D3.7 REPORT ON 3D MULTI LAYERED NTN ARCHITECTURE

Revision: v.1.0

Work package	WP 3
Task	Task 1
Due date	31/12/2025
Submission date	12/01/2026
Deliverable lead	DLR
Version	1.00
Authors	Sandro Scalise, Juraj Poliak, Samuele Raffa, Manuel Roth, Umut Güloglu (DLR) Madivanane Nadarassin, Nicolas Chuberre (TAS-F) Russell Hills (TAS-UK) Ji Lianghai (QCOM) Eduardo Medeiros, Per-Erik Eriksson, Sebastian Euler (ERIS) Laurent Reynaud, Fanny Parzysz (ORA) Joel Götz (SES)
Reviewers	Alessandro Guidotti, Carla Amatetti (UNIBO) Xavier Artiga (CTTC)

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Grant Agreement No.: 101096479
Call: HORIZON-JU-SNS-2022

Topic: HORIZON-JU-SNS-2022-STREAM-B-01-03
Type of action: HORIZON-JU-RIA

Abstract	This deliverable presents the NTN topology (type of UEs, type of NTN nodes and envisaged communication links), a preliminary network sizing via link budget analysis and an analysis of the most promising NTN architecture and functional split options suiting the user cases identified in D2.1.
Keywords	NTN Topology, NTN Nodes, Link Budgets, Functional Architecture, Functional Split

Document Revision History

Version	Date	Description of change	List of contributor(s)
V0.1	03/11/2025	List of additions / modifications wrt D3.6	Sandro Scalise (DLR)
V0.9	15/12/2025	Version ready for QA review	Sandro Scalise (DLR), Umut Güloglu (DLR) Madivanane Nadarassin, (TAS-F) Laurent Reynaud (ORA) Joel Götz (SES)
V0.99	22/12/2025	Version incorporating the comments from the QA review and some corrections to sections 2.4 and 2.5	Sandro Scalise (DLR) Madivanane Nadarassin, (TAS-F)
V1.0	12/01/2026	Approved for submission	Alessandro Vanelli-Coralli (UniBo)

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State Secretariat for Education, Research and Innovation SERI

6G-NTN (*6G Non Terrestial Network*) project has received funding from the **Smart Networks and Services Joint Undertaking (SNS JU)** under the European Union's **Horizon Europe research and innovation programme** under Grant Agreement No 101096479. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. This work has received funding from the Swiss State Secretariat for Education, Research and Innovation (SERI).

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OTHER: Software, technical diagram, algorithms, models, etc.

EXECUTIVE SUMMARY

Deliverable D3.7 is the fourth and last version of the '*Report on 3D multi layered NTN architecture*'.

The goal of this deliverable is to provide a consolidated version of the 6G-NTN network topology, carry out the sizing of the communication links, and perform an analysis of the required Radio Access Network (RAN), Core network (CN) functions, and the corresponding split options to be implemented in space to meet the 6G-NTN Use Cases (UC) requirements.

It is worth emphasizing that this deliverable supersedes D3.1, D3.5, and D3.6, so in case of any conflicting information, the content in this document prevails over D3.1, D3.5, and D3.6.

In this deliverable, firstly, the main elements of the 6G-NTN system have been identified and characterized, namely:

- User Equipment (UEs), classified according to their usage type and to the type and capabilities of the Front Ends they will have.
- Network nodes, further divided into deterministic (satellites) and flexible/opportunistic such as High-Altitude Platforms (HAPs) or special heavy drones.
- Communication links between the above elements, namely service links, inter-node links (INL) or inter-satellite links (ISL), and feeder links.

A three-layer architecture made of HAPs as opportunistic/flexible nodes to locally improve the capacity and/or the coverage, two Low Earth Orbit (LEO) polar constellations with altitude of 600km for C-band and Q/V band connectivity, and an overlay layer of three Geostationary (GEO) satellites have been retained. The focus has been put on the LEO constellations, where 2 possible configurations have been identified, namely:

- A **conventional architecture**, where all LEO satellites of the two envisaged constellations are identical and include the payload for service links in C or Q/V-band, optical and RF inter-satellite links, and feeder links to connect to the ground stations.

  For this architecture, the analysis based on the 6G-NTN UCs shows that different functional split options might be best suited for different UCs and, therefore, a "one size fits all" approach is not ideal. Therefore, a novel concept called "Adaptive Functional Split" has been proposed. How this flexibility could be implemented and especially the impact on 6G standardization shall be subject of further analysis.
- A **distributed architecture**, in which we distinguish between "service satellite" and "feeder satellite". The former includes only the payload for service links in C or Q/V-band and optical inter-satellite links. Clusters of 4 service satellites are connected via the aforementioned optical inter-satellite links to a feeder satellite. On the other hand, "feeder satellites" are connected to each other and to the HAPs and GEOs via optical and RF inter-satellite links, and to the ground via the feeder link, but do not directly connect to any user equipment.

  The rationale behind the distributed architecture is to maximize the service link throughput by using almost all available power and mass in the service satellites. Conversely, feeder satellites should have enough available power and mass to implement all necessary RAN and eventually CN functionalities in space. The two solutions have been analysed and compared in terms of delay and power/mass budgets as well as cost assessment.

According to this design philosophy, it is proposed to implement a functional split in which only the Radio Unit (RU) and the low PHY are placed in the service satellites, whereas all the rest of the Distributed Unit (DU), Centralized Unit (CU) and, if necessary, CN functionalities are located in the feeder satellites.

Last but not least, link budgets and throughput estimations **focusing on LEO satellites** have been performed, leading to the following initial conclusions:

- LEO C-Band satellites can support 6-10 and 1.7-3.1 Gbps aggregate throughput in the service uplink and downlink, respectively. For LEO Q/V-band satellites, the figures are 16 and 12 Gbps, respectively.
- The requirements for the optical ISL depend on several points, such as the adopted functional split, the routing algorithms, the number of ground stations, and the percentage of traffic that might be processed on board each satellite. Nevertheless, 100 Gbps appears as a reasonable figure in terms of required optical power and telescope size, which is also compatible with ongoing industrial developments.
- The sizing of the feeder link is less critical, since the number of ground stations could be increased and/or their capabilities improved, e.g., by using larger antennas.
- In general, the link budget, throughput and delay performance analysis have shown that no major bottleneck in the LEO constellation shall be expected.
- The cost analysis has shown that the LEO feeder satellites need to be cheap enough compared to the terrestrial infrastructure to make up for the difference in investment in the space infrastructure. If such condition is met, the distributed architecture could be a viable option also from a cost perspective.

The structure of this deliverable is as follows:

- Chapter 1 presents the main elements of the 6G-NTN network, namely the type of terminals, the type of non-terrestrial nodes, and the radio links between them. Here, the concepts of conventional vs. distributed LEO constellations are also presented. **Sections 1.5 and 1.6 are new and contain the ground segment sizing and some general considerations on routing principles, respectively.** The rest contains only minor updates with respect to D3.6.
- Chapter 2 contains the throughput and link budget analysis for the LEO constellations given the network topology, types of terminals, and considered communication links discussed in the previous chapter. A summary is provided for the sake of convenience in Section 2.4 for the reader who is not interested in the many and lengthy link budget calculations and related assumptions. This part of the chapter only contains minor updates with respect to D3.6. **Section 2.5 is new and shows the delay performance assuming source routing is employed for path determination**.
- **Chapter 3 contains the high-level estimation of the required mass and power for the LEO satellites of the two proposed constellations and a preliminary cost assessment and comparison. This is an important addition with respect to D3.6.**
- Chapter 4analyses the different functional split options for the LEO constellations. This Chapter contains no updates with respect to D3.6.
- Lastly, two appendixes provide further details on the lower layer split (LLS) proposed in Chapter 4 and a detailed comparison of the pros and cons of the different split options in the context of NTN.

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ABBREVIATIONS

5G	Fifth Generation	**MAC**	Medium Access Control
6G	Sixth Generation	**MCS**	Modulation and Coding Scheme
ABFN	Analog Beam-Forming Network	**MEO**	Medium Earth Orbit
ACM	Adaptive Coding and Modulation	**MIMO**	Multiple-Input Multiple-Output
ADC	Analog to Digital Converter	**MTU**	Maximum Transfer Unit
AF	Application Function	**NAS**	Non-Access Stratum
AFS	Adaptive Functional Split	**NF**	Noise Figure or Network Function
AMF	Access and Mobility Management Function	**NGSO**	Non-Geo-Synchronous Orbit
AODV	Ad-hoc On-Demand Distance Vector	**NR**	New Radio
AP	Access Point	**NTN**	Non-Terrestrial Networks
AR	Augmented Reality	**OADM**	Optical Add/Drop Multiplexer
ARPQ	Adaptive Routing for Quality of Service	**OCC**	Optical Camera Communication
ARQ	Automatic Repeat reQuest	**OFDM**	Orthogonal Frequency Division Multiplexing
AS	Access Stratum	**OISL**	Optical ISL
ATN	Aggregation Transport Node	**OLT**	Optical Line Terminal
AUSF	Authentication Server Function	**ONU**	Optical Network Unit
AWGN	Additive White Gaussian Noise	**OSPF**	Open Shortest Path First
BBU	Base Band Unit	**OWC**	Optical Wireless Communication
BER	Bit Error Rate	**PCB**	Printed Circuit Board
BW	Bandwidth	**PCF**	Policy Control Function

CCSDS	Consultative Committee for Space Data Systems	**PDCP**	Packet Data Convergence Protocol
CGR	Contact Graph Routing	**PDU**	Protocol Data Unit
CN	Core Network	**PHY**	Physical Layer
COC	Center of Coverage	**PoC**	Proof of Concept
COTS	Commercial Off-The-Shelf	**PON**	Passive Optical Network
CP	Control Plane or Cyclic Prefix	**POS**	Passive Optical Splitter
CPA	Coarse Pointing Assembly	**PPDR**	Public Protection and Disaster Relief
CU	Central Unit	**PRB**	Physical Resource Block
DAC	Digital to Analog Converter	**PSK**	Phase Shift Keying
DBFN	Digital Beam-Forming Network	**QAM**	Quadrature Amplitude Modulation
DL	Downlink	**QoS**	Quality of Service
DN	Data Network	**QPSK**	Quaternary Phase Shift Keying
DP-QPSK	Dual Polarisation Quaternary Phase Shift Keying	**RAN**	Radio Access Network
DRA	Direct Radiating Array	**RF**	Radio Frequency
DRL	Deep Reinforcement Learning	**RLC**	Radio Link Control
DTN	Disruption-Tolerant Networking	**RNC**	Radio Network Controller
DU	Distributed Unit	**RNTI**	Radio Network Temporary Identifier
E2E or e2e	End to end	**RRC**	Radio Resource Control
EIRP	Equivalent Isotropic Radiated Power	**RTGWG**	Routing Area Working Group
EOC	Edge of Coverage	**RTT**	Round Trip Time
ETN	Edge Transport Node	**RU**	Radio Unit

FDD	Frequency Division Duplex	**RX**	Reception / Receiver
FE or F/E	Front End	**SaaS**	Software as a Service
FFT	Fast Fourier Transform	**SABR**	Schedule-Aware Bundle Routing
FiWi	Fiber Wireless	**SCS**	Sub-Carrier Spacing
FL	Feeder Link	**SDA**	Space Development Agency
FOV	Field of View	**SDAP**	Service Data Adaptation Protocol
FSO	Free Space Optic	**SDN**	Software-Defined Networking
GA	General Assembly	**SFP**	Small Factor Pluggable
GEO	Geostationary Earth Orbit	**SINR or SNIR**	Signal to Noise plus Interference Ratio
gNB	Next Generation Node B	**SL**	Service Link or Side Link
GNN	Graph Neural Network	**SMF**	Session Management Function
GS	Ground Station	**SNR**	Signal to Noise Ratio
GSO	Geo-Synchronous Orbit	**SSPA**	Solid State Power Amplifier
GUI	Graphical User Interface	**SWaP**	Size, Weight, and Power
GW	Gateway	**TCP**	Transmission Control Protocol
HAP	High Altitude Platform	**TDD**	Time Division Duplex
HAPS	High Altitude Platform Systems	**TDM**	Time Division Multiplexing
HARQ	Hybrid Automatic Repeat reQuest	**TDMA**	Time Division Multiple Access
HIBS	HAP station as IMT Base Station	**TN**	Terrestrial Network
HMD	Head Mounted Display	**TVR**	Time-Variant Routing
HO	Handover	**TWTA**	Travelling Wave Tube Amplifier
IAB	Integrated Access and Backhaul	**TX**	Transmission / Transmitter

IEEE	Institute of Electrical and Electronics Engineers	**U2U**	User Equipment to User Equipment
IETF	Internet Engineering Task Force	**UC**	Use Case
IFFT	Inverse Fast Fourier Transform	**UDM**	Unified Data Management
IMT	International Mobile Telecommunications	**UE**	User Equipment
INL	Inter-Node Link	**UHD**	Ultra-High Definition
IoT	Internet of Things	**UL**	Uplink
IP	Internet Protocol	**UP**	User Plane
IRIS²	Infrastructure for Resilience, Interconnectivity and Security by Satellite	**UPF**	User Plan Function
ISL	Inter-Satellite Link	**Uu**	Interface between UE and RAN
ITU	International Telecommunication Union	**VLEO**	Very Lowe Earth Orbit
LAN	Local Area Network	**VR**	Virtual Reality
LCT	Laser Communication Terminal	**VSAT**	Very Small Aperture Terminal
LDPC	Low Density Parity Check	**VT**	Virtual Topology
LED	Light-Emitting Diode	**WDM**	Wavelength Division Multiplexer
LEO	Low Earth Orbit	**WLAN**	Wireless Local Area Network
LiFi	Light Fidelity	**W-PON**	Wireless Passive Optical Network
LoS	Line of Sight	**Xn**	Network interface between NG-RAN nodes
L*x*	Layer *x* of the OSI Protocol Stack (*x* = 1...7)	**ZED**	Zero Energy Device

1 6G-NTN NETWORK TOPOLOGY

The architecture presented in this document is the outcome of an intense design activity, in which many different options have been analysed in terms of terminal and payload capabilities, as well as potential orbits to be considered, following a holistic approach and leading to the configuration presented in this chapter, which foresees two different options as far as the LEO constellation is concerned. The results from Tasks 2.1, 2.2, and 2.3, reported in the corresponding deliverables, have also been taken into consideration.

Furthermore, inputs from Task 2.5 on the availability of frequency bands have been considered, as well as input from other ongoing WP3 tasks regarding UE antennas, payload dimensioning, and LEO constellation sizing.

As already presented in the project proposal, the underpinning concept of 6G-NTN is a 3D multi-layered architecture, illustrated in Figure 1. The “3D” characteristic stems from the full integration of the non-terrestrial component with the terrestrial one, while the “multi-layered” feature is related to the integration of different layers consisting of communication nodes, i.e., satellites or HAPs flying at different and multiple altitudes. The flying nodes are interconnected by inter-node links (INL). We identify as horizontal links connections among nodes of the same constellation, e.g., LEO to LEO, and vertical links connections among nodes of different constellations, e.g., LEO to GEO. The differentiation between horizontal and vertical links plays a significant role in the definition of the architecture interfaces as the characteristics (e.g., delay, availability, etc.) of the links change significantly.

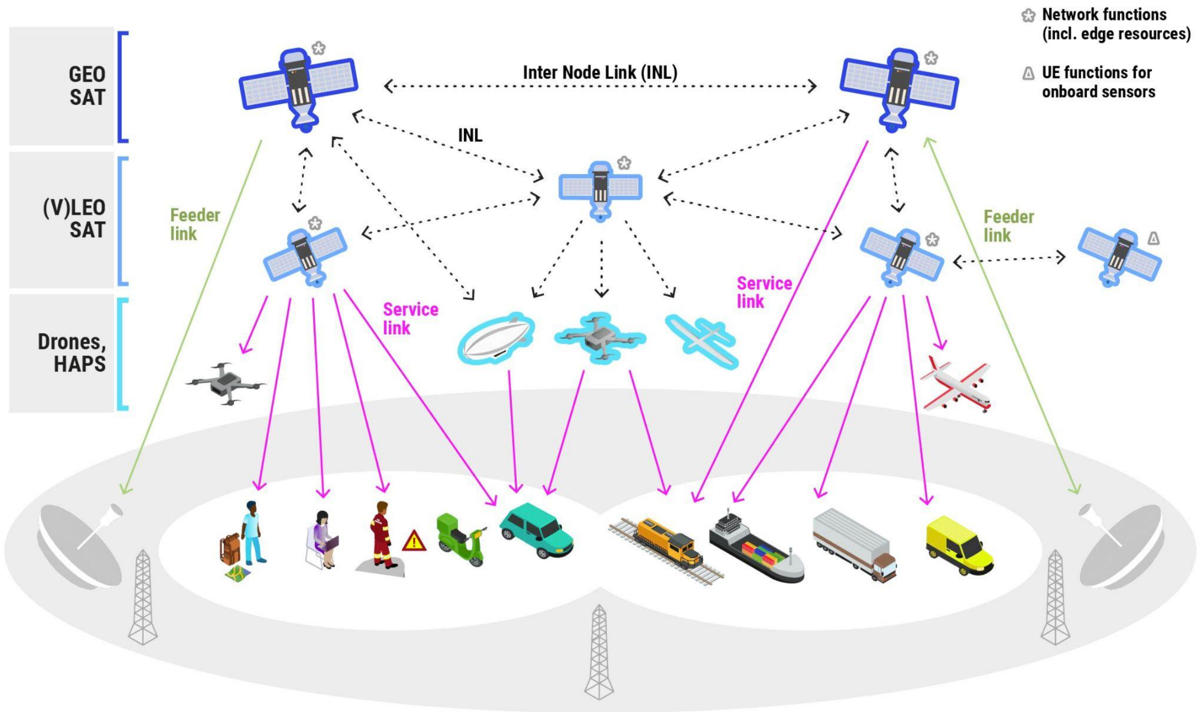

FIGURE 1: 6G-NTN 3D NETWORK CONCEPT

The rest of this chapter presents the main elements of the 6G-NTN network, namely the type of terminals, here after referred to as User Equipment (UE), the type of non-terrestrial nodes (HAPs and satellites at different altitudes), and the radio links between them.

1.1 TYPE OF USER EQUIPMENT

The following set of UEs was defined in D2.2 '*User requirements*', Section 4:

- Handheld
  - Consumer
  - Professional
- Drone-based
  - Light (and dismountable)
    - Max size 10x10x2 cm including antenna
    - Max weight 200-300 g
    - Max power consumption 10 mW / 1 W in idle / connected mode.
  - Heavy
    - Max size 20x20 cm including antenna
    - Max weight < 1 kg
    - Max power consumption 100 mW / 10 W in ideal idle / connected mode.
- Mounted UEs (please note that the types of mounted UEs defined in D2.2 '*User requirements*' follows a user centric classification, whereas here the antenna and amplifier performance are driving the breakdown reported below):
  - Automotive
  - Airborne (planes, helicopters, HAPs)
  - Vessel, train or bus-mounted

Furthermore, each type of terminal will typically have many Radio Frequency Front-Ends (RF FEs) to operate in different frequency bands, including Terrestrial Network (TN) and Non-Terrestrial Network (NTN) bands, and with different characteristics in terms of Noise Figure (NF), transmit power, and maximum antenna gain. The types of RF FEs considered so far are presented in Table 1. Insights on antenna design for UEs are reported in D3.2 '*Report on terminals*' and might influence the final figures to be considered.

TABLE 1: RF-FE TAXONOMY FOR 6G-NTN UE

Frequency Band	Remarks	NF [dB]	Max TX Power [dBm]	Max Antenna Gain [dBi]	RF-FE Acronym
Non-Terrestrial Frequency Bands					
C	Non-directive (hemispherical) antenna	7	26	-5	C_NTN_1
		7	26	-2	C_NTN_2

(see also Figure 3)		7	26	-2	C_NTN_3
Q/V (see also Figure 3)	Directive antenna	4	34	TX: 30.5-32 RX: 29.8-31.3	QV_NTN_1
		4	37	TX: 30.5-32 RX: 29.8-31.3	QV_NTN_2
Terrestrial Cellular Bands					
< 3 GHz and permitted for HIBS	The gNB in this case is on board a HAP	9	23	-3	HIBS_TN_1
< 3 GHz and permitted for aerial use					AERO_TN_1
Permitted for general use					CELL_TN_1

Accordingly, the mapping between the types of UEs and the available RF FEs has been defined and reported in Table 2. Please note that aerial platforms, such as HAPs, could have a double role in the 6G-NTN network since they can act both as UEs as well as Non-Terrestrial Nodes. Different classes of aerial nodes are envisaged and will be detailed further in D3.9 '*Report on software defined payload and its scalability*'.

