected use cases. These requirements will be exploited in the following tasks of WP3 to define the self-organised end-to-end, space segment, ground segment, and PoC architectures.

For each requirement, the following information is provided:

- an ID in the format UCx.y.z-<req_type>_<#>, where x.y.z denotes the Use Case (e.g., 1.1c), <req_type> the requirement type (i.e., FCN or SYS), and <#> its number;
- the priority, which can be optional or essential;
- the justification, i.e., whether it is a requirement already identified in 3GPP specifications or it is deduced from the Use Case described in D2.1;
- the architecture components it might impact;
- a short description.

3.1 USE CASE 1.1C: AIRWAY SCENARIO

Table 10: System and Functional Requirements for use case 1.1c.

Type	ID	Priority	Justification	Related component	Description
FCN	UC1.1.C-FCN_1	Essential	Use Case, 3GPP	RAN, UE	The NTN satellite system shall provide UEs with **indirect satellite access** for the delivery of 5G services
FCN	UC1.1.C- FCN _2	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	Through the subscriber profile, a UE shall have the possibility to select either a satellite-based access or the terrestrial-based access, whichever is available (the nature of the network, *i.e.*, satellite-/terrestrial-based, may be transparent to the user)
FCN	UC1.1.C- FCN _3	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support delay sensitive traffic and non delay sensitive traffic according to targeted performance of user profiles
FCN	UC1.1.C- FCN _4	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	In the NTN system, the SNO shall be able to allow the service provider (MNO) to select the NTN gateway and route the traffic through the RAN functionality
FCN	UC1.1.C- FCN _5	Essential	3GPP	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support slicing mechanism as defined in TS 22.261, [55], and TS 28.541, [56]
FCN	UC1.1.C- FCN _6	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support independent allocation and monitoring of its resources to the benefit of visiting UEs from several MNOs
FCN	UC1.1.C- FCN _7	Essential	3GPP	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support RAN sharing as defined in TS 22.261, [55]

FCN	UC1.1.C- FCN _8	Essential	3GPP	RAN, CORE, OSS/BSS	The NTN System shall support its interconnection with any 5GC (see TS 23.501, [5])
FCN	UC1.1.C- FCN _9	Essential	3GPP	RAN, CORE. OSS/BSS	A 5G system with satellite access shall enable roaming between 5G satellite access networks and 5G terrestrial access networks as specified in TR 22.822, section 5.1.5 (roaming)
FCN	UC1.1.C- FCN _10	Essential	Use Case	RAN, CORE, OSS/BSS	A 5G system with satellite access shall support network reselection based on the location of the user (on/off the plane), even when a UE is still in coverage of its current (terrestrial or non-terrestrial) network
SYS	UC1.1.C-SYS_1	Essential	3GPP	RAN, UE	The interface between the NTN Satellite System and the UEs shall comply with the NR radio protocols together with NTN extension
SYS	UC1.1.C-SYS_2	Essential	3GPP	RAN, CORE	The NTN System shall ensure interoperability with the terrestrial cellular network's management system
SYS	UC1.1.C-SYS_3	Essential	3GPP	RAN, CORE	The NTN Satellite System shall provide an NG interface with the 5GCs it interconnects with.
SYS	UC1.1.C-SYS_4	Essential	3GPP	RAN, CORE	The management of the NTN Satellite System shall be compliant with the specifications as set out in TS 28.540, [57], and TS 28.541, [58].
SYS	UC1.1.C-SYS_5	Optional	Use Case	RAN, CORE	The NTN system may support NTN-NTN MC solutions to the IAB-Donor.
SYS	UC1.1.C-SYS_6	Optional	Use Case	RAN, UE	The NTN system shall support NTN-NTN MC solutions to the UE in direct access.

3.2 USE CASE 1.2A: RESIDENTIAL BROADBAND – LEO OR GEO DEPENDING ON QOS

Table 11: System and Functional Requirements for use case 1.2a.

Type	ID	Priority	Justification	Related component	Description
FCN	UC1.2.A-FCN_1	Essential	Use Case, 3GPP	RAN, UE	The NTN satellite system shall provide UEs with **indirect satellite access** for the delivery of 5G services
FCN	UC1.2.A- FCN_2	Optional	Use Case, 3GPP	RAN, UE	The NTN satellite system shall provide UEs with **direct satellite access** for the delivery of 5G services
FCN	UC1.2.A- FCN_3	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	Through the subscriber profile, a UE shall have the possibility to select either a satellite-based access or the terrestrial-based access, whichever is available (the nature of the network, *i.e.*, satellite-/terrestrial-based, may be transparent to the user)
FCN	UC1.2.A- FCN_4	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support delay sensitive traffic and non-delay sensitive traffic according to targeted performance of user profiles.
FCN	UC1.2.A- FCN_5	Essential	Use Case	RAN, CORE, traffic model	The NTN System shall dynamically select the most appropriate SAN based on the identified 5QI