TABLE 2: MAPPING BETWEEN UE TYPES AND RF FE

UE Type	**Available RF FEs**			
	Non-Terrestrial		**Terrestrial**	
	Non-Directive	**Directive**	**gNB in HAP**	**gNB on ground**
Handheld Consumer	C_NTN_1		HIBS_TN_1	CELL_TN_1
Handheld Professional	C_NTN_2		HIBS_TN_1	CELL_TN_1
Automotive	C_NTN_3	QV_NTN_1	HIBS_TN_1	CELL_TN_1

Light Drone	C_NTN_1 or C_NTN_2	QV_NTN_1	HIBS_TN_1	AERO_TN_1
Heavy Drone	C_NTN_3	QV_NTN_2	HIBS_TN_1	
Airborne		QV_NTN_1 or QV_NTN_2		
Vessel / Train / Bus	C_NTN_3	QV_NTN_2	HIBS_TN_1	CELL_TN_1

1.2 TYPE OF NON-TERRESTRIAL NODES

Non-Terrestrial or flying nodes are basically HAPs or special heavy drones, as well as satellites in different orbits. Satellites can be either placed in a geosynchronous orbit (GSO), meaning they rotate around the Earth with a period equal to one sidereal day (and with an average angular speed equal to that of the Earth), or in lower orbits with a period lower than one sidereal day, i.e., with an angular speed faster than that of the Earth.

The 6G-NTN topology considers two types of non-terrestrial nodes, namely deterministic nodes with a fixed and predictable orbit (both GSO and NGSO) and flexible nodes, namely HAPs or special heavy drones, which might or might not be present at different points in time and at different locations to extend coverage or enhance the network capacity. The latter are supposed to be deployed "opportunistically" depending on specific needs but are not meant to be a permanent infrastructure with global coverage.

The detailed payload and antenna design for non-terrestrial nodes has been carried out in D3.9 '*Report on software defined payload and its scalability*'.

1.2.1 Deterministic Non-Terrestrial Nodes

Deterministic nodes are basically satellites at different orbits. The 3D 6G-NTN network foresees different layers, namely:

- **An upper GSO layer made of 3 satellites in geostationary orbits (GEO)**. This is a special type of circular geosynchronous orbit with 0° inclination and an altitude of approximately 35.786 km. GEO satellites fly on the equatorial plane with a constant angular speed equal to that of the Earth. Thus, for a user located on the Earth's surface, they appear as fixed in the sky, which means no tracking antenna capabilities are needed for fixed terminals. Three such satellites can provide almost global coverage, excluding polar regions from where the satellites are not visible (i.e., close to or below the horizon). The actual coverage is determined by the minimum elevation, i.e., the minimum angle with which the satellite is visible over the local horizon of a user located on the Earth's surface, as shown in Figure 2. Inclined GSO orbits are not further considered since one of the main advantages of GEO, namely, no need for tracking antennas, is lost in such a case, whereas link budgets remain tight, and delay stays high.

  The GSO role is expected to have mostly a complementary role with respect to NGSO, focusing on:

  - **Broadcast & multicast (legacy) mission**, especially targeting fixed ground stations located e.g. at the edge of coverage. This is a standalone mission in Ka-Band with no TN component and transparent payload, which is however, not the primary focus of the 6G-NTN project. Its relevance for this study is thus limited to the impact on the overall mass and power budgets.

- **Broadband access that is less performant in terms of data rate and delay compared to the one of NGSO** and shall therefore be considered either as backup or as complementary capacity in case of hotspots (assuming dual steer/connectivity between GSO and NGSO links). This requires Q/V-band user links and a transparent or regenerative payload with full or split gNB.

- **Initial network logon** exploiting the large coverage area without handover needs. This might also require sub-6GHz user links, but in principle could be supported even with a transparent payload.

- **Non-delay sensitive traffic offloading from the NGSO network** thanks to the presence of inter-satellite links between NGSO and GSO layers, and also ensures resilience and link recovery in case e.g. of failure of the lower constellations.

- **Providing essential control and management planes functionalities to the NGSO fleet** in case of unavailability of the feeder links/ground segment. This should allow resilient and autonomous operation (eventually with reduced capabilities) of the network even in the presence of major disruption of the ground infrastructure. This is considered a very interesting long-term scenario, which will not be further investigated in this project.

- **Improved positioning.**

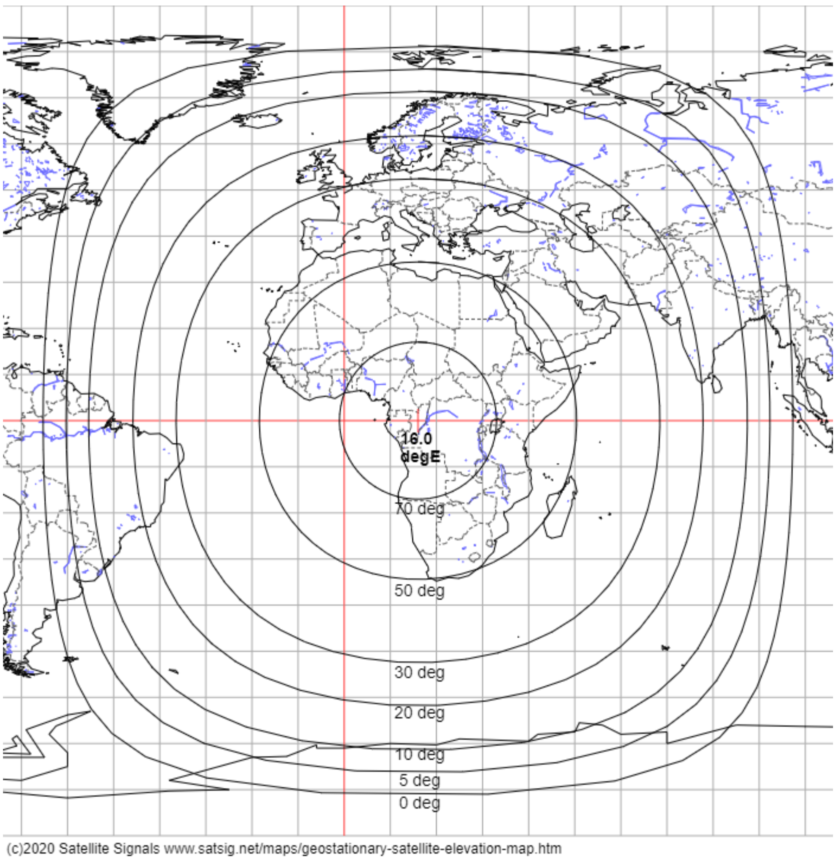

FIGURE 2: EXEMPLARY COVERAGE OF A GEO SATELLITE FOR DIFFERENT MINIMUM ELEVATION ANGLES

- **A lower layer made of NGSO satellites**, where LEO encompasses Earth-centred circular orbits with an altitude of 2.000 km or less, thus rotating around the Earth much faster than the Earth rotates around its axis. The main role of NGSO satellites is to provide broadband access to handhelds and to VSAT-like UEs (see also Table 2). This has been the main focus of WP3 and more specifically of Task 3.1. A summary of the initial constellation sizing performed in Tasks 3.4 is provided for the sake of completeness in Section 1.4.
- Medium Earth Orbit (MEO) satellites, flying typically at an altitude around 10.000 km, have not been considered, in order to limit the number of possible architectural options to be analysed. A MEO layer could be eventually considered as alternative to the GSO one to increase synergies with the expected solution for the IRIS2 (Infrastructure for Resilience, Interconnectivity and Security by Satellite) system of the European Commission [1].

1.2.2 Flexible NTN Nodes

Flexible nodes are basically HAPs and/or special heavy drones which might be temporarily deployed to provide additional capacity to specific areas. Remarkable examples are, for instance, disaster areas where no terrestrial infrastructure is available or areas where a sudden capacity increase is envisaged for a limited period of time, such as, large concerts or sport events both within cities but also in remote locations. Note that **it is not foreseen to have a permanent network of such nodes, rather they will be opportunistically deployed when and where needed**.

Examples of the usage of flexible NTN nodes are the following:

- Disaster areas where no terrestrial infrastructure is available. According to the required flexibility and mobility patterns for Public Protection and Disaster Relief (PPDR) as defined in D2.1 '*Use case definition'*, for UC #4, the HAP would be stationary when in operation as access node. However, when moving from one scenario of operation to another one, the HAP will be acting as UE using the available TN or NTN access for Telemetry Tracking and Control (TT&C).
- Areas where a sudden capacity increase is envisaged for a limited period of time, such as, e.g., large concerts or sport events both within cities but also in remote locations.

Very light platforms (e.g., Zephyr [2]) shall rely on transparent payload whereas larger and more powerful platforms can embark regenerative payload(s), eventually with additional resources for edge computing.

1.3 OVERVIEW OF COMMUNICATION LINKS

The following types of communication links are considered in the 6G-NTN architecture:

- **Feeder Links (FLs),** connecting deterministic or flexible nodes to a Ground Station (GS) / Gateway (GW) on the ground. GSs typically have large antennas and less stringent power limitations compared to UEs, therefore, FLs typically have a very high availability in the range of 99.5%, thanks to several advanced fading countermeasures, such as power control, Adaptive Coding and Modulation (ACM), predictive handover, etc. Still, the available data rate might vary in case of deep fading events caused, e.g., by rain. FLs might be both Downlinks (DLs) – Space to Earth and Uplinks (ULs) – Earth to Space.

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- **Inter-Node Links (INLs)** connecting non-terrestrial nodes. When both nodes are satellites, the term **Inter-Satellite Links (ISLs)** can also be used. When the link is realized using optical communication technologies, it will be named **Optical Inter-Satellite Link (OSIL)**. Otherwise, it is implicitly assumed that conventional RF technologies are used.
- **Service Links (SLs)** connecting deterministic or flexible nodes to a UE on the ground or mounted in a drone, plane, or HAP (see Table 2). Also, SLs might be both Downlinks (DLs) – Space to Earth and Uplinks (ULs) – Earth to Space.

An overview of the communication links of the 6G-NTN network is shown in Figure 3, including also the relevant frequency bands identified in D2.5 *'Report on regulatory requirements'*.

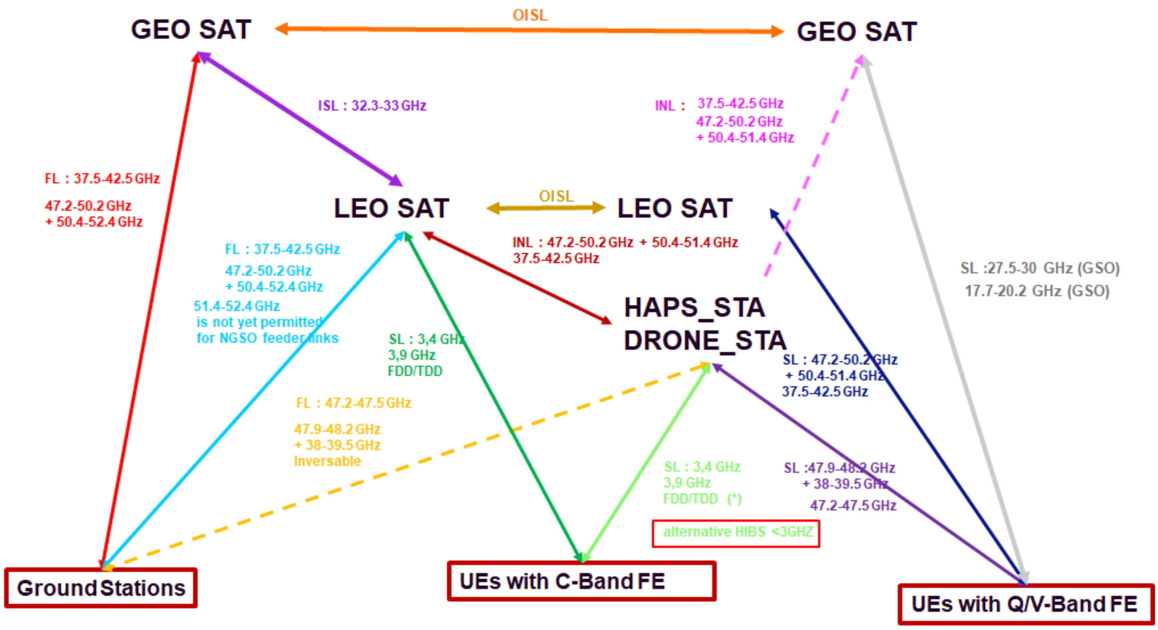

FIGURE 3: OVERVIEW OF RELEVANT COMMUNICATION LINKS AND FREQUENCY BANDS SERVICE LINKS

HAPs and (heavy) drones are marked with the "_STA" to denote they are meant as flying base stations and not as UEs.

Service links will be either in C-band with hemispherical/omnidirectional antennas in the UE or in Q/V band with highly directive antennas, as also reported in Table 1 and Table 2. For C-band links, FDD is assumed as a baseline, but the feasibility of TDD might be investigated in the future. For the Q/V-band links, FDD is the most logical approach, since the uplink and downlink are in separate frequency bands. Given the risk of not having C-band availability for HAPs due to regulatory issues, connectivity in lower frequency bands < 3 GHz is retained as a backup option.

It is worth emphasizing that Figure 3 also shows, for the sake of completeness, service links in Ka-band between UEs and GEO satellites. These are meant for the aforementioned legacy broadcast & multicast mission targeting fixed ground stations located, e.g., at the edge of coverage, which will be assumed to be part of the 6G-NTN system but not further analysed in the project and assumed to be largely based on state-of-the-art / available equipment and technologies. This mission will, however, affect the sizing of the GEO satellites in terms of mass and power budget.

On the contrary, backup complementary connectivity via GEO satellites in Q/V-band, although not shown in Figure 3, is also supposed to be part of the final 6G-NTN network and will be further investigated in the rest of the project.

1.3.1 Inter-Node Links

Four different types of INLs are potentially envisaged, namely:

1. Links between HAPs and LEO satellites, to be realized with RF technology in Q/V-Band. Since HAPs are mostly envisaged as standalone flexible network nodes, not necessarily in visibility of a ground station, all HAPs shall be able to connect to the LEO constellation. The same antenna could be eventually used to connect with a GEO in a worst-case scenario (with a lower rate), e.g., when the HAP is just acting as UE (moving between operational sites) and not in operation, and also to connect to a ground station if visible.
2. Links between LEOs and GEOs, to be realized in Ka-band using state-of-the-art / available equipment and available frequency allocation. Whether all LEO satellites will be equipped with ISL capabilities towards GEO or only a subset, shall be subject of further trade-off analysis. Eventually, optical technology might be used instead of the legacy RF solution if the data rate turns out to be not sufficient.
3. Links between LEO satellites, to be realized with optical technology.
4. Links between GEO satellites, to be realized also with optical technology. Due to the very large distance (close to 90.000 km assuming 3 GEOs equally spaced), their technical feasibility and meaningfulness given the achievable data rate shall be subject to future trade-off analysis.

In summary, **LEO-GEO in Ka-band, LEO-LEO with optical technology, and HAP-LEO in Q/V band are retained as baseline; GEO-GEO with optical technology shall be subject to further analysis.**

1.3.2 Feeder Links

All feeder links are supposed to be in Q/V-band. Although other frequencies may be considered, the Q/V band is the preferred choice, given the bandwidth available and the crowding of the spectrum. At present, they are mainly used as feeder links for GEO missions. Moreover, the beams are directive so that interference management with the other system will be less constraining to manage.

HAPs will have a direct connection to the ground only if they are in the visibility of a ground station. The sizing of the ground network in terms of a number of placements of the ground stations will be, however, driven by the need of the LEO constellation(s), so HAPs connectivity to a ground station will be merely opportunistic. In other words, no dedicated ground stations for HAPs will be considered, but HAPs can use any LEO ground station that is in visibility. Otherwise, they need to relay the traffic via the LEO network.

1.4 SUMMARY OF LEO & VLEO CONSTELLATION DESIGN

To achieve global coverage a certain number of satellites is required, typically grouped into a number of orbital planes with the same inclination but intersecting the equatorial plane at different positions. From the point of view of a user located on the Earth surface, satellites are moving (thus a non-negligible Doppler effect is present, although mostly deterministic) and frequent satellite handovers take place whenever a satellite is about to set and a new one is raising on the horizon. The design of a NGSO constellation is a complex exercise subject to many trade-offs between many parameters such as altitude, number and inclination of the orbital planes, overall number and size of satellites, coverage on ground, and, last but not least, also the number of required ground stations, which has been carried out in D3.10 '*Report on (V)LEO space segment*'.

From an architectural view point, two solutions are being considered for the functional architecture in Chapter 4, hereafter referred to as **conventional** and **distributed** architectures respectively.

1.4.1 Conventional Architecture

In the **conventional architecture** as the one sketched in Figure 1, **all LEO/VLEO satellites of the constellation are identical** and shall include:

- Service links with multibeam coverage.
- 4 bidirectional laser terminals for the ISL, connecting the two adjacent satellites in the same orbital plane and the 2 nearest satellites in the two adjacent orbital planes (standard configuration). Please note that an additional laser terminal might be needed for redundancy purposes.
- 2 feeder links as a minimum (for redundancy and/or seamless ground station handover)
- A Ka-band payload for the ISL to the GEO satellites, which might be eventually present only in some LEO satellites (not considered in this study)
- Suitable on-board processing units to implement all required RAN and possibly some Core Network functionalities.

TABLE 3: LEO CONSTELLATION SIZING AT 600KM ALTITUDE (CONVENTIONAL ARCHITECTURE)

	Minimum User Elevation 30°			Minimum User Elevation 45°		
Minimum number of Visible Satellites	Satellites per plane	Number of planes	Total number of satellites	Satellites per plane	Number of planes	Total number of satellites
1 (with minimum 10s handover duration)	28	17	476	**47**	**27**	**1269**
2	57	16	912	89	26	2314

TABLE 4: VLEO CONSTELLATION SIZING AT 350 KM ALTITUDE (CONVENTIONAL ARCHITECTURE)

	Minimum User Elevation 35°		
Minimum number of Visible Satellites	Satellites per plane	Number of planes	Total number of satellites

1 (with minimum 10s handover duration)	**55**	**32**	**1760**

The constellation sizing is summarized in Table 3 for LEO (600 km) and Table 4 for VLEO (350 km) showing the required number of satellites and orbital planes to have single or double satellite visibility for two different minimum elevation angles. The selected reference constellations are identified in bold. The working assumption is to have 2 of such constellations at 600 km in nearly polar orbit (approximately 87° inclination), one for C-band connectivity and another one for Q/V-band connectivity. The total number of LEO satellites for the 6G-NTN network is therefore twice the one reported in Table 3. Further details are available in in D3.10 '*Report on (v)LEO Space Segment'*. The final choice is to retain the following configurations:

- LEO (600) km with coverage of 45° minimum user elevation
- VLEO (350) km with coverage of 35° minimum user elevation

With the conventional approach (only one type of satellite), potential bottlenecks are to be expected as far as the availability of resources in space (complexity, power, and mass) is concerned, so a careful selection regarding RAN and CN functionalities to be implemented respectively in the satellite and on ground shall be performed. A thorough analysis of the advantages of the different functional split options currently considered in 5G has been carried out in Chapter 4.

1.4.2 Distributed Architecture

In the **distributed architecture**, the **satellites of the constellation are not all identical**. Specifically, we distinguish between **service satellites** and **feeder satellites**. As shown in Figure 4, service satellites are mainly devoted to provide connectivity to the UEs but they don't have feeder links. Most of the available payload mass and power is thus devoted to maximizing the service up- and downlink capacity, so these satellites will connect via ISLs to the feeder satellites but will have neither feeder links nor ISLs among them.

On the other hand, feeder satellites do not have direct link to the UEs, but they implement the full transport network in space using ISLs and feeder links and providing additional processing capabilities in space to implement RAN and if needed Core Network and Edge Computing functionalities.

Although from Figure 4 one might infer that service satellites are flying lower than feeder satellites, this is only a logical representation. As a matter of fact, the constellation design in Task 3.4 foresees the same altitude for all satellites and the following parameters (further details in D3.10 '*Report on (V)LEO space segment*'), depending on whether LEO or VLEO satellites are considered:

- 600 km / 350 km altitude (for all satellites) for the LEO / VLEO case respectively
- 45° / 35° minimum user elevation for the LEO / VLEO case respectively
- Near-polar inclination (~87°) in order to provide global coverage.
- Minimum of 1 satellite always visible.
- Minimum 10 s of overlap between 2 satellites for a user on ground to allow handover from one satellite to another.
- Each feeder satellite nominally serves 4 service satellites in each of the C and Q/V constellations.

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TABLE 5: LEO CONSTELLATION SIZING AT 600KM ALTITUDE (DISTRIBUTED ARCHITECTURE)

Type of satellite	Minimum number of Visible Satellites	Satellites per plane	Number of planes	Total number of satellites	FOV (°)	Altitude (km)
Service	**1 (with minimum 10s handover duration)**	**47**	**27**	**1269**	**45**	**600**
Feeder	**N/A**	**24**	**14**	**336**	**10**	**600**

TABLE 6: VLEO CONSTELLATION SIZING AT 350KM ALTITUDE (DISTRIBUTED ARCHITECTURE)

Type of satellite	Minimum number of Visible Satellites	Satellites per plane	Number of planes	Total number of satellites	FOV (°)	Altitude (km)
Service	**1 (with minimum 10s handover duration)**	**47**	**27**	**1760**	**35**	**350**
Feeder	**N/A**	**28**	**16**	**448**	**10**	**350**

A polar orbit allows global coverage with a minimum number of satellites, although this does create excess capacity over the poles where the orbital planes cross. Reducing the inclination by a few degrees maintains global coverage with a minimal change in the number of satellites, while significantly increasing the separation between satellites at the poles to simplify management of the constellation with regards to potential collisions.

Referring to the LEO case, the number of feeder satellites is larger than 318 (~1269/4) as might be expected. This is because each feeder satellite serves two service satellites in two adjacent planes. As there are an odd number of service satellites per plane, there will be one feeder satellite in each plane that only serves two service satellite. Also, there is an odd number of service satellite planes, meaning there will be planes of feeder satellites that only serve one service plane, and therefore only serve two service satellites (assuming the relative geometry of service and feeder satellites is kept constant). As not all feeder satellites are fully utilised, slightly more satellites are required.

The overall resulting LEO constellation is sketched in Figure 5, where red stars are service satellites, green stars are feeder satellites, magenta links are the ISL between service and feeder satellites and cyan links are the ISL between feeder satellites.

Service satellites will implement the service links in either C or Q/V-band with multibeam coverage and shall have at least two bidirectional laser terminals, one to connect to the nearest feeder satellite plus a second one for hot redundancy. The constellation configuration

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described above provides global coverage with a single satellite visible at all times but does not consider the frequency band. To provide both C-band and Q/V-band global coverage, and assuming service satellites can provide only C- or Q/V-band (not both due to size constraints), it is assumed that there effectively will be two independent service constellations of 1269 satellites each – one for C-band and one for Q/V-band. These will each provide global coverage in their respective bands, and as it is currently assumed they will both have the same configuration (altitude, inclination etc), then both constellations can co-orbit in a 'fixed' formation (ignoring the periodic variation in one orbit). This fixed formation allows both the C- and Q/V-band constellations to be served by the same feeder constellation, with each feeder satellite serving 4 satellites from each of the C- and Q/V-band constellations.

Feeder satellites will implement up to 4 feeder links (for redundancy and/or seamless ground station handover) and up to 13-14 bidirectional laser terminals:

- 4 to connect to the C-band service satellites.
- 4 to connect to the Q/V-band service satellites.
- 4 to connect to other feeder satellites (2 in plane and 2 inter-plane).

Considering however that not all terminals will be active simultaneously, the actual total number of required laser terminals could be subject of a detailed optimization depending on the estimated load in order to reduce mass and power requirements as shown in the next chapter.

Moreover, a Ka-band payload for the ISL link to the GEO satellites shall be considered, which might be eventually present only in a reduced number of feeder satellites

The advantages of this architectural solution are manifold, namely:

- **It allows higher service link throughput**, since no resources have to be provisioned for feeder link, only one ISL is needed, and thus almost all the available power can be devoted to the service link.
- **It offers better scalability and flexibility**, since the feeder satellites are totally agnostic regarding which spectrum and bandwidth is used for the service links. As long as the ISL and feeder links capacity does not become the bottleneck, new service satellites (more powerful and/or operating in a different frequency bands) could be progressively and seamlessly added.

Basically, through the distributed architecture the service links are completely decoupled from the transport network in space. Although this concept is not new, so far it has been considered mostly at academic level. As a matter of fact, all existing constellations including e.g. Starlink (if we exclude the fact that different generations are coexisting in space) adopts a conventional design where all satellites are (functionally) identical. **For the first time in the 6G-NTN project, a detailed constellation, payload and functional architecture design for this distributed solution is proposed.**

On the other hand, this solution requires approximately 15% more satellites and additional payload design and accommodation. This has been analysed in the comparative cost assessment performed in Chapter 3.

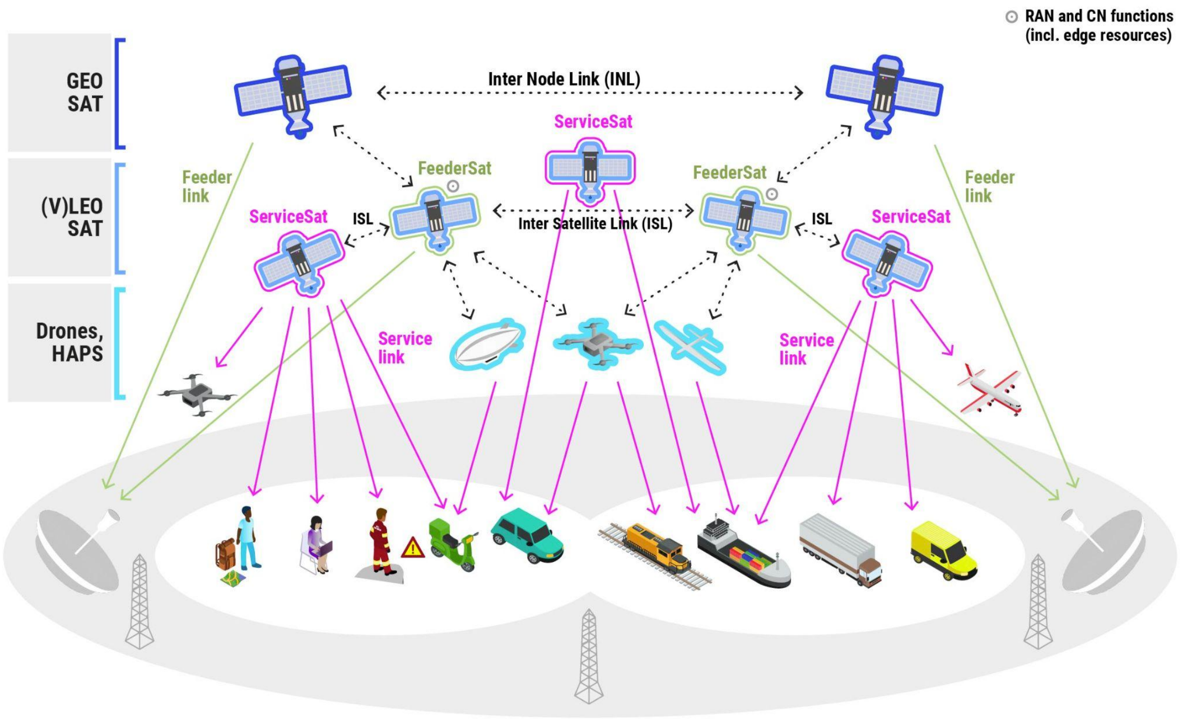

FIGURE 4 LEO CONSTELLATION (DISTRIBUTED ARCHITECTURE)

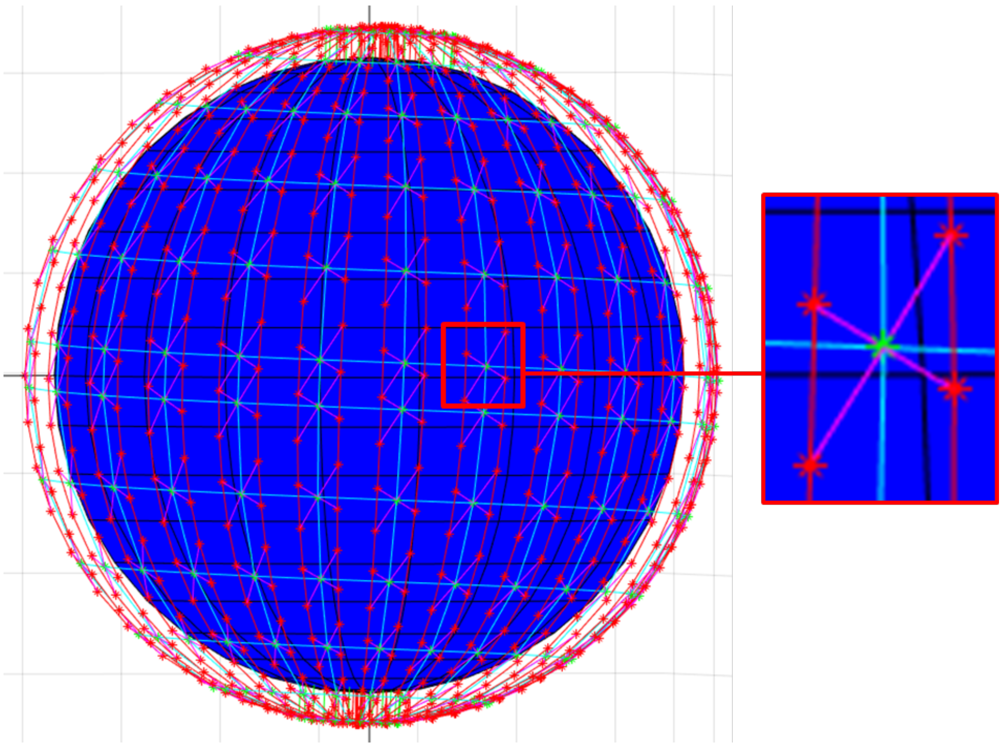

FIGURE 5 SERVICE AND FEEDER SATELLITES CONSTELLATION.

1.5 GROUND SEGMENT SIZING

The two main architectures require feeder-gateway links. In the first case (conventional architecture), one type of satellite must handle this connection in addition to other functions (users and inter-links). In the second case (distributed architecture), this function is offloaded to a second type of satellite (feeder satellite) that aggregates the traffic from four service satellites. These two scenarios were analysed in D3.10 '*Report on (V)LEO space segment*' under several assumptions.

The results are summarized in Table 7 and Table 8, respectively for LEO and VLEO constellations; in these tables, Architecture 1 and 2 refer to the conventional and distributed solutions, respectively.

TABLE 7: LEO CONSTELLATION GROUND SEGMENT

LEO	constellation	altitude 600 km		
the user coverage is 45° in Elmin				
		number of gateways	FOV (GW)	remark
	Architecture 1	85	20°	(1)
	Architecture 2	42	10°	(2)

TABLE 8: VLEO CONSTELLATION GROUND SEGMENT

VLEO	constellation	altitude 350 km		
the user coverage is 35° in Elmin				
		number of gateways	FOV (GW)	
	Architecture 1	140	20°	(3)
	Architecture 2	59	10°	(4)

(1) The user coverage 45°, the feeder FOV is limited to 20° to fulfil constraint of accommodation in the platform earth deck (shared by the main user mission antenna)
(2) The feeder FOV is reduced to 10°, no constraints in accommodation
(3) See (1)
(4) See (2)

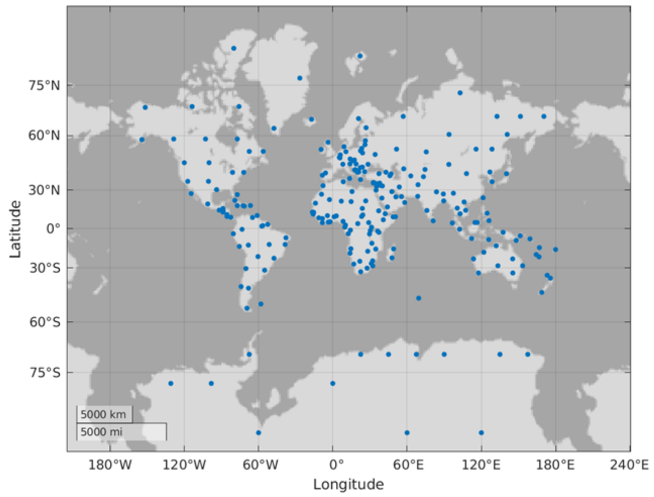

FIGURE 6: POSSIBLE GATEWAYS LOCATIONS

All these optimizations have been performed with the constraint to have a minimum of 1 gateway station on earth.

1.6 ROUTING PRINCIPLES

This section addresses the prominent architectural challenge of routing within multi-orbit NTN. In this context of integrated 6G with multiple altitudes of NTN operations (e.g., HAP, LEO, MEO, and GEO), the routing strategy must evolve from static terrestrial paradigms to handle the specific dynamic and scalable topology of the space domain.

1.6.1 Core Routing Challenges in NTN

Multi-orbit NTN requires a careful redesign of routing strategies, as off-the-shelf terrestrial solutions cannot address the environment's specific constraints. A series of salient challenges can be highlighted:

- High Dynamics and Predictable Mobility: Unlike terrestrial networks where link failures are anomalies, NTN topology changes are frequent but predictable. However, significant propagation delays (often >150ms in multi-hop or high-orbit paths) make real-time, centralized control difficult. This invalidates purely reactive strategies and offers a unique opportunity for protocols to plan for changes proactively using orbital mechanics.
- Link Heterogeneity and Intermittency: Algorithms must manage a multi-metric state across a heterogeneous environment of service links, feeder links, and ISLs. In that regard, satellites often lack continuous backbone availability (ground segment connectivity), requiring routing logic that can handle intermittent partitioning or exclusive reliance on ISLs.
- Massive scale versus finite resources: Routing must scale to constellations of hundreds up to tens of thousands of satellites while respecting the strict SWaP (Size, Weight, and Power) budget of the space segment. Solutions must be computationally efficient to run on solar-powered platforms with limited processing and storage.
- Regenerative payload architecture: The generational move toward on-board processing, decoupling UL/DL waveforms, and on-board base station functionality requires routing protocols that can leverage these capabilities, notably for efficient ISL forwarding [3]

1.6.2 Different Approaches for Space Routing

The following sections present a concise taxonomy of potential and noteworthy routing candidates for NTN.

1.6.2.1 Topology Abstraction

To manage the complexity of satellite motion, one approach utilizes the *virtual node* principle, which overlays a fixed logical grid of nodes upon the Earth's surface. In this scheme, physical satellites are dynamically mapped to the nearest virtual node as they traverse the corresponding geographical area, keeping the logical topology static while shifting complexity to the mapping of node dynamics [4]. An alternative method involves *virtual topology* or time-slicing, where the constellation's operational period is divided into discrete intervals. For each time slice, the network topology is treated as static and routing tables are pre-computed, requiring satellites to simply switch tables at specific intervals. However, this method is often criticized for lacking flexibility and generating a volume of routing information that does not scale well with large constellation sizes.

1.6.2.2 Adapting Terrestrial Protocols

Standard terrestrial protocols face significant hurdles when applied to the space domain. For instance, proactive link-state protocols like OSPF are difficult to transpose and deploy because the high link dynamics of NGSO constellations tend to trigger major detrimental issues (such as packet storm effects) regarding signalling messages. Instead, on-demand reactive protocols such as AODV may handle link dynamics better. However, those incur high latency during the route reconstruction of initial packets.

To address these limitations, the IETF has investigated Time-Variant Routing (TVR), which utilizes pre-scheduled information about future topological changes to compute paths valid over specific time intervals [5]. By using ephemeris data as a direct input, TVR enables a system that proactively plans for network dynamics rather than reacting to them after they occur.

1.6.2.3 Disruption-Tolerant Networking (DTN)

DTN architectures rely on a store-carry-and-forward mechanism to handle intermittent connectivity, often using *bundles* rather than standard packets. Variations of this approach include flooding-based schemes, which maximize delivery ratios at the cost of significant overhead, and quota-based schemes that limit the number of bundle replicas to achieve a more balanced performance. While forwarding-based approaches that use a single bundle are more resource-efficient, they suffer from lower delivery probabilities. Generally, traditional DTN protocols are viewed as too resource-intensive to be used "as is" for the high-throughput requirements of modern NTN. However, evolved standards like Schedule-Aware Bundle Routing (SABR) are emerging to better align DTN principles with the deterministic nature of satellite orbits [6].

1.6.2.4 Other Advanced Routing Paradigms

Advanced routing paradigms aim to shift from basic path discovery to multi-objective optimization capable of meeting specific QoS requirements. One such approach uses middleware to abstract the underlying network heterogeneity, presenting a unified virtual network service layer to applications while a specialized QoS routing scheme manages the translation to physical links. For scenarios involving imprecise metrics, fuzzy logic algorithms have been proposed to evaluate candidate links based on trade-offs between delay, throughput, and packet drop rates [7]. Another specific solution is Adaptive Routing for QoS (ARPQ), which employs a hierarchical strategy to dynamically offload traffic from LEO to MEO layers when delay thresholds or congestion limits are exceeded.

Finally, AI-driven routing transforms the problem into a continuous resource optimization task, often combining Graph Neural Networks (GNN) to represent the massive network state with Deep Reinforcement Learning (DRL) agents that learn optimal forwarding policies [8].

1.6.3 Relevant Normative Works

Among the standardization bodies which are actively addressing these challenges, three relevant works are worth highlighting:

- IETF TVR (Time-Variant Routing): The TVR Working Group is defining requirements to allow ephemeris data to serve as a direct input to path computation, standardizing the proactive routing paradigm [9].
- IETF DetNet (Deterministic Networking): While originally for terrestrial industrial networks, DetNet principles are well-suited to the deterministic motion of satellites. The concept of reserving time-slotted capacity on ISLs to create low-jitter virtual circuits aligns with DetNet's goal of bounded latency and loss [10].
- IETF Routing Area Working Group (RTGWG): Drafts such as Satellite Network Routing Use Cases and Routing in Satellite Networks propose layered routing structures where

simplified forwarding is performed on-board, managed by a more intelligent ground-based control plane [11].

1.6.4 Routing Design Recommendations

1.6.4.1 Synthetic comparison table

Table 9 provides a synthetic comparison of the five aforementioned routing paradigms identified for multi-orbit NTN, respectively described in Sections 1.6.2.1, 1.6.2.2, 1.6.2.3, 1.6.2.4 / first paragraph and 1.6.2.4 / second paragraph.

TABLE 9: ROUTING COMPARISON FOR MULTI-ORBIT NTN

Routing strategy	Behavior Principle	Dynamics Handling	Scalability (Size)	QoS Support	Comp. Overhead
Virtual Topology (VT)	Discrete static snapshots	Pre-computed (Rigid)	Low (Table storage)	Low (Best effort)	Low
Adapted Terrestrial (AODV)	On-demand discovery	Reactive (Rebuilds)	Low (Signalling)	Low (High Jitter)	Medium
Disruption-Tolerant (DTN)	Store-carry-forward	Schedule-Aware	Medium	High (Reliability)	Medium
QoS-based (Fuzzy/ARPQ)	Multi-objective rules	Adaptive / Hierarchical	Medium	Medium (Trade-offs)	Medium
AI/ML (DRL + GNN)	Dynamic optimization	Predictive / Learnt	High (Representation)	High (Adaptive)	High

The criteria used in Table 9 highlight the specific trade-offs inherent to the space domain:

- Behaviour Principle defines the fundamental logic of the protocol, ranging from the static time-slicing of VT to the intelligent, autonomous decision-making of AI/ML agents.
- Dynamics Handling assesses how the system copes with satellite motion. VT and DTN rely on deterministic inputs (ephemeris/contact plans), whereas Adapted Terrestrial protocols like AODV react only after links fail, causing latency spikes.
- Scalability refers to the ability to support constellations of thousands of nodes. VT-based approaches struggle here due to the explosion of routing table sizes, and default reactive protocols like AODV fail due to signalling packet storms. In contrast, AI/ML approaches, and specifically GNNs, excel by learning compact representations of massive graphs.
- QoS Support indicates the capability to guarantee performance. DTN-based solutions prioritize delivery ratio (reliability) over latency, while QoS-based and AI approaches actively optimize for specific metrics like delay or throughput.
- Finally, Computational Overhead reflects the burden on satellite SWaP budget. While VT is lightweight (simple lookups), AI/ML strategies incur the highest on-board processing

cost due to model inference, which explain why a careful design of this layer is particularly important to control this overhead.

1.6.4.2 Recommended Two-Layer NTN Routing Scheme

Based on the analysis provided in previous sections, Table 9 and given the conflicting aspects of the deterministic nature of orbital mechanics and the unpredictable nature of data traffic, a generalized, truly segment-as routing protocol appears inappropriate for the purpose of integrated multi-orbit NTN. Purely reactive protocols struggle with scale, while purely static ones fail to manage congestion and QoS. To resolve this conflict and bridge the gap between stability and agility, a promising solution could be provided by a hybrid, composite architecture that splits routing responsibilities across two distinct layers:

- **Layer 1: Deterministic Underlay (TVR-based).** Utilizing the principles of Time-Variant Routing, the network pre-computes baseline, stable paths using ephemeris data. This provides a robust, predictable backbone for data forwarding, ensuring basic connectivity without the signaling storms of reactive protocols.
- **Layer 2: AI-Driven Overlay (Traffic Engineering).** Layered on top, an AI/ML-based system performs real-time traffic engineering. This layer does not perform path discovery but optimizes forwarding decisions to handle unpredictable variations (e.g., congestion, weather-induced link degradation, and hardware failures), that the deterministic underlay cannot foresee.

This composite architecture shows promises via its ability to redefine space-based routing by leveraging the best attributes of two complementary layers. The TVR underlay acts as the backbone, guaranteeing that the network topology remains synchronized with the physical topology of the constellation without constant signalling overhead. Simultaneously, the AI overlay provides the added knowledge required for 6G services, dynamically steering flows to optimize QoS metrics like latency and jitter in real-time. By decoupling topology management from traffic optimization, this two-layer approach ensures that the network remains robust enough to scale to thousands of nodes. Yet, such an architecture should remain flexible enough to support the stringent demands of future multi-orbit services.