FCN	UC1.2.A- FCN_6	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	In the NTN system, the SNO shall be able to allow the service provider (MNO) to select the NTN gateway and route the traffic through the RAN functionality
FCN	UC1.2.A- FCN_7	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support independent allocation and monitoring of its resources to the benefit of visiting UEs from several MNOs
FCN	UC1.2.A- FCN_8	Essential	3GPP	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support RAN sharing as defined in TS 22.261, [55]
FCN	UC1.2.A- FCN_9	Essential	3GPP	RAN, CORE, OSS/BSS	The NTN System shall support its interconnection with any 55C (see TS 23.501, [5])
SYS	UC1.2.A-SYS_1	Essential	3GPP	RAN, UE	The interface between the NTN Satellite System and the UEs shall comply with the NR radio protocols together with NTN extension
SYS	UC1.2.A-SYS_2	Essential	3GPP	RAN, CORE	The NTN System shall ensure interoperability with the terrestrial cellular network's management system
SYS	UC1.2.A-SYS_3	Essential	3GPP	RAN, CORE	The NTN Satellite System shall provide an NG interface with the 5GCs it interconnects with.
SYS	UC1.2.A-SYS_4	Essential	3GPP	RAN, CORE	The management of the NTN Satellite System shall be compliant with the specifications as set out in TS 28.540, [57], and TS 28.541, [58].
SYS	UC1.2.A-SYS_5	Optional	Use Case	RAN, CORE	The NTN system shall support NTN-NTN MC solutions to the IAB-Donor.
SYS	UC1.2.A-SYS_6	Optional	Use Case	RAN, UE	The NTN system shall support NTN-NTN MC solutions to the UE in direct access.
SYS	UC1.2A-SYS_7	Essential	3GPP	RAN, CORE	The NTN Satellite System shall provide an NG interface with the 5GCs it interconnects with.

3.3 USE CASE 1.2B: RESIDENTIAL BROADBAND – IAB FOR RESIDENTIAL BROADBAND

Table 12: System and Functional Requirements for use case 1.2b.

Type	ID	Priority	Justification	Related component	Description
FCN	UC1.2.B- FCN_1	Essential	Use Case, 3GPP	RAN, UE	The NTN satellite system shall provide UEs with **indirect satellite access** for the delivery of 5G services
FCN	UC1.2.B- FCN_2	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	Through the subscriber profile, a UE shall have the possibility to select either a satellite-based access or the terrestrial-based access, whichever is available (the nature of the network, *i.e.*, satellite-/terrestrial-based, may be transparent to the user)
FCN	UC1.2.B-FCN_4	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support delay sensitive traffic and non delay sensitive traffic according to targeted performance of user profiles.
FCN	UC1.2.B-FCN_5	Essential	Use Case	RAN, CORE, traffic model	The NTN System shall dynamically select the most appropriate SAN based on the identified 5QI

FCN	UC1.2.B-FCN_6	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	In the NTN system, the SNO shall be able to allow the service provider (MNO) to select the NTN gateway and route the traffic through the RAN functionality
FCN	UC1.2.B-FCN_7	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support independent allocation and monitoring of its resources to the benefit of visiting UEs from several MNOs
FCN	UC1.2.B-FCN_8	Essential	3GPP	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support RAN sharing as defined in TS 22.261, [55]
FCN	UC1.2.B-FCN_9	Essential	3GPP	RAN, CORE, OSS/BSS	The NTN System shall support its interconnection with any 5GC (see TS 23.501, [5])
SYS	UC1.2.B-SYS_1	Essential	3GPP	RAN, UE	The interface between the NTN Satellite System and the UEs shall comply with the NR radio protocols together with NTN extension
SYS	UC1.2.B-SYS_2	Essential	3GPP	RAN, CORE	The NTN System shall ensure interoperability with the terrestrial cellular network's management system
SYS	UC1.2.B-SYS_3	Essential	3GPP	RAN, CORE	The NTN Satellite System shall provide an NG interface with the 5GCs it interconnects with.
SYS	UC1.2.B-SYS_4	Essential	3GPP	RAN, CORE	The management of the NTN Satellite System shall be compliant with the specifications as set out in TS 28.540, [57], and TS 28.541, [58].
SYS	UC1.2.B-SYS_5	Optional	Use Case	RAN, CORE	The NTN system shall support NTN-NTN MC solutions to the IAB-Donor.
SYS	UC1.2.B-SYS_6	Essential	3GPP	RAN, CORE	The NTN Satellite System shall provide an NG interface with the 5GCs it interconnects with.