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2 6G-NTN THROUGHPUT, LINK BUDGETS AND DELAY PERFORMANCE ANALYSIS

This chapter contains the link budget analysis for the LEO constellation given the network topology, types of terminals, and considered communication links discussed in the previous chapter. **A summary is provided for the sake of convenience in Section 2.4 for the reader who is not interested in the many and lengthy link budget calculations and related assumptions.**

2.1 AGGREGATE THROUGHPUT PER SPACECRAFT

This chapter refers to D3.9 '*Report on Software defined payload and its scalability'* and to D3.10 '*Report on (V)LEO space segment'* to evaluate the total throughput per satellite.

The approach is to use the preliminary design elements in this document as a basis for assessing the maximum capacity of each satellite, in order to properly size the inter satellite links. Intensive details are given in D3.9 *'Report on software defined payload and its scalability'*

The satellite maximum capacity is evaluated over a coverage with minimum elevation angle of 45°, containing 499 cells of approximately 45 km diameter. An optimization process has been applied to identify the scenarios where the maximum rate has been reached.

The implemented methodology is as follows:

1. For the downlink, consider, for the maximum available power, the maximum achievable throughput as a function of the number of active beams, with a maximum of 100 beams. The process is to optimize the X beam/499 configuration to achieve this maximum.
2. For the uplink, we look at the achievable throughput as a function of the number of active beams in the X beam/499 distribution for a maximum of beams.

2.1.1 C-Band Satellite

2.1.1.1 Coverage

The constellation shall cover 98% of the Earth surface (sea and land) and the satellite will be placed in a polar orbit in order to achieve global coverage.

The constellation can be optimized with a wide tilt angle to minimize the number of satellites. This implies some restrictions and, above all, a reduction in polar coverage. A polar constellation with a slight inclination to ensure maximum coverage have been selected even if a number of satellites coverage superpose at the poles. This disadvantageous feature will be used to mute off a number of payloads in order to ensure an efficient thermal control. A trade-off performed on several parameters allowed to define a best compromise solution, and the details are given in D3.9 '*Report on Software defined payload and its scalability*'.

For LEO satellites at 600 km altitude, the coverages for C-band and Q/V band have been taken identically for definition congruence and consistency (see D3.9 for more details). Each satellite ensures a coverage of a minimum elevation angle of 45°, which represents 499 cells of 45 km arranged in a hexagonal lattice, as shown in the leftmost picture of Figure 7.

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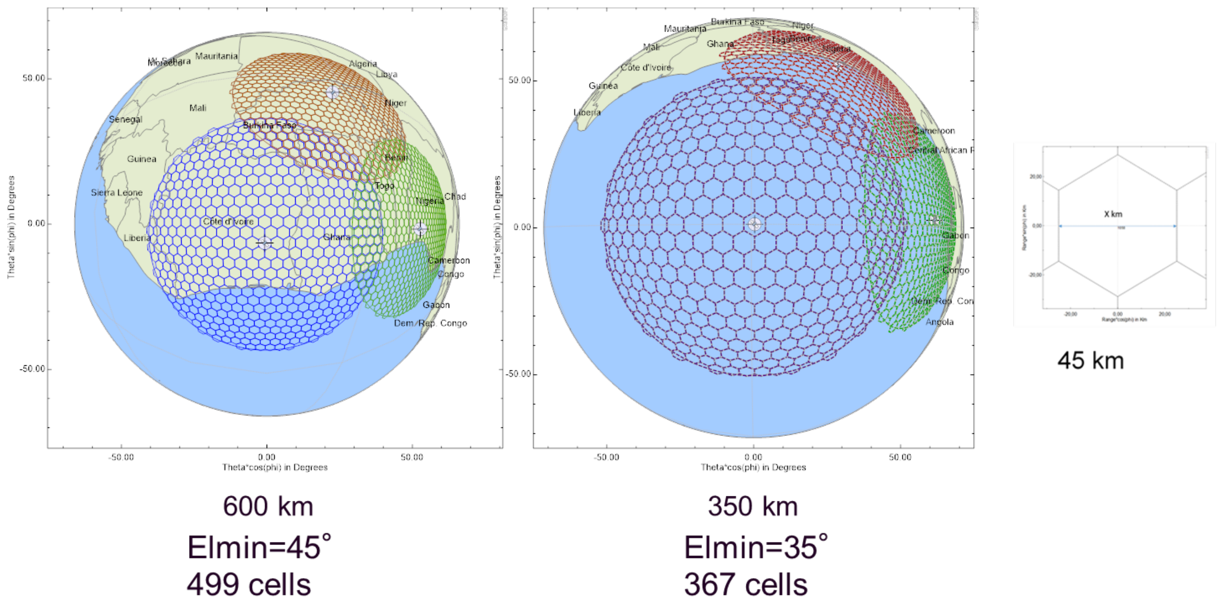

FIGURE 7: VIEW OF SATELLITE COVERAGE / CELL SIZE

For VLEO satellites at 350 km altitude, the coverage for C-band, each satellite ensures a coverage of a minimum elevation angle of 35°, which represents 367 cells of 45 km arranged in a hexagonal lattice as shown in the middle picture of Figure 7.

2.1.1.2 C-Band Payload Characteristics

The main parameters relevant to the calculations and figures presented in this chapter are:

- The EIRP density is 28-30 dBW/MHz per beam, approximately (maximum 37-100 beams).
- The satellite is designed to deliver 33-33.6 dBW RF total power, which could be distributed over the beams with the aforementioned EIRP density. The number of beams could be adjusted according to the demand and in the purpose to optimize the resource.
- 100 active beams are taken as a nominal value, which represent 20% of the beams in the coverage. The number of active beams could be adjusted to respond optimally to the demand.
- A bandwidth of 100 MHz is assumed for the link budget.

These parameters have been taken as a possible set for constellation and performance estimation. Several alternatives are possible to manage the performance and depend on the best way to optimize the resources. The only constraint is the maximum power available on board.

2.1.1.3 C-band UE Characteristic

With respect to the types of RF-FE presented in Table 1, a worst-case assumption in FDD mode is taken here, considering a noise figure NF = 7 dB, an antenna gain taking into account only the scan losses and a TX power of 26 dBm and a gain of - 5dBi have been taken for the performance estimation (which could be the most common UE characteristics).

The FDD mode is taken for the analysis and the one used on the most common terminal will be the C_NTN_1.

The others C_NTN_2 & C_NTN_3 (professional and vehicle mounted terminal) will allow to reach better performances but are not the most largely used.

2.1.1.4 C-Band Numerology

The considered C-band numerology is show in the table below.

TABLE 10: NUMEROLOGY C-BAND

	Frequency Range				Used Frequency		Channel Bandwidth		PRB					
ID	UL		DL		UL	DL	UL	DL	UL	DL	# carriers	SCS BW	PRB BW	# PRB
	Fmin (GHz)	Fmax (GHz)	Fmin (GHz)	Fmax (GHz)	GHz	GHz	MHz	MHz	kHz	kHz	-	kHz	kHz	-
C1	3.9	4	3.2	3.3	3.9	3.4	100	100	360	360	12	30	360	273

2.1.1.5 Downlink and Uplink Budget: Max Throughput

For the 3 cases (A = reference LEO, B = VLEO, C = enhanced LEO) in C-band investigated in D3.9 '*Report on Software defined payload and its scalability*', the table below summarizes the performances. RE is the envisaged number of radiating elements.

TABLE 11: DOWNLINK (MAX) AND UPLINK THROUGHPUT

	CASE A	CASE B	CASE C
C-BAND	600 km	350 km	600 km
	1056 RE	1536 RE	2048 RE
nb active beams	60	37	60
% actives beams	12	10	12
Downlink max (Gbps)	1.7	3.1	2
Uplink (Gbps)	7.5	6.1	9.7

The uplink budgets are calculated at the maximum of throughput in downlink.

2.1.2 Q/V-Band

2.1.2.1 Coverage

The definition of satellite coverage for Q/V band is the result of a trade-off performed in Task 3.3 taking into account all the dimensioning parameters. As technical maturity in Q/V is more difficult to assess, several assumptions have been made to define the satellite antenna and UE antenna solutions. Satellite coverage has an impact on the constellation size, while the cell size is linked to the antenna aperture size. The results converge towards a payload solution comprising several Direct Radiating Antennas (DRA) of limited size and beams-generating capacity. Ttechnological advances might allow moving from Analog Beamforming Network (ABFN) or Digital Beamforming Network (DBFN). The definition of cells is also constrained by the ability to keep the satellite stable, so as not to make pointing errors and ensure good cell performance. For this reason, we chose not to dimension very small cells. The choice was

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made to keep the same coverage and cell definition as for C-band, which means we only need one “cell definition” in 6G-NTN.

Therefore, the coverage is the same as the C-Band coverage shown in Figure 6 with 45° as a maximum elevation and 499 cells of 45 km in a hexagonal lattice. Taking the same coverage will allow to have only one cell definition on earth.

The maximum capacity of a satellite is evaluated in the same way as the C-Band satellite. Thus, an optimization process has been applied to determine the maximum throughput achievable according to the number of active beams (maximum 28 beams in Q/V band case) for a coverage of minimum elevation of 45° composed of 499 cells of 45 km.

2.1.2.2 Q/V-Band Payload Characteristics

A detailed payload sizing is reported in D3.9 ‘*Report on Software defined payload and its scalability*’. As mentioned in this document, the payload is composed of two antenna panels one in Q band (Tx) and the second in V band (Rx). Each panel is composed itself by 7 antennas of each type. Each antenna is able to generate 4 beams. The main parameters relevant to the calculations and figures presented in this chapter are:

- The EIRP flux is approximately 18.2 dBW/MHz per beam for 4 simultaneous beams per antenna.
- The maximum RF power per TX antenna is 53 W (4 beams). The TX panels RF power is 371 W in total.
- The payload is constituted of 7 antennas, and each one generates 4 active beams, which represents a maximum of 28 beams in RX and 28 beams in TX.
- The bandwidth of each antenna is 400 MHz.

2.1.2.3 Q/V-Band UE Characteristic

With respect to the types of RF-FE presented in Table 1, an “average terminal” with a noise figure NF = 4 dB and a RX gain of 31.3-28.8 dBi, an antenna TX gain of 30-32 dBi and a TX power of 34 dBm has been assumed.

2.1.2.4 Q/V-Band Numerology

The considered Q/V-band numerology is shown in Table 12.

TABLE 12: NUMEROLOGY Q/V-BAND

	Frequency Range				Used Frequency		Channel Bandwidth		PRB					
ID	UL		DL		UL	DL	UL	DL	UL	DL	# carriers	SCS BW	PRB BW	# PRB
	Fmin (GHz)	Fmax (GHz)	Fmin (GHz)	Fmax (GHz)	GHz	GHz	MHz	MHz	kHz	kHz	-	kHz	kHz	-
Q-V2	47.2	50.4	37.5	40.5	50	40	400	400	1440	1440	12	120	5760	264

2.1.2.5 Downlink and Uplink Budget: Max Throughput

The maximum aggregated throughput versus number of active beams is presented in the table blow.

TABLE 13: DOWNLINK (MAX) AND UPLINK (MAX) THROUGHPUT

	CASE Q/V
Q/V-BAND	**600 km**
	7x 512 RE
nb active beams	28
% actives beams	6
Downlink max (Gbps)	12
Uplink (Gbps)	16

2.2 INTER-NODE LINK BUDGETS

2.2.1 Inter-Orbit Link Budgets with RF Technologies

The inter-orbit links constitute the inter-node links between LEO and GEO satellites, and between HAPs and LEO satellites:

- HAP-LEO Link Budgets (Q/V-Band) → see Section 4.7 of D3.9 '*Report on Software defined payload and its scalability*'.
- LEO-GEO Link Budgets (Ka-Band) → see Section 4.10 of D3.9 '*Report on Software defined payload and its scalability*'.

2.2.2 Intra-Orbit Link Budgets with Optical Technology

Optical inter-satellite links (OISL) provide a reliable and high-throughput communication link between two satellites. Different scenarios are investigated, namely:

1. LEO-LEO OISL at altitude of 600 km for a conventional constellation design such as the one presented in Section 1.4.1.
2. GEO-GEO OISL assuming three equally spaced GEO satellites on the equatorial belt.
3. OISL between service and feeder LEO satellites for the distributed constellation presented in 1.4.2.
4. OISL between feeder satellites for the distributed constellation presented in 1.4.2.

Note that for intra-plane OISL (Scenario 1), Doppler rates, pointing angles rates as well as fast link switching mechanisms can be neglected lowering such the implementation effort. Inter-plane OISL (Scenarios 2 – 4) considerations are further discussed in Section 2.2.2.3.

In the following, we are presenting link budgets for the individual scenarios including justification for choice of system and channel parameters. The following system parameters are used to define the scenarios:

- Link distance.
- Size (diameter) of the TX and RX apertures.
- TX power launched from the communications system.

- Detector sensitivity in photons per bit that defines the required minimum received optical power at given data rate and Bit Error Rate (BER).

A coherent modulation format for both link directions was assumed. This is assumed to be valid for bitrates of 10 Gbps and beyond, where non-coherent modulations (such as on-off keying or pulse-position modulation) require significant implementation effort compared to lower bitrates whilst being inferior in terms of sensitivity and overall performance when compared to coherent (e.g., PSK and QAM) formats. State-of-the-Art (SoA) coherent communications systems with DP-QPSK modulation, pre-amplification and robust coding are capable of achieving sensitivities as low as 5 photons per bit (10 ppb value used in calculations below to allow for certain implementation margin).

In-line with the current SoA development in space optical terminals (based, e.g., on SDA recommendation [12]), we neglect interference between individual links. Low divergence of the transmitted beam (<1 mrad) in combination with narrow field-of-view (FOV) of individual terminals (~few mrad) ensures stable tracking. During acquisition, identification of the individual terminals is ensured during link (switchover) planning (based on the ephemeris) and using complementary wavelength bands for transmission and reception that can be planned considering also link geometry on-orbit. Additional strategies, such as link identification via tracking system or at link layer could be considered.

In general, channel is modelled as a loss-less Additive White Gaussian Noise (AWGN) channel without non-linearities. Losses are considered constant and described as follows:

- Free-space propagation is modelled as free-space loss due to link distance and wavelength.
- TX and RX gains are those inherent to the telescope size. The different values reflect the fact that, whilst reception occurs over the entire aperture, the transmitted beam must be smaller than the mechanical size of the telescope to avoid diffraction effects (by a factor of $2^{1/2}$).
- Optical losses at the transmitter and receiver are due to imperfect transmission and reflection properties of the optics.

Furthermore, we use optical system properties such as:

- RX splitting loss to model the loss due to splitting part of the optical power used for the tracking of the optical terminals.
- RX coupling loss models the limited performance of the optical fibre-coupling subsystem.
- Last, we assumed 4dB coding gain provided by a low-complexity channel code.

2.2.2.1 LEO-LEO Link Budgets

Orbital parameters of a LEO-LEO link are as follows:

- LEO altitude of 600 km.
- Feeder-feeder OISL range of 2040 km.
- Feeder-service OISL range of 820 km.

From the link budgets elaborated in D3.10 ‘*Report on (V)LEO space segment’*, we could observe following:

- By increasing the aperture size of the Feeder Satellite to 80 mm (e.g., TESAT SCOT-80 optical terminal [13]), the 100G OISL is feasible with reasonable optical power and optical terminals that are available “off-the-shelf”.

- The Service Satellite aperture can then be decreased to 20 mm, being in-line, e.g., with a commercial TESAT SCOT-20 optical terminal [13].

TABLE 14: LINK BUDGET LEO FEEDER-FEEDER OISL WITH 80 MM APERTURE.

Parameter	Units	Feeder-Feeder OISL
Link Distance	km	2040
Tx Aperture	m	0.08
Rx Aperture	m	0.08
Tx Power	dBm	27.0
Tx Gain	dB	101.2
Tx Optical Loss	dB	-0.7
Tx Pointing Loss	dB	-2.0
Free Space Loss	dB	264.4
Rx Gain	dB	104.2
Rx Optical Loss	dB	-1.5
Coding Gain	dB	4.0
Rx Splitting Loss	dB	-1.0
Rx Coupling Loss	dB	-3.0
Received optical power	dBm	-40.2
Effective received optical power*	dBm	-36.2
Detector Sensitivity	PPB	10
Req. Power at 100G	dBm	-39.0
Link Margin at 100G	dB	+2.8

TABLE 15: LINK BUDGET LEO FEEDER-SERVICE OISL WITH 20 MM APERTURE.

Parameter	Units	Feeder-Service OISL	Service-Feeder OISL
Link Distance	km	820	820
Tx Aperture	m	0.08	0.02
Rx Aperture	m	0.02	0.08
Tx Power	dBm	30.0	30.0
Tx Gain	dB	101.2	89.1
Tx Optical Loss	dB	-0.7	-0.7
Tx Pointing Loss	dB	-2.0	-2.0

Free Space Loss	dB	256.5	256.5
Rx Gain	dB	92.2	104.2
Rx Optical Loss	dB	-1.5	-1.5
Coding Gain	dB	4.0	4.0
Rx Splitting Loss	dB	-1.0	-1.0
Rx Coupling Loss	dB	-3.0	-3.0
Received optical power	dBm	-41.3	-41.3
Effective received optical power*	dBm	-37.3	-37.3
Detector Sensitivity	PPB	10	10
Req. Power at 100G	dBm	-39.0	-39.0
Link Margin at 100G	dB	+1.7	+1.6

* the effective optical power considers coding gain w.r.t the (nominal) received optical power

2.2.2.2 GEO-GEO Link Budgets

To close the link budget of the GEO-GEO OISL, the aperture size of 250 mm would need to be used (such as 260 mm telescope on the recently launched TELEO demonstration on-board BADR-8 satellite [14]) to enable 100G GEO-GEO OISL. The dependency of the achievable capacity for various terminal aperture sizes and launch (transmit) powers is also illustrated in Figure 8. This also shows that a relaxation of the data rate to 10 Gbps would potentially allow the use of TESAT SCOT-135 optical terminal.

TABLE 16: LINK BUDGET GEO OISL FOR 250 MM APERTURE SIZE

Parameter	Units	GEO-GEO
Link Distance	km	70000
Tx Aperture	m	0.25
Rx Aperture	m	0.25
Tx Power	dBm	37.0
Tx Gain	dB	111.1
Tx Optical Loss	dB	-0.7
Tx Pointing Loss	dB	-2.0
Free Space Loss	dB	-295.1
Rx Gain	dB	114.1
Rx Optical Loss	dB	-1.5
Coding Gain	dB	4.0
Rx Splitting Loss	dB	-1.0
Rx Coupling Loss	dB	-3.0
Total Transmission	dBm	-41.1

Effective Power	dBm	-37.1
Detector Sensitivity	PPB	10
Req. Power at 100G	dBm	-39.0
Link Margin at 100G	dB	1.9

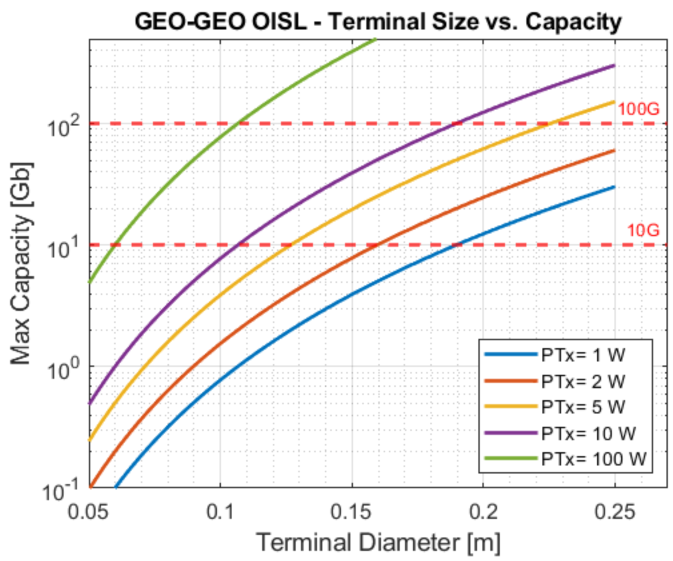

FIGURE 8: CAPACITY ASSESSMENT IN GBPS OF A GEO OISL AS A FUNCTION OF THE USED TERMINAL DIAMETER FOR VARIOUS TRANSMITTED OPTICAL POWER LEVELS.

2.2.2.3 Service-Feeder OISL

Next, we consider Service-Feeder scenario. For the sake of the analysis, we first consider symmetrical nodes (i.e., same TX and RX sizes). This allows us to investigate the changing link geometry as can be seen in Figure 9. However, one may want to scale the aperture sizes to close the link budget for a given target data rate.

Link distance variation in this scenario is relatively small and causes only minimal changes in physical RTT (UE → Service Satellite → Feeder Satellite and back) at most approx. 15-20%. Azimuth and elevation graphs show that nearly hemispherical coarse pointing assembly (CPA) would be required, but at given (very small) angular rates and considered terminal sizes, such CPA realizations are commercially available.

Considering maximum link distance of 820 km and following link capacity considerations in Section 2.2.2.1, capacity estimations for asymmetrical system realizations, i.e., for different service and feeder satellite optical terminal sizes were analysed for 100 Gbps link capacity in Figure 10 at the top and bottom, respectively.

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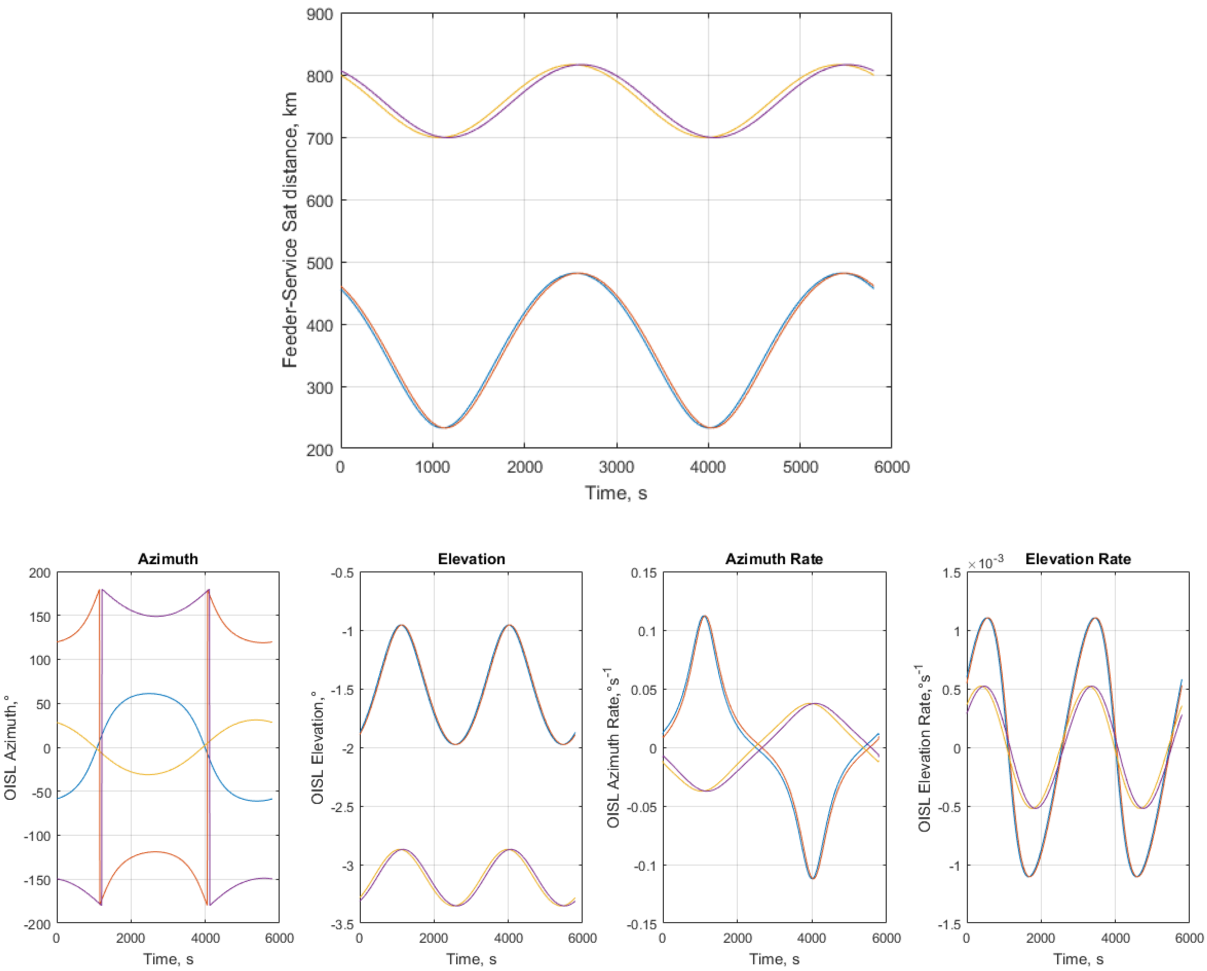

FIGURE 9: LINK DISTANCE (TOP) AND AZIMUTH AND ELEVATION ANGLES AND RATES (BOTTOM) IN SERVICE-FEEDER OISL SCENARIO.

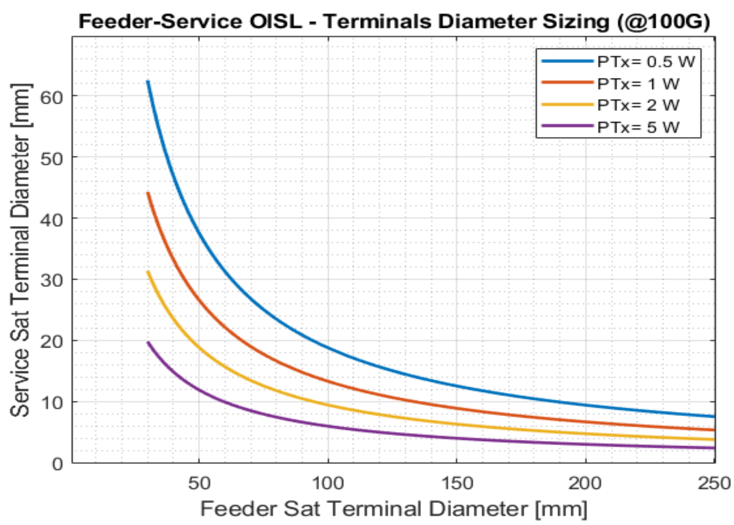

FIGURE 10: TERMINAL SIZING FOR SERVICE AND FEEDER SATELLITE OPTICAL TERMINALS FOR VARIOUS (FEEDER) TRANSMIT POWERS AT 100GBPS.

2.2.2.4 Feeder-Feeder OISL

For Feeder-Feeder OISL, the situation varies, whether intra-plane or inter-plane OISLs are considered. Figure 11 shows nearly constant link distance of approx. 1850 km for intra-plane OISL, but significant variation for inter-plane OISL. In such scenario, adaptive data rates or modulation formats or transmit power (or a combination of these) can be used to optimize the available resources at the cost of reduced link capacity or achievable link distance (and so coverage).

In Figure 11 we can also observe a somewhat reduced field-of-regard, which allows for more flexibility in the optical terminal placement on the spacecraft, for instance at positions that would provide partially obscuration by other payloads, antennas or solar panels. More critically, angular (particularly azimuth) rates at link switchovers would not allow for an instantaneous switchover around polar regions. Gaps in order of lower tens of seconds are expected as angular rates up to approximately 5 deg/s are more realistic. This only includes physical link re-acquisition and omits the additional delay caused by data and link layers.

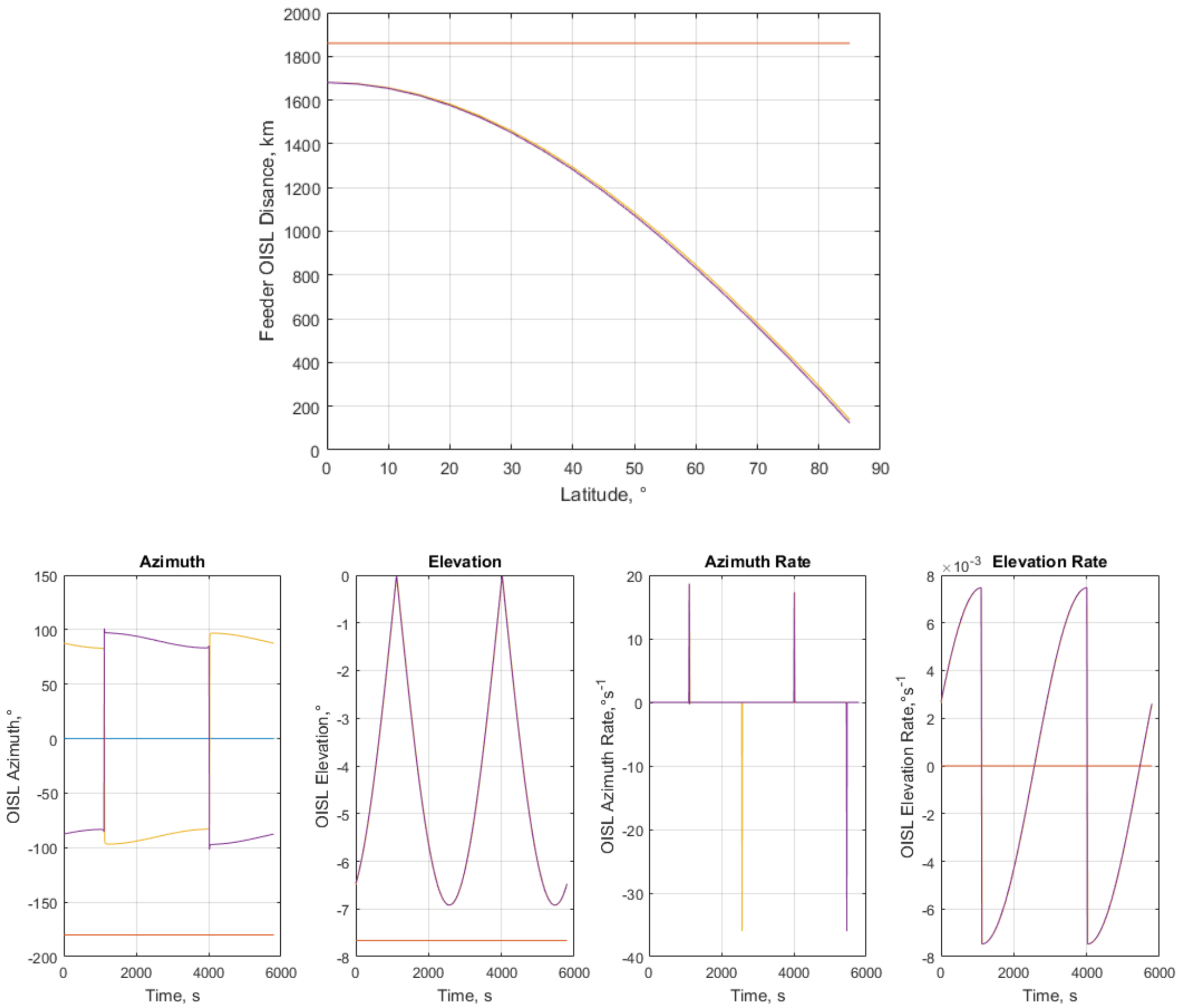

FIGURE 11 TOP: FEEDER-FEEDER OISL DISTANCE ANALYSIS FOR INTRA-PLANE (YELLOW) AND INTER-PLANE (RED) OISL. BOTTOM: AZIMUTH AND ELEVATION ANGLES AND RATES.

To overcome the aforementioned problem an alternative (diagonal) configuration has been considered in D3.10 '*Report on (V)LEO space segment'*, as shown in Figure 12 (vs. rightmost picture of Figure 5). A slightly longer however more constant link distances for both inter-plane and intra-plane OISLs can be achieved, with max. distance of approx. 2040 km. For this distance, the capacity assessment was carried out and is shown in Figure 13. As discussed at the beginning of Section 2.2.2, relatively small angles between individual links are considered to not cause any interference.

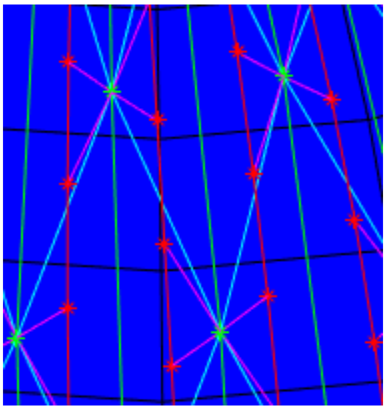

FIGURE 12: DISTRIBUTION OF FEEDER (GREEN) AND SERVICE (RED) SATELLITES ON ORBIT WITH SERVICE-FEEDER OISL (MAGENTA) AND FEEDER-FEEDER OISL (CYAN).

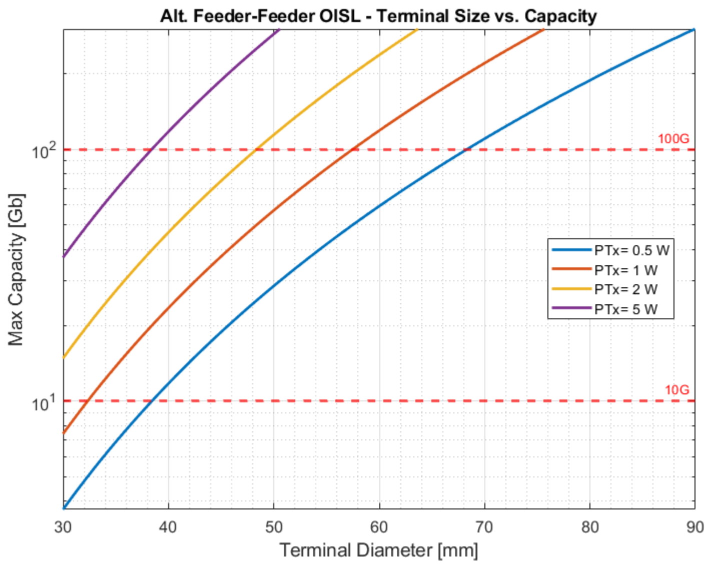

FIGURE 13: CAPACITY ASSESSMENT IN GBPS OF AN ALTERNATIVE FEEDER-FEEDER OISL AS A FUNCTION OF THE USED TERMINAL DIAMETER FOR VARIOUS TRANSMITTED OPTICAL POWER LEVELS.

2.3 FEEDER LINKS

The feeder link budgets for LEO satellites assumes 99.5% availability, clear sky conditions, and a ground station located in Toulouse.

In order to estimate the capacity of the feeder links, we need to define the size of the antennas and realistic parameters for estimating the achievable throughput. The aim is not to perform a sensitivity analysis, but to make reasonable assumptions on what will be achievable in the near future (2030), even if it means adjusting the design for optimization reasons. Table 17 summarizes the characteristics of the space and ground antennas and Table 18 the parameters used for the link budget calculation.

TABLE 17: ANTENNA PERFORMANCES GROUND STATION AND FEEDER SATELLITE

GATEWAY	earth	Diameter 9.3 m		
TX		GAIN	67.9	dBi
50	GHz	EIRP	87.0	dBW
RX		GAIN	68.4	dBi
40	GHz	G/T	40.7	$dB.K^{-1}$
FEEDER	**satellite**	**diameter 700 mm**		
TX		GAIN	43.9	dBi
40	GHz	EIRP	52.7	dBW
RX		GAIN	46.2	dBi
50	GHz	G/T	12.7	$dB.K^{-1}$

TABLE 18: PARAMETERS FOR LINK BUDGET COMPUTATION (UPPER = FEEDER SATELLITES)

	Parameter	Unit	Value
	Band Name	-	Q-V
	Downlink Frequency	GHz	40.00
	Uplink Frequency	GHz	50.00
Constellation	Selection for Feeder Link	-	Upper constellation
	Reference - Number of satellite	-	1380
	Reference - Altitude	km	600
	Reference - Elevation Min	°	10
	Upper - Number of satellite	-	196
	Upper - Altitude	km	600
	Upper - Elevation Min	°	10
	Selected - Number of satellite	-	196
	Selected - Altitude	km	600
	Selected - Elevation Min	°	10
Satellite	Satellite Antenna Gain Tx	dBi	43.90
	Satellite EIRP	dBW	52.70
	Satellite Antenna Gain Rx	dBi	46.20
	Satellite G/T	dB/K	12.70
Gateway	Gateway Antenna Gain Tx	dBi	67.90
	Gateway EIRP	dBW	87.00
	Gateway Antenna Gain Rx	dBi	68.40
	Gateway G/T	dB/K	40.70
C/I	Downlink (Sat TX)	dB	18
	Uplink (SatRX)	dB	18

The link budget is driven by the C/I (Carrier to Interference Ratio) of the link. This value is a hypothesis taken and will depend on the interference environment. In other words, it depends on the number of stations and their distribution. Nevertheless, these antennas are very large compared to the working wavelength, which suggests that the C/I value is achievable. However, in the budget we have limited ourselves to spectral efficiency, which leaves room for strong attenuation and availability, especially in tropical areas.

In all tables, the throughput has been calculated by limiting the spectral efficiency in NR to 2.7140 bits/s/Hz in uplink and 1.39 bits/s/Hz in downlink. It is possible to work at higher spectral efficiencies, which would enable access to higher throughput if needed. It is also possible to provide the link using DVB-S2x with higher data rates, and to reach flow rates 2 or 3 times higher than the values reported above. There are several possible ways to investigate, bearing in mind that the system will have to be optimized in terms of deployment cost, which also presupposes optimal dimensioning of the ground stations (antenna size/power/number).

As a consequence, the values considered to evaluate each feeder link are target values rather than values to be optimized, and it will be necessary to guarantee them to a certain extent by playing on the design elements of antenna noise figure in the amplification chain, SSPA (Solid State Power Amplifier) or TWTA (Travelling Wave Tube Amplifier), antenna surface, as well as pointing errors. The sensitivity of the link to handover and overhead have not been evaluated. Each feeder work in the two polarizations and the throughput is given in Table 19.

The number of feeders can be adjusted according to need, depending on whether it's the conventional architecture, which is more restrictive in terms of layout, or the distributed one, which is more flexible in terms of layout.

TABLE 19: CAPACITY FEEDER/GATEWAYS LINKS

FEEDER	(double polarization)	
	Tx	Rx
	Gbps	Gbps
	13.9	**16.3**

2.4 SUMMARY OF LINKS CAPACITY

A calculation of the maximum throughput that can be carried by the various links is shown in the figure below (where feeder satellites are referred to a link satellite). This is a preliminary dimensioning to estimate the areas of work: system dimensioning, identification of blocking points (bottlenecks) and orientation of the subsequent design effort. An additional 20% overhead in addition to the figures reported in Section 2.1 has been considered.

2.4.1 C-Band

In C-band, 3 cases have been analysed (see D 3.9 for more details):

- Case A: LEO satellites at 600 km , 1056 RE (reference performance), min. user elevation 45°
- Case B: VLEO satellites at 350 km, 1536 RE (improved) , min. user elevation 35°
- Case C: LEO satellites at 600 km, 2048 RE (enhanced), min. user elevation 45°/ could ensure down to 30°

For each case, 3 architectures namely 1, 2 & 2' are analszed:

1. A conventional constellation with all identical satellites
2. A distributed constellation with service & feeder satellites
3. A modified distributed constellation with service "light" & feeder satellites

2.4.2 Q/V-Band

In Q/V band only one case is considered, namely LEO satellites at 600 km, 2x7 DRA of 512 RE, min. user elevation 45°. The same 3 architectures as for C-Band are analysed.

2.4.3 Summary and Final Space Network Sizing

The summary of all link required capacity is summarised in Figure 14. The following comments and explanations are in order:

- All data rates values referring to
  - the feeder links HAPs – Ground station
  - the feeder links LEO Feeder Satellites – Ground stations
  - the links between the GEO and the LEO Feeder Satellites
  - the links between the HAPs and the LEO Feeder Satellites
  - the links between the LEO Service and the LEO Feeder Satellites

  have been derived from the link budgets performed in D3.10 '*Report on (V)LEO Space Segment'* and summarized in Chapter 2 so they represent the maximum achievable data rates, but are not based on a traffic model / estimation. As it can be seen, the downlink/pulink ratio is significantly deviating from the typical values, especially for C-Band.

- The aggregated capacity for optical ISLs between LEO feeder satellites have been obtained for C-band (**black values**) and for Q/V-band (**red values**) by considering that each feeder satellite is serving 4 service satellites and additionally adding 25% to account for traffic coming from the adjacent satellites:
  - Aggregate_Capacity_OISL_Out = 1,25 x 4 x Data_Rate_ServiceSat_Up
  - Aggregate_Capacity_OISL_In = 1,25 x 4 x Data_Rate_ServiceSat_Down

  The minor contributions from the GEO and the HAP have been disregarded.
- A more detailed estimation of the traffic coming from the adjacent satellites should take into account the fraction of traffic that can be terminated at each feeder satellite and it also depends on the number / location of ground stations and on the adopted routing scheme.
- Last not least, it shall be noted that the above values for the aggregated capacity of optical ISLs might also be considered representative of the required OISL capacity also for the conventional architecture.

With the values shown in Figure 14, the following conclusion regarding the sizing of the OISL can be drawn:

- **OISL between service and feeder satellites:** one might infer that a 10 Gbps link could be enough, at least for the C-Band service satellites. However, depending on the functional split architecture (discussed in Chapter 4), there might be a bandwidth expansion factor to be considered (see Section 4.2.1) → **OISL at 100 Gbps shall be therefore considered as baseline**.
- **OISL among feeder satellites:** considering that the feeder satellites shall serve both the C-Band and the Q/V-Band service satellites, the corresponding figures of the aggregated incoming and outgoing capacity shall be added together → **OISL at 100 Gbps seems a reasonable baseline and the simulation results presented in the next section confirms this assumption.**
- Last not least, as far as feeder links are concerned, an optimization in terms of total throughput according to the needs can be performed by adding more ground station, increasing each ground station capability (e.g. antenna size) or simply adding additional

feeder link payloads in the LEO feeder satellite, so this part of the space network is not considered a potential bottleneck.