3.4 USE CASE 1.2C: RESIDENTIAL BROADBAND – TN TO NTN BACKUP FOR ENERGY SAVING PURPOSE

Table 13: System and Functional Requirements for use case 1.2c.

Type	ID	Priority	Justification	Related component	Description
FCN	UC1.2.C-FCN_1	Essential	Use Case	RAN, CORE, UE, OSS/BSS	NTN System shall support seamless network layer switching **from TN to NTN** (this corresponds to the case where the terrestrial mobile site goes into sleep mode)
FCN	UC1.2.C-FCN_2	Essential	Use Case	RAN, CORE, UE, OSS/BSS	NTN System shall support seamless network layer switching **from NTN back to TN** (this corresponds to the case where the terrestrial mobile is available again)
FCN	UC1.2.C-FCN_3	Essential	Use Case, 3GPP	RAN, UE	The NTN satellite system shall provide UEs with **indirect satellite access** for the delivery of 5G services
FCN	UC1.2.C-FCN_4	Optional	Use Case, 3GPP	RAN, UE	The NTN satellite system shall provide UEs with **direct satellite access** for the delivery of 5G services
FCN	UC1.2.C-FCN_5	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support delay sensitive traffic and non delay sensitive traffic according to targeted performance of user profiles.

FCN	UC1.2.C-FCN_6	Essential	Use Case	RAN, CORE, traffic model	The NTN System shall dynamically select the most appropriate SAN based on the selected energy-saving policy
FCN	UC1.2.C-FCN_7	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support independent allocation and monitoring of its resources to the benefit of visiting UEs from several MNOs
FCN	UC1.2.C-FCN_8	Optional	3GPP	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support RAN sharing as defined in TS 22.261, [55]
FCN	UC1.2.C-FCN_9	Essential	3GPP	RAN, CORE, OSS/BSS	The NTN System shall support its interconnection with any 5GC (see TS 23.501, [5])
SYS	UC1.2.C-SYS_1	Essential	3GPP	RAN, UE	The interface between the NTN Satellite System and the UEs shall comply with the NR radio protocols together with NTN extension
SYS	UC1.2.C-SYS_2	Essential	3GPP	RAN, CORE	The NTN System shall ensure interoperability with the terrestrial cellular network's management system
SYS	UC1.2.C-SYS_3	Essential	3GPP	RAN, CORE	The NTN Satellite System shall provide an NG interface with the 5GCs it interconnects with.
SYS	UC1.2.C-SYS_4	Essential	3GPP	RAN, CORE	The management of the NTN Satellite System shall be compliant with the specifications as set out in TS 28.540, [57], and TS 28.541, [58].
SYS	UC1.2.C-SYS_5	Optional	Use Case	RAN, CORE	The NTN system shall support NTN-NTN MC solutions to the IAB-Donor.
SYS	UC1.2.C-SYS_6	Optional	Use Case	RAN, UE	The NTN system shall support NTN-NTN MC solutions to the UE in direct access.
SYS	UC1.2.C-SYS_7	Optional	Use Case	RAN, CORE	The NTN system shall support TN-NTN MC solutions to the IAB-Donor.
SYS	UC1.2.C-SYS_8	Optional	Use Case	RAN, UE	The NTN system shall support TN-NTN MC solutions to the UE in direct access.

3.5 USE CASE 2.1: VEHICLE CONNECTED

Table 14: System and Functional Requirements for use case 2.1.

Type	ID	Priority	Justification	Related component	Description
FCN	UC2.1-FCN_1	Essential	Use Case	RAN, UE	The NTN satellite system shall provide UEs with **direct satellite access** for the delivery of 5G services
FCN	UC2.1-FCN_2	Optional	3GPP	RAN, CORE, OSS/BSS, traffic model	The NTN system shall be able to support QoS monitoring/assurance (see TS 22.186, [55])
FCN	UC2.1-FCN_3	Essential	3GPP	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support RAN sharing as defined in TS 22.261, [48]
FCN	UC2.1-FCN_4	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	The NTN system shall support TN to NTN handover triggered by geolocation information of the UE (*e.g.*, autonomous vehicle reaching edge of coverage of TN network)
FCN	UC2.1-FCN_5	Optional	3GPP	RAN, CORE, OSS/BSS, traffic model	The NTN System shall be able to perform geolocation of V2X autonomous/remote driving vehicles (see TS 22.261, [55])
FCN	UC2.1-FCN_6	Essential	Use Case, 3GPP	RAN, CORE, UE	The NTN system shall support positioning services