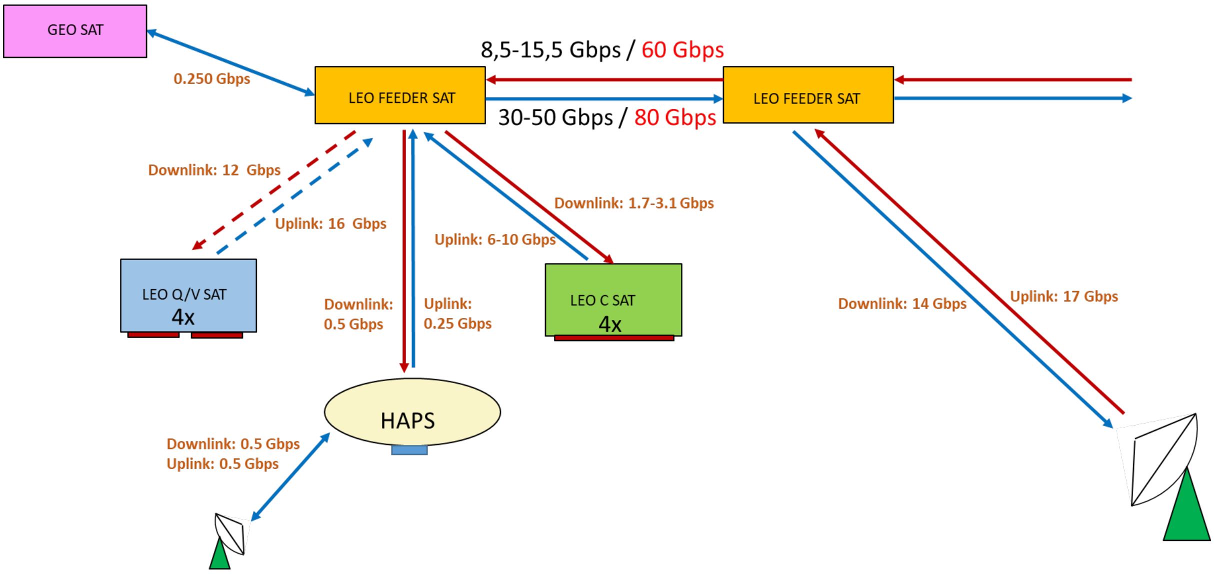

FIGURE 14: SUMMARY OF LINKS CAPACITY (DISTRIBUTED ARCHITECTURE)

2.5 DELAY PERFORMANCE

A simulation environment is developed to evaluate the routing and delay performance of the proposed distributed architecture. The assessment is conducted using a packet-based, end-to-end SatCom simulator developed by the German Aerospace Center (DLR). To simplify the analysis, the proposed two-layer service and feeder satellite constellation architecture is reduced to its feeder-side component, which is then simulated. A fixed delay is added to take into account for the link between the service and the feeder satellites.

In the simulator, source routing is employed for path determination. In this approach, the source node computes the shortest path to the destination and embeds the complete route in the packet header. The packet is then forwarded along the predetermined path, reducing the need for routing computations at intermediate nodes in space. This significantly lowers the processing overhead on satellites and ground nodes. However, a key limitation of source routing is its vulnerability to handovers. If a satellite or link becomes unavailable during transmission due to mobility or orbital dynamics, packets may be lost or fail to reach their destination, representing a notable drawback of this scheme in dynamic satellite networks.

2.5.1 Assumptions Underlying the Simulation Model

The feeder constellation consists of 336 satellites arranged in a Walker-Star configuration, comprising 14 orbital planes with 24 satellites per plane. A direct connection between users and the feeder constellation is assumed. An additional constant 1.875 ms delay introduced to account for the propagation and processing delay across the link between the feeder and service satellites. This delay is derived from the average inter-satellite distance calculated based on the distances shown in Figure 9.

In the simulation, user equipment (UE) accessing the service satellites is assumed to connect directly to the feeder satellites, bypassing any intermediate routing through service satellites. This design implies that all user equipment and gateway traffic, both uplink and downlink, is routed exclusively through the feeder satellite system. As a result, the total uplink and downlink capacity of the entire satellite system is effectively aggregated at the feeder satellites, making them the central point for traffic ingress and egress.

The per-satellite traffic capacities are derived from Figure 14. The total amount of data each LEO feeder satellite has to process includes also the incoming / outgoing traffic from / to the GEO satellite, the HAPs and the feeder links to the ground station. As discussed in the previous section, all OISLs between feeder satellites are assumed to provide a raw data rate of **100 Gbps**.

A total of 30,000 user equipment (UEs) are distributed globally, generated based on a user density threshold of 50 km^{-2} and the assumptions outlined in D3.10 '*Report on (V)LEO Space Segment'*. While a minimum elevation angle of 45° is specified for the service satellite constellation, this value is not feasible for the feeder constellation, as it would result in significant coverage gaps and many users would not have any visible feeder satellite above the horizon. The coverage areas corresponding to different minimum elevation angles for 600 km altitude satellites are illustrated in Figure 15. To ensure adequate coverage, each feeder satellite in the simulation is required to cover the combined footprint of four service satellites. Therefore, a minimum user elevation angle of 20° is adopted for the feeder constellation to maintain sufficient visibility and connectivity across the globe just for the simulation purposes.

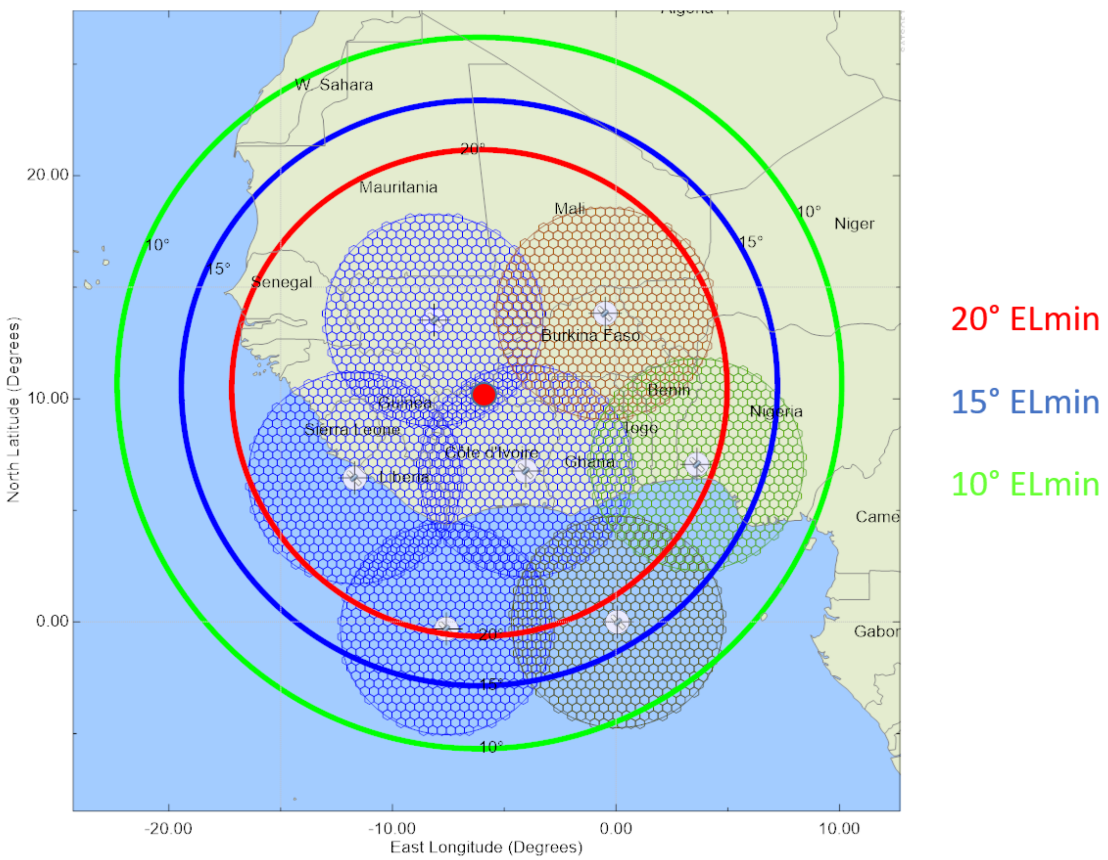

FIGURE 15: GEOGRAPHIC COVERAGE OF 600 KM LEO SATELLITES AT VARYING MINIMUM ELEVATION ANGLES

In addition to UEs, the scenario includes 20 gateways (GWs). Their geographic locations, i.e., their latitudes and longitudes are determined in D3.10 '*Report on (V)LEO Space Segment'*. A recap of the gateway locations is provided in Table 20. For gateways, a minimum elevation angle of 10° is used.

TABLE 20: GW LOCATIONS IN THE SIMULATION

Longitude	Latitude	Country
15	-71,1627907	Antarctica
124,137931	-66,9767442	Antarctica
-62,8571429	-64,8837209	Antarctica
-65,2173913	-28,5467033	Argentina
-58,8461538	51,0501051	Canada
-130	64,1751051	Canada
43,6363636	5,29706	Ethiopia
179,160839	-16,7227726	Fiji
30,0696056	61,8918277	Finland
73,9163498	27,8492557	India
100,507614	1,48211778	Indonesia
-107,210031	31,2054953	Mexico
16,119403	-24,280756	Namibia
170,864198	-43,8672628	New Zealand
5,27472527	13,1294831	Nigeria
141,395349	-7,06840529	Papua New Guinea
-66,5371666	18,4949826	Puerto Rico
95	55,7460107	Russia
161,19403	58,1784432	Russia
-7,86885246	43,3780427	Spain

A number of different scenarios are evaluated. In each scenario, a total of 10,000 sessions are simulated: 6,000 between UEs and GWs, and 4,000 between user equipment (UE–UE). The traffic model for each session adheres to the assumptions defined in D3.3, *“Software defined payload and its scalability”*. The average daily data consumption per user is 357.25 MB, derived from a monthly average of 10.72 GB.

2.5.2 Simulation Results

In the first scenario, traffic is assumed to be uniformly generated between 09:00 and 19:00 local time, which yields an average session data rate of roughly 0.08 Mbps. Session durations follow a normal distribution with a mean of 36,000 seconds (10 hours) and a standard deviation of 500 seconds. The start time of each session is drawn uniformly from the interval 09:00–10:00, with the exact instant selected at random within that hour. Under normal operating conditions, 90% of the traffic is downlink and 10% is uplink between communicating parties. However, for the sake of simulation simplicity, the scenario is configured such that 100% of the traffic is downlink.

The end-to-end latency of the sessions is shown in Figure 16. The plot includes multiple QoS classes; however, under the applied source routing approach, the simulator does not implement any prioritization or special handling for higher-priority classes. As a result, no meaningful performance differentiation is observed between the classes, and all traffic is treated uniformly. **On average, the end-to-end latency is measured as approximately 57 ms, with a maximum observed latency of around 134 ms.**

The jitter characteristics are illustrated in Figure 17, where the delay differences between consecutive packets are shown. It can be seen that **approximately 90% of the inter-packet delay variations are below 27 ms**, while the maximum delay difference reaches about **136 ms**.

In the second scenario, the same simulation approach is applied; however, the total daily data consumption is concentrated within a single hour, as opposed to being spread over 10 hours in the first scenario. This results in a data rate that is 10 times higher, while the session duration is reduced by a factor of 10. The end-to-end latency and jitter performance for this scenario are presented in Figure 18 and Figure 19, respectively.

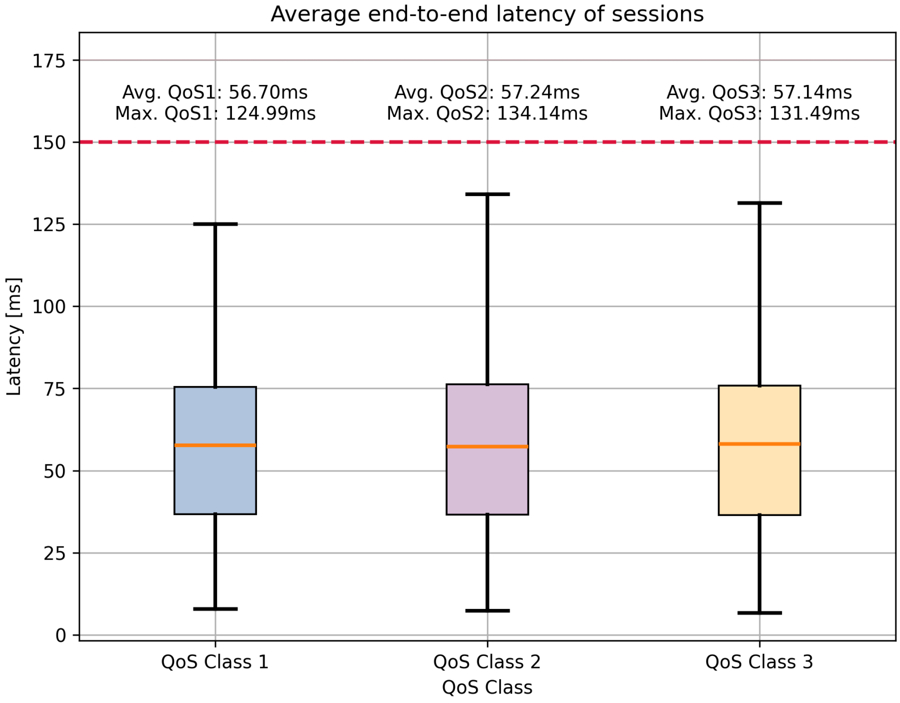

FIGURE 16: AVERAGE LATENCY RESULTS FOR THE FIRST SCENARIO

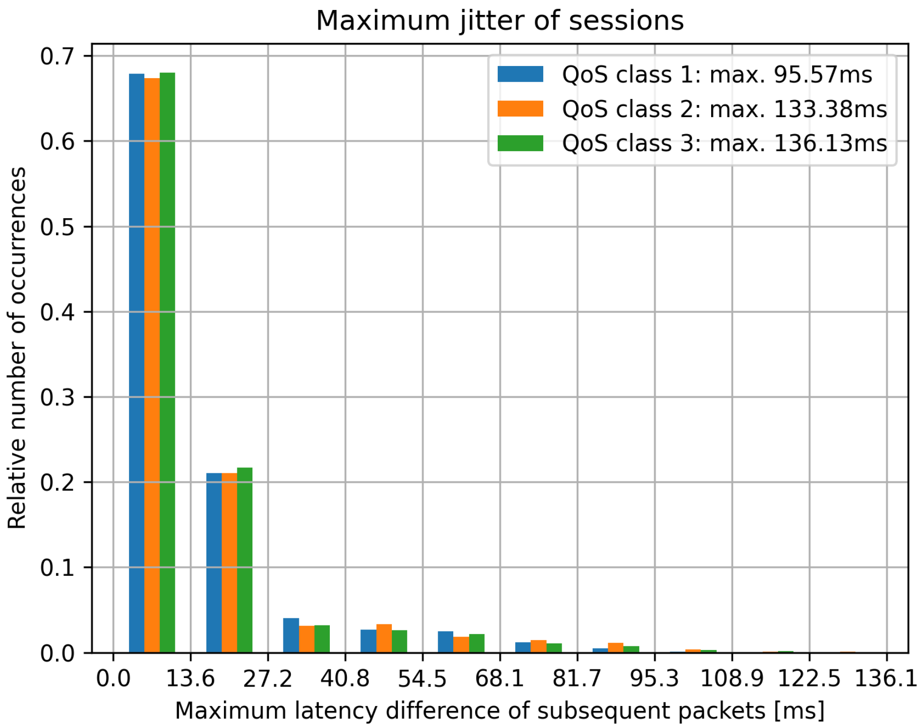

FIGURE 17: JITTER RESULTS FOR THE FIRST SCENARIO

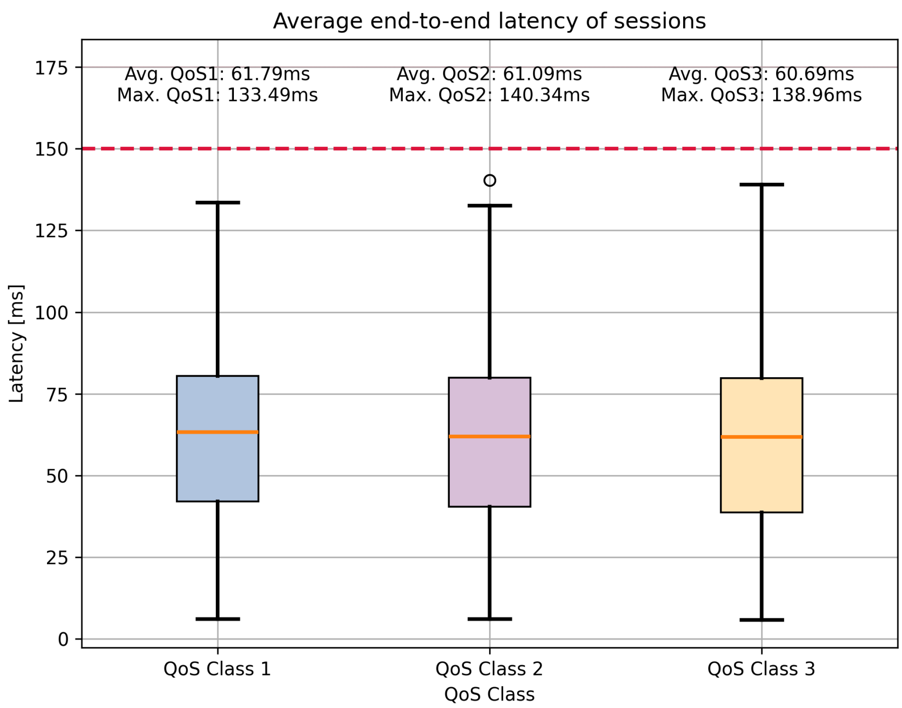

FIGURE 18: AVERAGE LATENCY RESULTS FOR THE SECOND SCENARIO

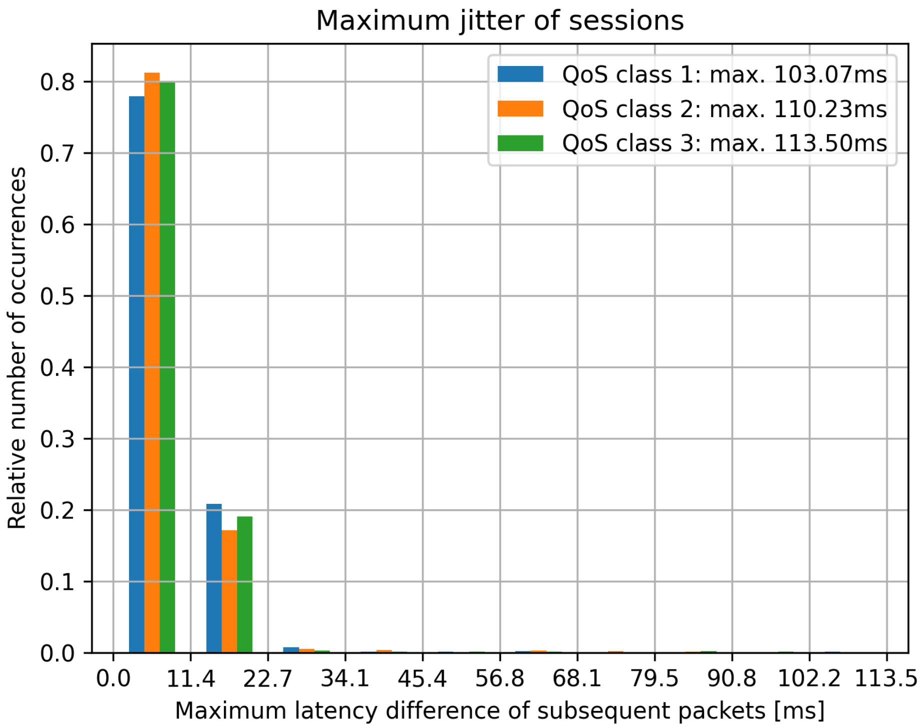

FIGURE 19: JITTER RESULTS FOR THE SECOND SCENARIO

The average latency in the second scenario is measured at approximately **61 ms**, which is 4 ms higher than in the initial scenario. The maximum latency reaches **140 ms**, an increase of 6 ms compared to the first case. This rise was expected, as traffic is concentrated into peak hours, leading to higher congestion and increased queuing delays.

On the other hand, jitter performance improves significantly. Approximately **98% of inter-packet delay differences are below 22.7 ms**, indicating a much more stable transmission behavior. This reduction in jitter is primarily attributed to the shorter session duration and higher data rates. By concentrating the data traffic into a narrow time window, the orbital dynamics of the satellite constellation change relatively little during a single session. Furthermore, the reduced inter-sending time between consecutive packets results in more consistent link and network conditions across successive transmissions. As a result, delay variations within individual sessions are significantly minimized, leading to more predictable and stable end-to-end performance.

It should be noted that the available link capacities are significantly higher than the generated traffic load. As a result, no packet drops occur due to buffer overflow, even with a buffer size of 2.4 Mbit. However, a small number of packet losses are observed, as indicated in Table 21. These losses are attributed solely to handover events, where temporary disruptions in connectivity occur during satellite transitions.