FCN	UC2.1-FCN_7	Essential	Use Case	RAN, UE	The Minimum Set of Data (MSD) sent by the In Vehicle System (IVS) to the network shall not exceed 140 bytes.
FCN	UC2.1-FCN_8	Essential	Use Case	RAN, CORE, UE	To reduce the time taken to establish an eCall, an IVS, whilst in eCall only mode, may receive network availability information whilst not registered on a PLMN
FCN	UC2.1-FCN_9	Essential	Use Case	RAN, CORE, UE	A PLMN shall indicate to an IVS whether IMS emergency call based eCalls are supported
FCN	UC2.1-FCN_10	Essential	Use Case	RAN, CORE, UE	PLMNs shall make use of eCall indicators, received in the emergency call set-up, to differentiate eCalls from other emergency calls
FCN	UC2.1-FCN_11	Essential	3GPP	RAN, CORE, OSS/BSS	The NTN System shall support its interconnection with any 5GC (see TS 23.501, [5])
SYS	UC2.1-SYS_1	Essential	3GPP	RAN, UE	The interface between the NTN Satellite System and the UEs shall comply with the NR radio protocols together with NTN extension
SYS	UC2.1-SYS_2	Essential	3GPP	RAN, CORE	The NTN System shall ensure interoperability with the terrestrial cellular network's management system
SYS	UC2.1-SYS_3	Essential	3GPP	RAN, CORE	The NTN Satellite System shall provide an NG interface with the 5GCs it interconnects with.
SYS	UC2.1-SYS_4	Essential	3GPP	RAN, CORE	The management of the NTN Satellite System shall be compliant with the specifications as set out in TS 28.540, [57], and TS 28.541, [58].
SYS	UC2.1-SYS_5	Optional	Use Case	RAN, UE	The NTN system shall support NTN-NTN MC solutions to the UE in direct access.
SYS	UC2.1-SYS_6	Essential	Use Case	UE	The vehicle shall automatically initiate an eCall in the event of a serious road accident.
SYS	UC2.1-SYS_7	Essential	Use Case	UE	An IVS, or other UE designed to support eCall functionality, shall include in the emergency call set-up an indication that the present call is either a Manually Initiated eCall (MIeC) or an Automatically Initiated eCall (AIeC)
SYS	UC2.1-SYS_8	Essential	Use Case	RAN, CORE	The PSAP shall be given an indication that the incoming call is an eCall
SYS	UC2.1-SYS_9	Optional	Use Case	RAN, UE	The satellite shall route the eCall to the most appropriate public safety access point
SYS	UC2.1-SYS_10	Optional	Use Case	RAN, CORE	To support edge computing on the satellite, a UPF shall be deployed on the satellite
SYS	UC2.1-SYS_11	Optional	Use Case	RAN, UE, CORE	The NTN system shall enable continuous driving support when vehicles switch the communication from TN to NTN
SYS	UC2.1-SYS_12	Essential	3GPP	RAN, CORE	The NTN Satellite System shall provide an NG interface with the 5GCs it interconnects with.

3.6 USE CASE 2.2: PPDR COMMUNICATIONS

Table 15: System and Functional Requirements for use case 2.2.

Type	ID	Priority	Justification	Related component	Description
FCN	UC2.2-FCN_1	Essential	Use Case, 3GPP	RAN, UE	The NTN satellite system shall provide UEs with **direct satellite access** for the delivery of 5G services
FCN	UC2.2-FCN_2	Optional	Use Case, 3GPP	RAN, UE	The NTN satellite system shall provide UEs with **indirect satellite access** for the delivery of 5G services
FCN	UC2.2-FCN_3	Essential	Use Case, 3GPP	RAN, CORE, UE	The NTN system shall support per packet priority (*e.g.*, emergency alerts)
FCN	UC2.2-FCN_4	Essential	Use Case, 3GPP	RAN, CORE, UE	The NTN system shall support identity management
FCN	UC2.2-FCN_5	Essential	Use Case, 3GPP	RAN, CORE, UE	The NTN system shall support positioning services
FCN	UC2.2-FCN_6	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support delay sensitive traffic and non-delay sensitive traffic according to targeted performance of user profiles.
FCN	UC2.2-FCN_7	Essential	Use Case	RAN, CORE	The NTN system shall provide real time acknowledgements of reception
FCN	UC2.2-FCN_8	Essential	Use Case	RAN, CORE	The NTN system shall support multiple private networks and enable communication amongst them
FCN	UC2.2-FCN_9	Essential	Use Case	RAN, CORE	The user shall be able to use dedicated 3GPP networks as well as public 3GPP networks. When possible, private 3GPP networks are preferably used.
FCN	UC2.2-FCN_10	Essential	Use Case	RAN, CORE, OSS&BSS	The NTN system shall be interoperable with non 3GPP systems (*e.g.*, TETRA) at IP level
FCN	UC2.2-FCN_11	Essential	Use Case	RAN, CORE, UE, OSS/BSS	NTN System shall support in-sequence and lossless handovers, which switches communication **from TN to NTN** (this corresponds to the case where the terrestrial mobile site is not available)
FCN	UC2.2-FCN_12	Essential	Use Case	RAN, CORE, UE, OSS/BSS	NTN System shall support in-sequence and lossless handovers, which switch communication **from NTN back to TN** (this corresponds to the case where the terrestrial mobile is available again)
FCN	UC2.2-FCN_13	Essential	Use Case	RAN, CORE	The NTN system shall support backhaul links for command posts and indoor communication
FCN	UC2.2-FCN_14	Essential	Use Case	RAN, CORE	The NTN system shall support group communication
FCN	UC2.2-FCN_15	Essential	Use Case	RAN, UE	The NTN system shall be able to use dedicated frequencies for PPDR assigned on national level
FCN	UC2.2-FCN_16	Essential	Use Case	RAN, CORE	The NTN system shall allow to pre-emption lower priority communications in