TABLE 21: PACKET DROP RATES DUE TO HANDOVERS

	First Scenario (10 hours session with 0.08 Mbps)	Second Scenario (1 hour session with 0.8 Mbps)
Packet Drop Rate	$1{,}9168 \times 10^{-5}$	$6{,}3944 \times 10^{-5}$

3 6G-NTN CONSTELLATION SIZING AND PRELIMINARY COST ASSESSMENT

3.1 PAYLOAD MASS AND POWER CONSUMPTION ESTIMATES

The analysis presented here is based on material included in the next chapter covering the functional splits, fronthaul interface capacity, and constellation types, as well as *D3.9 'Report on software defined payload and its scalability'* and *D3.10 'Report on (V)LEO space segment'* covering dimensioning, demand forecasts, and constellation sizing.

The information provided here is based on assumptions and demand estimates for service in C-band where mass is the main limiting factor. For Q/V, preliminary analysis has shown that mass should not be the main challenge, but maturity is still low on many key components, which makes a detailed analysis as done for C-Band almost impossible.

3.1.1 Baseband and Radio Nodes

In this section we will provide estimates for the mass and power consumption for RAN nodes that could be included in satellite payloads to provide 6G NTN service. The content is based on our industrial experience and knowledge of existing commercial products as well as estimates of what components and capabilities will be available in the expected lifetime of commercial 6G NTN deployments.

3.1.1.1 Scope of the Analysis

For this analysis, we estimate the mass and power consumption for baseband (BB) and RU nodes. Later, based on those, we extend the analysis for considering two types of constellation architectures

- The conventional architecture (see Section 1.4.1), where all satellites are identical and contain a full base station onboard (i.e., baseband and radio node).
- The distributed architecture, described in Section 1.4.2, where satellites are not identical and may house different functionality.
  - We assume that the functional split defined in Section 4.2 (LLS in space) is used.
  - We assume that one satellite (feeder satellite) contains the BB functionality and have a connection (via feeder link) to the ground station (GW).
  - The other satellite(s) in a cluster (named service satellites) shall carry a radio unit (RU) and provide the access link to the user terminals on the ground.

3.1.1.2 Assumptions

We assume that the constellation will serve users (with handhelds) in C-band, using FDD and a maximum bandwidth of 100 MHz. We assume an equivalence between one service satellite in the distributed architecture with one satellite in the conventional architecture. For the purposes of this analysis, the requirements for both are considered the same (number of users to serve, spot beams to generate, and so on).

Given the above, one service satellite shall support:

- At peak demand, up to 100 spot beams simultaneously may be served.
- 1 cell per spot beam.
- Each cell has a maximum bandwidth of 100 MHz.
- We also assume that the waveform is CP-OFDM, with subcarrier spacing of 30 kHz and that each physical resource block consists of 12 subcarriers.
- We assume that the highest modulation scheme used is 16QAM.
- The satellite antenna uses circular polarization, with a single polarization active per transmit direction (LHCP or RHCP).
- Only one spatial stream is sent per cell (i.e., single layer transmission).
- The beamforming processing and the radio front-end (PA, mixers, filters etc..) will be provided by the satellite vendor.

3.1.1.3 Payload Contents

To evaluate the characteristics of each payload type, we describe in high level what functional components are assumed to be part of each satellite type. We consider that there is a separation of responsibilities between a satellite vendor and a telecom equipment vendor. The focus on this section is then towards the components under the responsibility of the telecom vendor.

3.1.1.4 Service Satellite Functional Blocks

The RU in the service satellite will be separated into two partitions as illustrated in Figure 20 below. To the left there is the telecom vendor partition, which is the focus of the analysis.

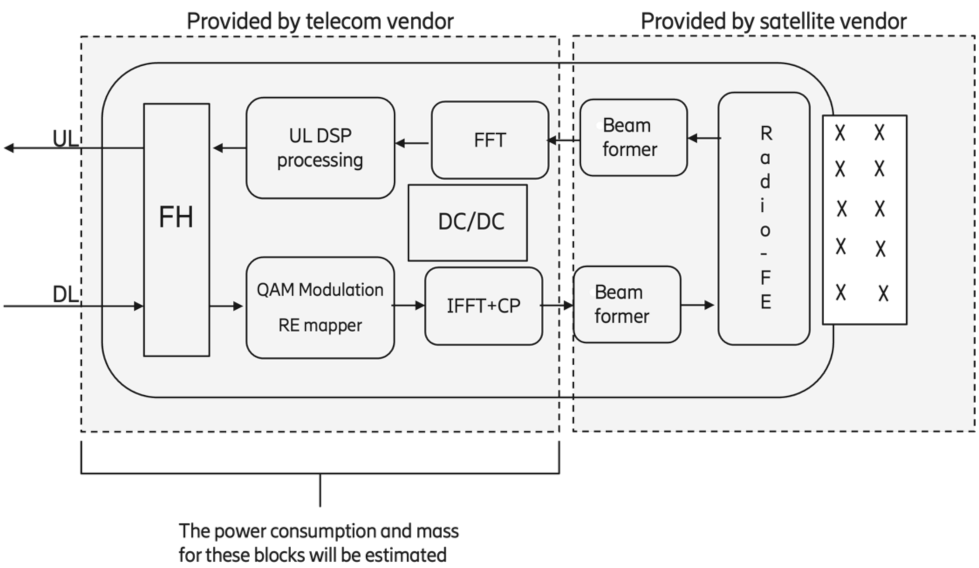

FIGURE 20: HIGH LEVEL SCHEMATIC OF A RU INSIDE A SERVICE SATELLITE

To the right of Figure 20 there is the satellite vendor partition (e.g., Thales): for the purposes of this analysis, this partition will consist of the satellite antennas, power amplifiers (PAs), low-noise amplifiers (LNA), mixers, oscillators, filters, analog to digital and digital to analog converters as well as the beamforming processing block. This is represented in Figure 20 as “Radio front-end (FE)”.

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To the left of Figure 20 there is the telecom vendor partition (e.g., Ericsson): this will consist of the fronthaul interface block and the OFDM modulator / demodulator functions. Details on the included components are given below

1. For the DL branch (lower path in Figure 20): includes the resource element (RE) mapper, QAM modulator and inverse Fast Fourier transform (IFFT) and cyclic prefix (CP) addition. We envision that the output of the OFDM modulator (time-domain samples) is sent via a (digital) interface to the satellite beamforming block.

2. In UL the branch (upper path in Figure 20) signal received from the UL beamforming block is transmitted via a (digital) interface towards the FFT. The output of the FFT goes into the UL digital signal processing (DSP) block for some further signal processing before being sent to the FH (frounthaul) interface, where it is encapsulated and sent over FH interface towards the feeder satellite.

3. Also included in the figure is a DC/DC converter representing the power distribution in the telecom vendor partition.

3.1.1.5 Feeder Satellite Functional Blocks

The feeder satellite is assumed to serve four service satellites (for each frequency band) in the distributed architecture. As such, the main part of its payload is four baseband nodes. This is illustrated in Figure 21 below. For the purposes of this analysis, we omit parts of the satellite that are not the telecom payload.

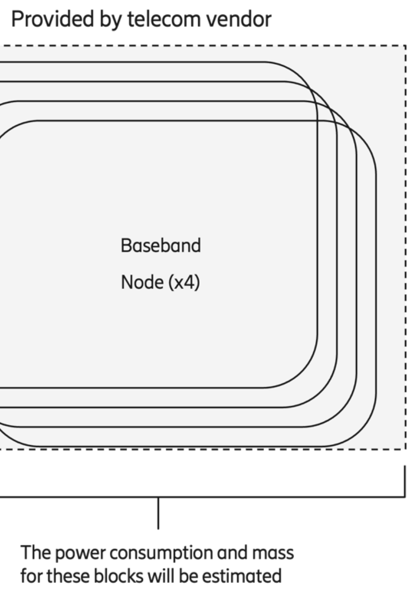

FIGURE 21: HIGH LEVEL SCHEMATIC OF THE FEEDER SATELLITE'S TELECOM PARTITION

3.1.1.6 Satellites in the Conventional Architecture (Full Base Station Onboard)

The third and final variant which we consider consists of a full base station onboard a satellite. Here a single baseband and a single radio unit are paired in one satellite. The resulting arrangement is depicted in Figure 22 below. The notes related to the contents of the RU payload in the service satellite also apply to this architecture.

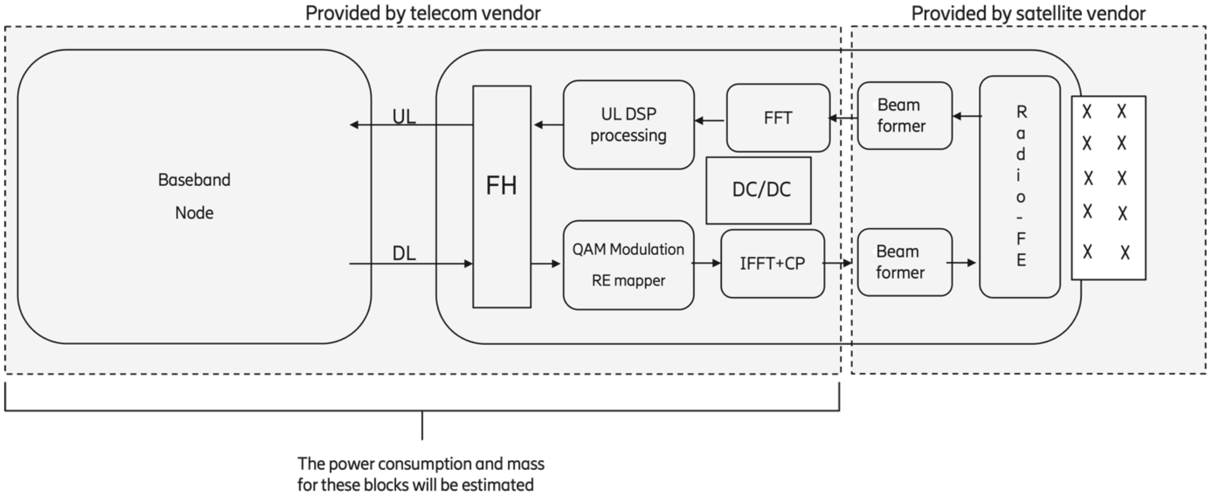

FIGURE 22: HIGH LEVEL SCHEMATIC FOR THE PAYLOAD IN THE CONVENTIONAL ARCHITECTURE. A FULL BASE STATION IS ON BOARD THE SATELLITE, WITH BASEBAND AND RADIO UNIT FUNCTIONS.

3.1.1.7 Dimensioning Scenarios

For the dimensioning calculations, we assume two scenarios, the first being a "pragmatic" option and a second where all calculations are based on simultaneous peak demand.

- The pragmatic dimensioning scenario assumes that at most 20 spot beams are served at full bandwidth per service satellite.
- The peak demand scenario assumes that 100 spot beams are served simultaneously at full bandwidth per service satellite.

The following disclaimers are made considering the results to follow

1. The scenarios are distinguished by the number of active simultaneous cells (spot beams) that are served at full bandwidth utilization simultaneously.
   a. This is not to indicate or impose any beam hopping scheme, but rather to facilitate the estimation procedure.
   b. In practice the utilization of each cell will vary, and the number of simultaneous beams supported by a satellite could vary accordingly.
   c. Additionally, the bandwidth utilization is controlled by the base station(s) scheduler(s), which can take the computational, fronthaul and other constraints into account.
2. Regarding the peak demand scenario, it is provided here as an upper bound and does not indicate a practical or recommended dimensioning guideline. In our experience peak demands occur at different times, cells and spatial dimensions even for a single cell site in a terrestrial network. For NTN, we expect the different cells served by a satellite to express similar variability in demand. Dimensioning for the simultaneous peak would result in very low average utilization of the node resources at high cost.

3.1.1.8 Estimates for Power Consumption and Mass

3.1.1.8.1 Single RU Node

For a single RU node, the power consumption and mass estimates are listed in Table 22.

TABLE 22: MASS AND POWER ESTIMATES, SINGLE RU NODE

	Mass (kg)	Power Consumption (W)
Pragmatic dimensioning	30	60
Peak demand dimensioning	30	120

3.1.1.8.2 Single Baseband Node

For a single BB node, the power consumption and mass estimates are listed in Table 23.

TABLE 23: MASS AND POWER ESTIMATES, SINGLE BASEBAND NODE

	Mass (kg)	Power Consumption (W)
Pragmatic dimensioning	10	< 200
Peak demand dimensioning	10	200

3.1.1.8.3 Service Satellite Telecom Payload

Since it houses a single RU (see Figure 20 for an illustration), the values here are the same as noted in Table 22.

3.1.1.8.4 Feeder Satellite Telecom Payload

For the feeder satellite (illustrated in Figure 21), we assume that 4 baseband nodes are needed for the pragmatic dimensioning, while 12 are needed for the peak demand dimensioning. The resulting numbers are listed in Table 24.

TABLE 24: MASS AND POWER ESTIMATES, FEEDER SATELLITE PAYLOAD

	Mass (kg)	Power Consumption (W)
Pragmatic dimensioning	40	< 800
Peak demand dimensioning	120	2400

3.1.1.8.5 Full Base Station Onboard the Satellite

For this option, the telecom payload would consist of a baseband node and a radio node as illustrated in Figure 22. The resulting numbers are listed in Table 25.

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TABLE 25: MASS AND POWER ESTIMATES, FULL BASE STATION ONBOARD SATELLITE, CONVENTIONAL ARCHITECTURE

	Mass (kg)	Power Consumption (W)
Pragmatic dimensioning	40	< 260
Peak demand dimensioning	40	320

3.1.2 FE and Beam Forming

In the previous section, a schematic view of the payload was described, where the FE part and beamformer are separated from the BB/RU digital part. This part is devoted to the FE and Beamformer.

In a satellite where the constraints of power consumption, compactness and mass are very severe, the cost impact is not negligible. Generally, the architecture optimizes all parameters at once to obtain a design compatible with requirements. In our case, hardware architecture is not the object of this study. The aim is to estimate as pragmatically as possible the points that determine the system's dimensions.

The mass/volume/power consumption of the payload have been estimated for C-band payload in D3.9 '*Report on software defined payload and its scalability*' with the data of all equipment and the satellite mass evaluation in D3.10 '*Report on (V)LEO space segment*'. These data have been estimated in terms of launcher accommodation and cost effort according to the complexity of each satellite and participate to the evaluation for the cost assessment in Section 3.2.

3.1.3 Optical Terminals

SWaP for given data rates is an essential consideration in an overall technical budget of the payload. For LEO terminal, DLR OSIRISv3 [15] and NASA T-BIRD [16] developments together with TESAT SCOT-20 and SCOT-80 commercial optical terminals [13] were considered as a baseline to establish a reasonable SWaP estimate for 100G LEO terminals with 20mm and 80mm apertures, respectively.

Future product will have to be designed and optimized for the 6G-NTN application. These adaptions are two-fold: i) communications transceiver (new functions, higher data rates and increased robustness) and ii) optical terminal (hemispherical coverage, range optimization and electronics unit accommodation capable to host the 6G-NTN communications transceiver incl. network functions, e.g. a switch).

The target SWaP was estimated according based on following assumptions:

- TBIRD terminal is representative in terms of communications capacity, but due to its demonstration scope lacks a CPA requiring satellite body pointing to the counter-terminal (OGS)
- OSIRISv3 includes the CPA with nearly hemispherical coverage required for inter-orbit links [15]

The SWaP of the 6G-NTN is therefore assumed based on the two assumptions above together with expected future developments towards 2030 with implementation in 6G-NTN in 2035.

*TABLE 26: SWAP ESTIMATE FOR OPTICAL TERMINALS. WHERE * INDICATES ASSUMPTION OF COTS COHERENT 100G TRANSCEIVER UPGRADE.*

	OSIRISv3 / TOSIRS	*NASA TBIRD*	LEO 6G-NTN	LEO 6G-NTN
Size [U / mm3]	*150x200x280*	*100x200x300*	~100x200x200	~310x290x470 + 260x190x240
Weigt [kg]	*~10**	*<3*	13	20+
Power Consumption [W]	*~150**	*100*	75 to 130	100-200
Aperture [mm]	*30*	*22-23*	**20**	**80**
Data rate	*1G*	*200G*	**100G**	**100G**

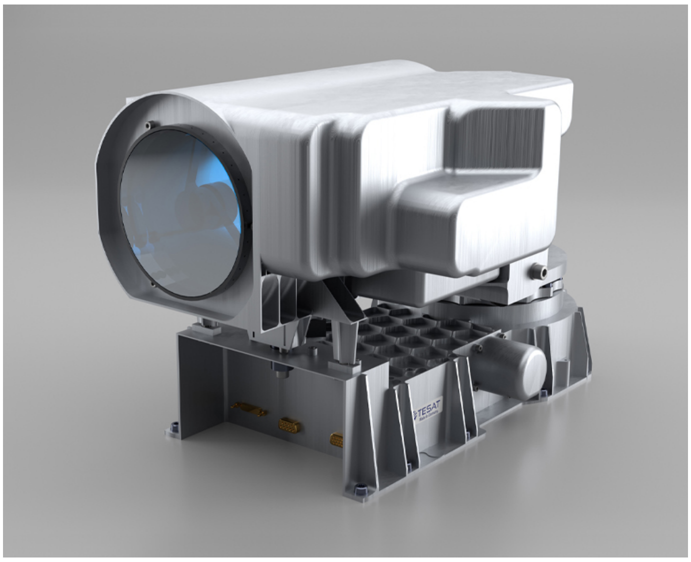

FIGURE 23: EXAMPLE OF A LASER COMMUNICATIONS TERMINAL SCOT-80 BY COMPANY TESAT SPACECOM

3.1.4 Aggregate Mass and Power Estimates

The figures presented in this section refer to a C-band constellation only. As previously mentioned, a similar analysis for Q/V is subject to huge uncertainties due to low level of maturity of several components and is therefore not considered meaningful at this point in time.

3.1.4.1 Satellite Conventional Architecture

In this case, the RF equipment is requiring ca. 90% of the power and also ca. 60% of the mass. A total power consumption around 10 kW and an overall mass above 300 kg would be required.

TABLE 27: PAYLOAD AGGREGATE MASS AND POWER ESTIMATES, FULL BASE STATION ONBOARD SATELLITE, CONVENTIONAL ARCHITECTURE WITH C-BAND LEO SATELLITES AT 600KM ALTITUDE

Subsystem	Power Consumption [W]	Power Consumption [% total]	Mass [kg]	Mass [% total]
RF FE and Beamforming	8600	93% - 88%	200	63%
Full Base Station	260 – 320	ca. 3%	40	12%
Optical Terminals (80mm)	4 x 100 – 200	4% - 8%	4 x 20+	25%
Total (best – worst cases)	*9260 – 9720*		*320*	

3.1.4.2 Service Satellite Distributed Architecture

As expected, the relative weight of the RF equipment is even higher in the case of the service satellites, given only the RU is present and a smaller optical terminal can be used given the minor distance to the feeder satellites. Two optical terminals have been assumed for redundancy purpose, since a malfunction would result in the service satellite becoming isolated from the rest of the constellation and therefore unusable. A total power consumption below 10 kW and an overall mass above 200 kg would be required.

TABLE 28: PAYLOAD AGGREGATE MASS AND POWER ESTIMATES, DISTRIBUTED ARCHITECTURE WITH C-BAND LEO SERVICE SATELLITES AT 600KM ALTITUDE

Subsystem	Power Consumption [W]	Power Consumption [% total]	Mass [kg]	Mass [% total]
RF FE and Beamforming	8750	98% - 96%	167	75%
RU	60 – 120	ca 1%	30	13%
Optical Terminals (20mm)	2 x 75 – 130	2% - 3%	2 x 13	12%
Total (best – worst cases)	*8960 - 9130*		*223*	

3.1.4.3 Feeder Satellite Distributed Architecture

In this case, the relative weight of the RF equipment is clearly remarkably lower. A total power consumption around 10 kW and an overall mass above 300 kg would be required. The number of required optical terminals play here a key role. To allow connectivity to 4 additional feeder satellites and 4 C-Band service satellites, 8 optical terminals would be required. The power consumption of the base station fluctuates significantly depending on the load assumptions. This suggests that a detailed optimization of the feeder satellite dimensioning depending on the expected load scenario is required.

TABLE 29: PAYLOAD AGGREGATE MASS AND POWER ESTIMATES, DISTRIBUTED ARCHITECTURE WITH LEO FEEDER SATELLITES AT 600KM ALTITUDE

Subsystem	Power Consumption [W]	Power Consumption [% total]	Mass [kg]	Mass [% total]
RF FE and Beamforming	370	19% - 8%	28	12% - 9%
Base Station w/o RU	800 – 2400	41% - 55%	40 – 120	18 - 39%
Optical Terminals (80mm)	8 x 100 – 200	41% - 37%	8 x 20+	70 – 52%
Total (best – worst cases)	*1970 – 4370*		*228-308*	

For feeder satellites, it's possible to extend the analysis to the case of connecting both C-band and Q/V-band service satellites, which basically result in 4 additional laser terminals to be considered. However, the total number of laser terminals might be subject of further analysis to figure out if the number of terminals could be reduced, given they might not be all simultaneously active.