					case of resource shortage to complete higher priority communication
FCN	UC2.2-FCN_17	Essential	Use Case	RAN, UE	The NTN system shall synchronize group communication
FCN	UC2.2-FCN_18	Essential	Use Case	RAN, UE, CORE	The NTN system shall be scalable for small and large agencies.
FCN	UC2.2-FCN_19	Essential	3GPP	RAN, CORE, OSS/BSS	The NTN System shall support its interconnection with any 5GC (see TS 23.501, [5])
SYS	UC2.2-SYS_1	Essential	3GPP	RAN, UE	The interface between the NTN Satellite System and the UEs shall comply with the NR radio protocols together with NTN extension
SYS	UC2.2-SYS_2	Essential	3GPP	RAN, CORE	The NTN System shall ensure interoperability with the terrestrial cellular network's management system
SYS	UC2.2-SYS_3	Essential	3GPP	RAN, CORE	The NTN Satellite System shall provide an NG interface with the 5GCs it interconnects with.
SYS	UC2.2-SYS_4	Essential	3GPP	RAN, CORE	The management of the NTN Satellite System shall be compliant with the specifications as set out in TS 28.540, [57], and TS 28.541, [58].
SYS	UC2.2-SYS_5	Optional	Use Case	RAN, CORE	The NTN system shall support NTN-NTN MC solutions to the IAB-Donor.
SYS	UC2.2-SYS_6	Optional	Use Case	RAN, UE	The NTN system shall support NTN-NTN MC solutions to the UE in direct access.
SYS	UC2.2-SYS_7	Essential	Use Case	RAN, UE	The NTN system shall support operation in extreme environment (high mobility, rain, high/low temperature).
SYS	UC2.2-SYS_8	Essential	Use Case	RAN, UE	The NTN system shall support rapid deployable solutions for the field.
SYS	UC2.2-SYS_9	Essential	Use Case	RAN, UE	The NTN system shall support device to device communications.
SYS	UC2.2-SYS_10	Essential	3GPP	RAN, CORE	The NTN Satellite System shall provide an NG interface with the 5GCs it interconnects with.

3.7 USE CASE 2.3: GLOBAL PRIVATE NETWORKS

Table 16: System and Functional Requirements for use case 2.3.

Type	ID	Priority	Justification	Related component	Description
FCN	UC2.3-FCN_1	Essential	Use Case, 3GPP	RAN, UE	The NTN satellite system shall provide UEs with **direct satellite access** for the delivery of 5G services
FCN	UC2.3-FCN_2	Optional	Use Case, 3GPP	RAN, UE	The NTN satellite system shall provide UEs with **indirect satellite access** for the delivery of 5G services
FCN	UC2.3-FCN_3	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	Through the subscriber profile, a UE shall select satellite-based access over the terrestrial-based access, when available

FCN	UC2.3-FCN_5	Essential	Use Case	RAN, CORE, OSS/BSS, traffic model	In the NTN system, the SNO shall be able to allow the service provider (MNO) to select the NTN gateway and route the traffic through the network selecting the shortest path
FCN	UC2.3-FCN_6	Essential	3GPP	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support slicing mechanism as defined in TS 22.261, [55], and TS 28.541, [56]
FCN	UC2.3-FCN_7	Essential	Use Case	CORE	The number of CPs shall be dimensioned and placed as to be able to trade-off space resources vs. longer data path vs. differentiated data paths for the same UE.
FCN	UC2.3-FCN_7	Essential	Use Case	CORE	The number of Space UPF (SUPF) shall be dimensioned and placed as to be able to trade-off space resources vs. longer data path vs. differentiated data paths for the same UE.
FCN	UC2.3-FCN_8	Essential	3GPP	RAN, CORE, OSS/BSS	The NTN System shall support its interconnection with any 5GC (see TS 23.501, [5])
FCN	UC2.3-FCN_9	Essential	3GPP	RAN, CORE. OSS/BSS	A 5G system with satellite access shall enable roaming between 5G satellite access networks and 5G terrestrial access networks as specified in TR 22.822, section 5.1.5 (roaming)
FCN	UC2.3-FCN_9	Essential	Use Case	RAN, CORE	A zero packet loss handover between SUPFs shall be provided (triggered by UE or by SUPF mobility)
FCN	UC2.3-FCN_9	Essential	Use Case	RAN, CORE	The subscriber state shall be placed in space nodes in order to secure it and to reduce the delay of procedures
SYS	UC2.3-SYS_1	Essential	3GPP	RAN, UE	The interface between the NTN Satellite System and the UEs shall comply with the NR radio protocols together with NTN extension
SYS	UC2.3-SYS_2	Essential	3GPP	RAN, CORE	The NTN System shall ensure interoperability with the terrestrial cellular network’s management system
SYS	UC2.3-SYS_3	Essential	3GPP	RAN, CORE	The NTN Satellite System shall provide an NG interface with the 5GCs it interconnects with.
SYS	UC2.3-SYS_4	Essential	3GPP	RAN, CORE	The management of the NTN Satellite System shall be compliant with the specifications as set out in TS 28.540, [57], and TS 28.541, [58].
SYS	UC2.3-SYS_5	Optional	Use Case	RAN, CORE	The NTN system shall support NTN-NTN MC solutions to the IAB-Donor.
SYS	UC2.3-SYS_6	Optional	Use Case	RAN, UE	The NTN system shall support NTN-NTN MC solutions to the UE in direct access.
SYS	UC2.3-SYS_7	Optional	Use Case	RAN, CORE	The NTN system shall support TN-NTN MC solutions to the IAB-Donor.
SYS	UC2.3-SYS_8	Optional	Use Case	RAN, UE	The NTN system shall support TN-NTN MC solutions to the UE in direct access.
SYS	UC2.3-SYS_9	Essential	Use Case	RAN, UE	The NTN system shall support operation in extreme environment (high mobility, rain, high/low temperature).
SYS	UC2.3-SYS_10	Essential	3GPP	RAN, CORE	The NTN Satellite System shall provide an NG interface with the 5GCs it interconnects with.

4 CONCLUSIONS

In this document, we reported a detailed and thorough overview of the system architectures (including the NTN, TN, and 5GC components, as well as O-RAN concepts), CP/UP protocol stacks and interfaces, and NTN/TN spectrum allocations.

In general, the following architectures have been identified for further evaluations and trade-offs in the upcoming WP3 tasks:

- regenerative payload with direct access: V2N, PPDR, Global Private Networks;
- regenerative payloads with indirect access (on-board IAB-Donor): Airway, Residential Broadband (LEO/GEO based on QoS, IAB access, TN to NTN backup), PPDR, Global Private Networks.

In addition, for all Use Cases the possibility of adding Multi-Connectivity from multiple NTN payloads has been also selected. Such technology is considered as an optional feature to be added on top of the baseline architecture when the service requires further enhanced capacity and the system architecture allows its implementation (at least two NTN nodes, even though some cases might implement TN-NTN MC).

Based on the identified architectures, both mandatory and optional, the functional and system requirements are identified for each Use Case. These shall be considered in the other WP3 tasks when defining the self-organised architecture (Task 3.2), the space segment (Task 3.3), and the ground segment (Task 3.4), which will then feed the Proof-of-Concepts architectures in Task 3.5. A comprehensive list of functional/system requirements is summarised in Table 17 in Annex A.

In terms of spectrum, notably NTN can already operate in FR1 (S-band) to provide connectivity to handheld terminals; the extension to FR2 for VSATs (fixed or on moving platforms) is currently being investigated in Rel. 18 and no common agreement has already been achieved. In addition, spectrum coexistence in adjacent bands in Ka-band is also begin assessed and the 3GPP studies will be monitored to be exploited as input for other tasks. For the TN component, a detailed overview of the potential allocations and market trends is reported, based on up-to-date information from both regulators and operators.

This document defines a detailed and common framework in terms of architectures, protocols, interfaces, and functional requirements that will be used as a baseline for all other tasks and WPs of the 5G-STARDUST Project. As such, no final decisions/agreements are reported, as further analyses and trade-offs will be needed and reported in D3.2.

Finally, it is worthwhile to remark that one essential topic to be addressed in 5G-STARDUST is to provide a deep analysis and clarify the implications behind inter-network switching between TN and NTN. As a reference point, there are already a few technical solutions standardized by 3GPP to address inter network switching requirement (*e.g.*, roaming, RAN Sharing with MORAN dedicated, RAN Sharing with MOCN Shared, etc.).

Still, the NTN integration with TN might challenge the existing respective roles of traditional network operators (SNO) and terrestrial MNOs. Further analyses are then required to see how these "role models" would evolve elaborating on the following questions, which provide an example of the discussions to be addressed:

- How is the SNO willing to commercialize its services? Who are the SNO's end-users? Who owns the credentials of these end-users?

- What would mean elaborating a model where SNO would commercialize “payload as a service"?

- How to guarantee SLAs when slices are proposed to several MNOs?

- What impacts on these points when we elaborate more particularly on TN/NTN interoperability?

The above points will be addressed during the activities of Task 7.4 “Exploitation and sustainability”.

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APPENDIX A

Table 17 lists all of the identified system and functional requirements, highlighting in which use case they shall be implemented.

Table 17: Summary of system and functional requirements. Green: essential; yellow: optional.

Type	Justification	Related component	Description	UC1.1c	UC1.2a	UC1.2b	UC1.2c	UC2.1	UC2.2	UC2.3
FNC	Use Case, 3GPP	RAN, UE	The NTN satellite system shall provide UEs with **indirect satellite access** for the delivery of 5G services							
FNC	Use Case, 3GPP	RAN, UE	The NTN satellite system shall provide UEs with **direct satellite access** for the delivery of 5G services							
FNC	Use Case	RAN, CORE, OSS/BSS, traffic model	Through the subscriber profile, a UE shall have the possibility to select either a satellite-based access or the terrestrial-based access, whichever is available (the nature of the network, *i.e.*, satellite-/terrestrial-based, may be transparent to the user)							
FNC	Use Case	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support delay sensitive traffic and non delay sensitive traffic according to targeted performance of user profiles							
FNC	Use Case	RAN, CORE, OSS/BSS, traffic model	In the NTN system, the SNO shall be able to allow the service provider (MNO) to select the NTN gateway and route the traffic through the RAN functionality							
FNC	3GPP	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support slicing mechanism as defined in TS 22.261, [55], and TS 28.541, [56]							
FNC	Use Case	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support independent allocation and monitoring of its resources to the benefit of visiting UEs from several MNOs							
FNC	3GPP	RAN, CORE, OSS/BSS, traffic model	The NTN System shall support RAN sharing as defined in TS 22.261, [55]							
FNC	3GPP	RAN, CORE, OSS/BSS	The NTN System shall support its interconnection with any 5GC (see TS 23.501, [5])							

FNC	3GPP	RAN, CORE. OSS/BSS	A 5G system with satellite access shall enable roaming between 5G satellite access networks and 5G terrestrial access networks as specified in TR 22.822, section 5.1.5 (roaming)							
FNC	Use Case	RAN, CORE, OSS/BSS	A 5G system with satellite access shall support network reselection based on the location of the user (on/off the plane), even when a UE is still in coverage of its current (terrestrial or non-terrestrial) network							
FCN	Use Case	RAN, CORE, traffic model	The NTN System shall dynamically select the most appropriate SAN based on the identified 5QI							
FCN	Use Case	RAN, CORE, UE, OSS/BSS	NTN System shall support seamless network layer switching **from TN to NTN** (this corresponds to the case where the terrestrial mobile site goes into sleep mode)							
FCN	Use Case	RAN, CORE, UE, OSS/BSS	NTN System shall support seamless network layer switching **from NTN back to TN** (this corresponds to the case where the terrestrial mobile is available again)							
FCN	Use Case	RAN, CORE, traffic model	The NTN System shall dynamically select the most appropriate SAN based on the selected energy-saving policy							
FCN	3GPP	RAN, CORE, OSS/BSS, traffic model	The NTN system shall be able to support QoS monitoring/assurance (see TS 22.186, [55])							
FCN	Use Case	RAN, CORE, OSS/BSS, traffic model	The NTN system shall support TN to NTN handover triggered by geolocation information of the UE (*e.g.*, autonomous vehicle reaching edge of coverage of TN network)							
FCN	3GPP	RAN, CORE, OSS/BSS, traffic model	The NTN System shall be able to perform geolocation of V2X autonomous/remote driving vehicles (see TS 22.261, [55])							
FCN	Use Case, 3GPP	RAN, CORE, UE	The NTN system shall support positioning services							
FCN	Use Case, 3GPP	RAN, CORE, UE	The NTN system shall support per packet priority (*e.g.*, emergency alerts)							

FCN	Use Case, 3GPP	RAN, CORE, UE	The NTN system shall support identity management							
FCN	Use Case, 3GPP	RAN, CORE, UE	The NTN system shall support positioning services							
FCN	Use Case	RAN, CORE	The NTN system shall provide real time acknowledgements of reception							
FCN	Use Case	RAN, CORE	The NTN system shall support multiple private networks and enable communication amongst them							
FCN	Use Case	RAN, CORE	The user shall be able to use dedicated 3GPP networks as well as public 3GPP networks. When possible, private 3GPP networks are preferably used.							
FCN	Use Case	RAN, CORE, OSS&BSS	The NTN system shall be interoperable with non 3GPP systems (*e.g.,* TETRA) at IP level							
FCN	Use Case	RAN, CORE	The NTN system shall support backhaul links for command posts and indoor communication							
FCN	Use Case	RAN, CORE	The NTN system shall support group communication							
FCN	Use Case	RAN, UE	The NTN system shall be able to use dedicated frequencies for PPDR assigned on national level							
FCN	Use Case	RAN, CORE	The NTN system shall allow to pre-emption lower priority communications in case of resource shortage to complete higher priority communication							
FCN	Use Case	RAN, CORE, OSS/BSS, traffic model	Through the subscriber profile, a UE shall select satellite-based access over the terrestrial-based access, when available							
FCN	Use Case	RAN, CORE, OSS/BSS, traffic model	In the NTN system, the SNO shall be able to allow the service provider (MNO) to select the NTN gateway and route the traffic through the network selecting the shortest path							
FCN	Use Case	CORE	The number of CPs shall be dimensioned and placed as to be able to trade-off space resources vs. longer data path vs. differentiated data paths for the same UE.							

FCN	Use Case	CORE	The number of Space UPF (SUPF) shall be dimensioned and placed as to be able to trade-off space resources vs. longer data path vs. differentiated data paths for the same UE.							
FCN	3GPP	RAN, CORE. OSS/BSS	A 5G system with satellite access shall enable roaming between 5G satellite access networks and 5G terrestrial access networks as specified in TR 22.822, section 5.1.5 (roaming)							
FCN	Use Case	RAN, CORE	A zero packet loss handover between SUPFs shall be provided (triggered by UE or by SUPF mobility)							
FCN	Use Case	RAN, CORE	The subscriber state shall be placed in space nodes in order to secure it and to reduce the delay of procedures							
FCN	Use Case	RAN, CORE, UE	To reduce the time taken to establish an eCall, an IVS, whilst in eCall only mode, may receive network availability information whilst not registered on a PLMN							
FCN	Use Case	RAN, CORE, UE	A PLMN shall indicate to an IVS whether IMS emergency call based eCalls are supported							
FCN	Use Case	RAN, CORE, UE	PLMNs shall make use of eCall indicators, received in the emergency call set-up, to differentiate eCalls from other emergency calls							
SYS	3GPP	RAN, UE	The interface between the NTN Satellite System and the UEs shall comply with the NR radio protocols together with NTN extension							
SYS	3GPP	RAN, CORE	The NTN System shall ensure interoperability with the terrestrial cellular network's management system							
SYS	3GPP	RAN, CORE	The NTN Satellite System shall provide an NG interface with the 5GCs it interconnects with.							
SYS	3GPP	RAN, CORE	The management of the NTN Satellite System shall be compliant with the specifications as set out in TS 28.540, [57], and TS 28.541, [58].							
SYS	Use Case	RAN, CORE	The NTN system may support NTN-NTN MC solutions to the IAB-Donor.							

SYS	Use Case	RAN, UE	The NTN system may support NTN-NTN MC solutions to the UE in direct access.							
SYS	Use Case	RAN, CORE	The NTN system may support TN-NTN MC solutions to the IAB-Donor.							
SYS	Use Case	RAN, UE	The NTN system may support TN-NTN MC solutions to the UE in direct access.							
SYS	Use Case	UE	The vehicle shall automatically initiate an eCall in the event of a serious road accident.							
SYS	Use Case	UE	The vehicle shall automatically initiate an eCall in the event of a serious road accident.							
SYS	Use Case	UE	An IVS, or other UE designed to support eCall functionality, shall include in the emergency call set-up an indication that the present call is either a Manually Initiated eCall (MIeC) or an Automatically Initiated eCall (AIeC)							
SYS	Use Case	RAN, CORE	The PSAP shall be given an indication that the incoming call is an eCall							
SYS	Use Case	RAN, UE	The satellite shall route the eCall to the most appropriate public safety access point							
SYS	Use Case	RAN, CORE	To support edge computing on the satellite, a UPF shall be deployed on the satellite							
SYS	Use Case	RAN, UE, CORE	The NTN system shall enable continuous driving support when vehicles switch the communication from TN to NTN							
SYS	Use Case	RAN, UE	The NTN system shall support operation in extreme environment (high mobility, rain, high/low temperature).							
SYS	Use Case	RAN, UE	The NTN system shall support rapid deployable solutions for the field.							
SYS	Use Case	RAN, UE	The NTN system shall support device to device communications.							
SYS	Use Case	RAN, UE	The NTN system shall support operation in extreme environment (high mobility, rain, high/low temperature).							