TABLE 30: PAYLOAD AGGREGATE MASS AND POWER ESTIMATES, DISTRIBUTED ARCHITECTURE WITH LEO FEEDER SATELLITES AT 600KM ALTITUDE SERVING BOTH C AND Q/V BAND SERVICE SATELLITES

Subsystem	Power Consumption [W]	Power Consumption [% total]	Mass [kg]	Mass [% total]
RF FE and Beamforming	370	16% - 7%	28	9% - 7%
Base Station w/o RU	800 – 2400	34% - 46%	40 – 120	13 - 31%
Optical Terminals (80mm)	12 x 100 – 200	50% - 46%	12 x 20+	80 – 62%
Total (best – worst cases)	*2370 – 5170*		*308-388*	

3.2 PRELIMINARY COST ASSESSMENT

We consider for the assessment the following scenarios:

- Case A: LEO satellites at 600 km, 1056 RE (reference performance), min. user elevation 45°
- Case B: VLEO satellites at 350 km, 1536 RE (improved), min. user elevation 35°
- Case C: LEO satellites at 600 km, 2048 RE (enhanced), min. user elevation 45°/ could ensure down to 30°

For each case, 3 architectures namely 1, 2 & 2' are analysed:

1. A conventional constellation with all identical satellites
2. A distributed constellation with service & feeder satellites
3. A modified distributed constellation with service "light" & feeder satellites

Relevant input parameters for the cost assessment are summarized in Table 31, all details could be found in D3.9 '*Report on software defined payload and its scalability*' and D3.10 '*Report on (V)LEO space segment'*.

TABLE 31: INPUT PARAMETERS FOR THE COST ASSESSMENT

CASE A - 600km / 1056 RE					
	Architecture 1	Architecture 2		Architecture 2'	
	Sat User	Sat User	Sat Feeder	Sat User	Sat Feeder
Payload mass	320	253	223	248	193
Satellite mass (1)	1000	933	563	928	533
Diameter	2.8	2.3	N/A	2.3	N/A
Height (2)	1.05	0.65	0.95	0.55	0.95
Length (m)	2.8	2.3	1.4	2.05	1.2
Width (m)	2.8	2.3	0.8	2.05	1.2
Height (m)	0.8	0.4	0.7	0.3	0.7
power paylaod	9704	1980	9124	2086	9018
CASE B - 350km/ 1536 RE					
	Architecture 1	Architecture 2		Architecture 2'	
	Sat User	Sat User	Sat Feeder	Sat User	Sat Feeder
Payload mass	328	260	223	255	193
Satellite mass (1)	1008	940	563	935	533
Diameter	2.85	2.35	N/A	2.35	N/A
Height (2)	1.05	0.65	0.95	0.55	0.95
Length (m)	2.85	2.35	1.4	2.1	1.2
Width (m)	2.85	2.35	0.8	2.1	1.2
Height (m)	0.8	0.4	0.7	0.3	0.7
power paylaod	10905	1980	10324	2086	10219
CASE C - 600km / 2048 RE					
	Architecture 1	Architecture 2		Architecture 2'	
	Sat User	Sat User	Sat Feeder	Sat User	Sat Feeder
Payload mass	370	302	223	297	193
Satellite mass (1)	1050	982	563	977	533
Diameter	2.95	2.45	N/A	2.45	N/A
Height (2)	1.05	0.65	0.95	0.6	0.95
Length (m)	2.95	2.45	1.4	2.375	1.2
Width (m)	2.95	2.45	0.8	2.375	1.2
Height (m)	0.8	0.4	0.7	0.35	0.7
power payload	13030	1980	12450	2086	12344

The comparison for the cost assessment assumes of excessive demand, which is forward link dominated. This is for example typically the case if we consider having many distributed consumer broadband customers around the globe. This is a typical scenario for a large terminal network operating best effort service like mobile direct to device services to fix and mobile users with end consumer type of traffic mix.

3.2.1 Cost Comparison

For the cost assessment, we used the information about the three cases for the assumed constellations with relative per satellite cost assumptions provided

The cost is compared relative to the downlink capacity of the constellation as main metric for the overall capacity of the constellation to provide consumer grade services

This is computed as follows per case and per architecture considered:

> [Total Downlink capacity of the constellation computed] / [Cost of satellite / constellation] x [Number satellites / constellation and launches] + [Cost of Gateways required per constellation] x [Cost assumed per Gateway per constellation]

The cost comparison of architecture 2 and 2' leads to an outcome that there is an advantage in architecture 2 in terms of cost, if the cost per terrestrial Gateway exceeds around 200% of a LEO satellite cost with launch. In fact, the terrestrial infrastructure can be a significant cost and with mass production and launch of LEO satellites, the ratio of cost of Gateways to cost of LEO satellite (with launch) is an important reference in this case. For a ratio of 2 the separation of satellite function starts to make economic sense in the constellation design, even if more satellites are required.

If it can be feasible with large enough quantities and with cheap enough launches, a 200% Gateway cost for a cheap LEO could well be a practical hurdle to consider architecture 2.

The cost comparison also reveals that a VLEO constellation compared to a LEO constellation makes economic sense and it is interesting to have a VLEO constellation instead of LEO. There is clearly an interest in moving to VLEO, but in that case using architecture 1 (joint integrated service and feeder link satellites).

Comparing payload configurations, A and C, the higher complex payload does not pay off under these considered assumptions.

TABLE 32: CASES COMPARISON OF THE THREE ARCHITECTURES AND SCENARIOS ASSUMING A 200% COST OF A GATEWAY COMPARED TO A LEO SATELLITE (SERVICE TYPE).

		arch 1	arch 2	arch 2'	DL Gbps/sat	UL Gbps/sat	Capa/constellation		Cost/constellation			bps / Cost (rel.) / constellation			**Cost (rel) / bps / constellation (rel.)**		
Case A	user sats	1269	1269	1269	1.7	7.5	2157.3	9517.5									
	feeder sats		336	336													
	Gateways #	140	59	59					280	118	118						
	cost rel	1	0.49	0.41					1269	1433.6	1406.8	**1.4**	**1.4**	**1.4**	**0.72**	**0.72**	**0.71**
Case B	user sats	1760	1760	1760	3.1	6.1	5456	10736									
	feeder sats		448	448													
	Gateways #	85	42	42					85	42	42						
	cost rel	1.77	0.83	0.67					3115.2	3487	3415.4	**1.7**	**1.5**	**1.6**	**0.59**	**0.65**	**0.63**
Case C	user sats	1269	1269	1269	2.0	9.7	2538	12309.3									
	feeder sats		336	336													
	Gateways #	140	59	59					280	59	59						
	cost rel	1.58	0.72	0.58					2005	2246.9	2199.9	**1.1**	**1.1**	**1.1**	**0.90**	**0.91**	**0.89**

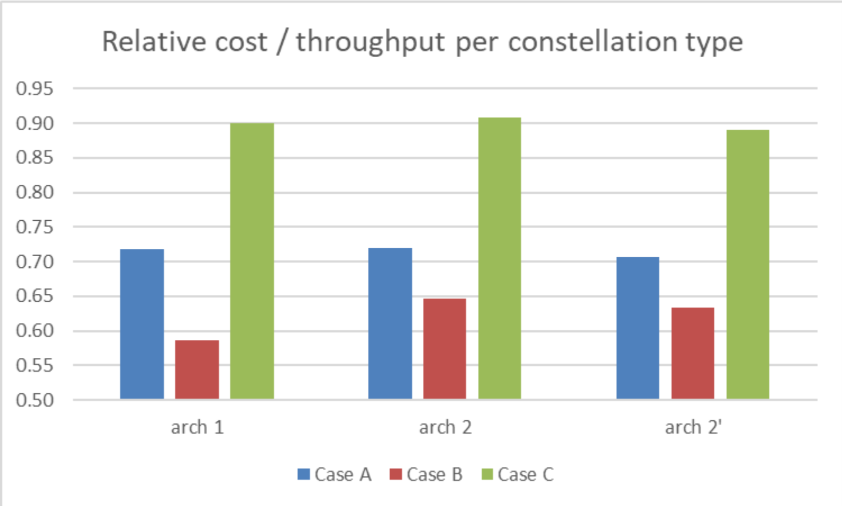

FIGURE 24: RELATIVE COST COMPARISON PER CONSTELLATION CASE AND ARCHITECTURE TYPE.

4 6G-NTN RAN SPLIT ARCHITECTURE

Throughout this chapter we will assume 5G terminology in the lack of a better alternative as 6G is not yet standardized. Moreover, unless otherwise specified, we will typically make use of the terminology commonly adopted by O-RAN, where the following three main elements of a gNB are considered, as summarized in [17]:

- **RU**: this is the radio unit that handles the digital front end and the parts of the PHY layer, as well as the digital beamforming functionality.
- **DU**: this is the distributed unit that sits close to the RU and runs the RLC, MAC, and parts of the PHY layer. This logical node includes a subset of the gNB functions, depending on the functional split option, and its operation is controlled by the CU.
- **CU**: this is the centralized unit that runs the RRC and PDCP layers. The gNB consists of a CU and (at least) one DU connected to the CU via Fs-C and Fs-U interfaces for CP and UP respectively. A CU with multiple DUs will support multiple gNBs. The split architecture allows to utilize different distribution of protocol stacks between CU and DUs depending on midhaul availability and network design. It is a logical node that includes the gNB functions like transfer of user data, mobility control, RAN sharing (MORAN), positioning, session management etc., with the exception of functions that are allocated exclusively to the DU. The CU controls the operation of several DUs over the midhaul interface.

4.1 OVERVIEW OF SPLIT OPTIONS FOR 6G-NTN

This section discusses the relevance in the context of 6G-NTN of the several architectural options, which were studied and captured in [18] during the development of 5G NTN, namely:

- Transparent satellite as sketched in Figure 25. It shall be mentioned that this is the baseline architecture assumption for Release 17/18 NTN design. In this option, no RAN and CN functionalities are implemented in space.

  In 6G-NTN the objective is that the LEO satellite payloads will be based on a regenerative architecture meaning that data can be processed and routed based on the properties of the data. This means that for the LEO constellation, which is the focus of this chapter, no transparent (repeater like) architecture as in Figure 25 will be studied. However, for GEO and HAPs, transparent payloads as depicted in Figure 25 might still be applicable.

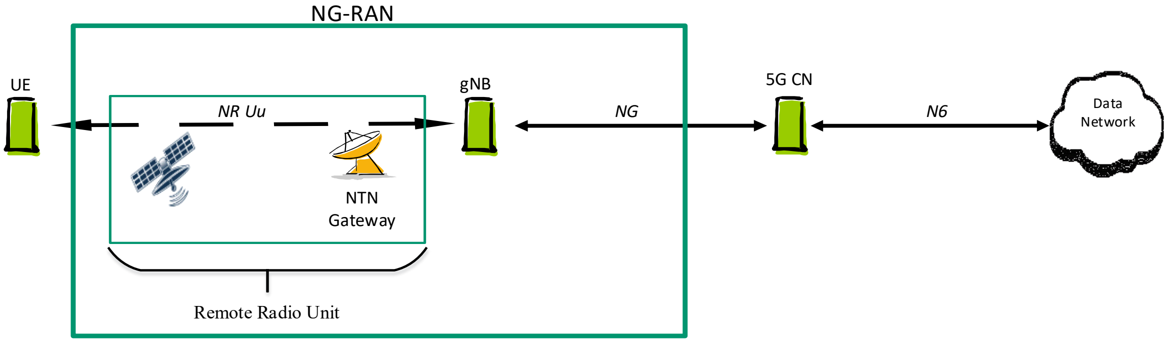

FIGURE 25: TRANSPARENT PAYLOAD [18]

- Regenerative satellite with full gNB on board, as sketched in Figure 26 which shall be supported by Rel-19.

This option foresees the integration of all required protocol stacks in the gNB to be implemented on the mobile base station, which implies the complete RU, gNB-DU and gNB-CU for the user as well as the control plane.

With a full base station onboard, the complete radio protocol stack must be implemented in each satellite, this would be SDAP (Service Data Adaptation Protocol), RRC (Radio Resource Control), PDCP (Packet Data Convergence protocol), RLC (Radio Link Control), MAC (Medium Access Control) and PHY (Physical). The feeder link (or the combination of ISLs and feeder links in case the satellite has no direct visibility to a ground station) will transport traditional backhaul, which for 5G would be NG interface between core and base station to transport N1, N2 and N3 from the 5G core and also Xn. All RRC signalling between the UE and gNB would be terminated in the satellite. The required capacity of ISLs and feeder links would scale with requested user data. One important observation is that the NG interface was not specified for frequent set-up / tear down due to a moving base station. That may be required when a satellite connects to another ground station. In future standardization of 6G, base station mobility capability should also be addressed.

One additional extension of this solution foresees the need for also bringing selected CN functionalities to space. The 5G core network is defined in logically independent functions and their placement is a matter of implementation. 6G Core is likely an evolution of 5G Core where incremental additions to the 5G Core will take place based on the need of new capabilities, but the concept of logically independent functions will be preserved. Adding CN functionalities in the satellites shall be evaluated regarding cost, complexity, power consumption, and its relation to use cases. For instance, one of the functions of the core that could facilitate the use case of UE-to-UE link over one satellite without the need to route traffic through a ground station is the aforementioned UPF, which is typically for the routing of data packets in the core network.

The distributed LEO constellation architecture presented in Section 1.4.2 has been conceived with the goal to allow sufficient resource (power and mass) to be available in space in order to support this configuration. Please note however that Figure 26 does not rule out the case in which a certain split of the gNB functionalities is taking place in space as it will be detailed in Section 4.2.

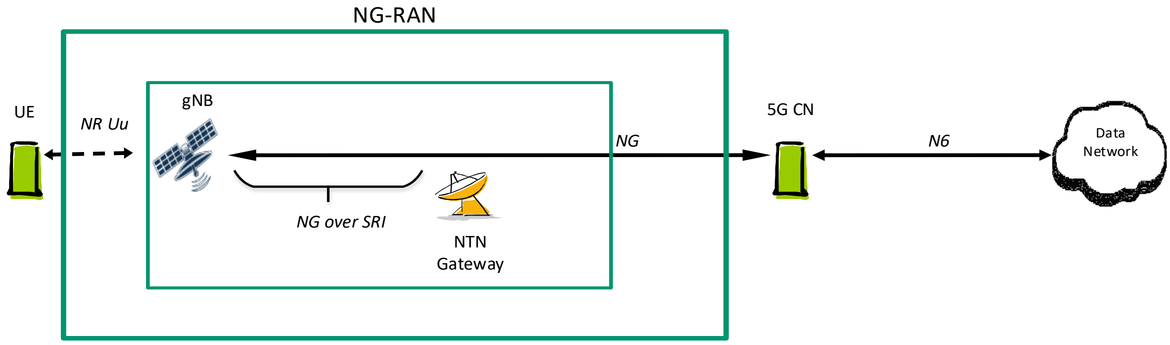

FIGURE 26: GNB PROCESSED PAYLOAD [18]

- Regenerative satellite with RU and gNB-DU on board and CU on ground, as sketched in Figure 27. As previously mentioned, Rel-19 has specified the full gNB, therefore, this last option was not retained for further work. We acknowledge moreover that most power consumption is occurring in the DU unit versus the CU unit consuming a fraction of that for a given processed bandwidth.

For the conventional architecture presented in Section 1.4.1, the configuration in Figure 26 might lead to a resource bottleneck in space. Depending on the mass and power budgets for the LEO satellite payload, , **the split of some RAN functionalities between space and**

ground could become necessary for the conventional architecture. An analysis of the pros and cons of the different split options from the network perspective and of the most suited split option depending on the considered use case in presented in Section 4.3.1. **What it turns out is that different split options might be best suited for different UCs and that a "one size fits all" approach is not ideal**. Therefore, an innovative concept named "Adaptive Functional Split" (AFS) is presented in Section 4.3.3.

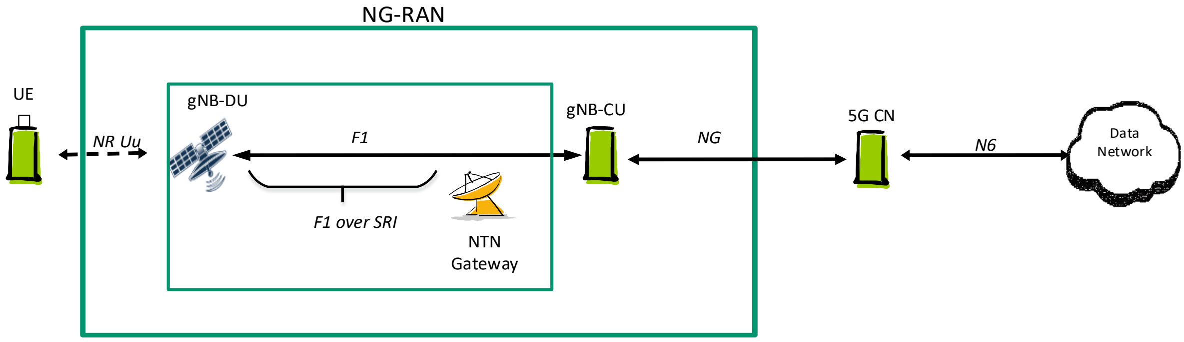

FIGURE 27: GNB-DU PROCESSED PAYLOAD [18]

In summary, the 6G-NTN architecture foresees a unified terrestrial and non-terrestrial network (i.e., 3D network) in a dynamic manner, which includes gNBs that are moving and following a satellite orbit or a flight path for HAPs. This network architecture then foresees a functional split that requires a comprehensive solution for the implementation of the RAN and core network functions in this environment of fix and mobile gNB base stations. Moreover, the satellite must have the means to route packets from one satellite to the other. Both routing within the same orbital plane as well as between orbital planes need to be supported.

4.2 LOWER LAYER SPLIT IN SPACE FOR THE DISTRIBUTED LEO CONSTELLATION DESIGN

As already mentioned in Section 1.4.2, due to constraints on the payload dimensions and power consumption, it may be advantageous to have constellations where groups of satellites providing the service link are anchored to an "aggregator" satellite via inter satellite links (ISL). Such aggregator satellite, hereafter referred to as feeder satellite for the sake of consistency with the terminology used in Section 1.4.2, may be connected to the ground station via a direct feeder link as shown in Figure 28 or indirectly via a number of ISLs plus a feeder link. The feeder satellite shall contain the baseband unit (BBU) functionality, whereas the service satellites in the cluster shall carry a radio unit (RU) and provide the service link to the user terminals on the ground.

It should be understood that baseband includes the whole upper layers of the radio protocol stack while the lower (physical) layer processing functionalities are split between the feeder satellite and the service satellites. The connection from the feeder satellite to the service satellites in the cluster is done via optical ISLs (OISLs) supporting some variant of the fronthaul interfaces.

The split between baseband unit and radio unit is known as the lower layer split (LLS) where the O-LLS is the Open-RAN (ORAN) standardized version of such a split.

Figure 29 shows how the switch/router in the BBU satellite can be used to route the backhaul from the feeder link to another feeder satellite in a neighbour cluster.

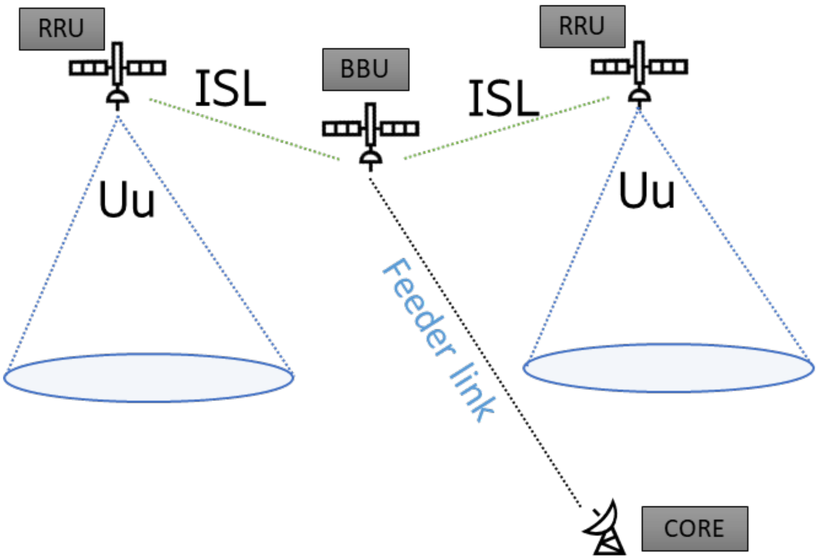

FIGURE 28: NTN SYSTEM WITH AN FEEDER SATELLITE AND SERVICE SATELLITES

Some of the aspects that motivates this concept is that power budget and payloads can be optimized for the different roles of the satellites. The feeder satellites carrying the BBU does not have to be equipped with multiple power amplifiers for the service link, therefore more power and payload volume can be allocated for computation parts.

On the contrary, the service satellite carrying the radio unit (RU) will have less of its payload for computation, which means more volume and power for the power amplifier, antennas, and beamforming network for the service link.

One potential issue of this solution is that no centralized scheduling will be possible as each feeder satellite will have its own scheduler. The system could, on the other hand support slower radio resource management coordination, such as is done in terrestrial networks.

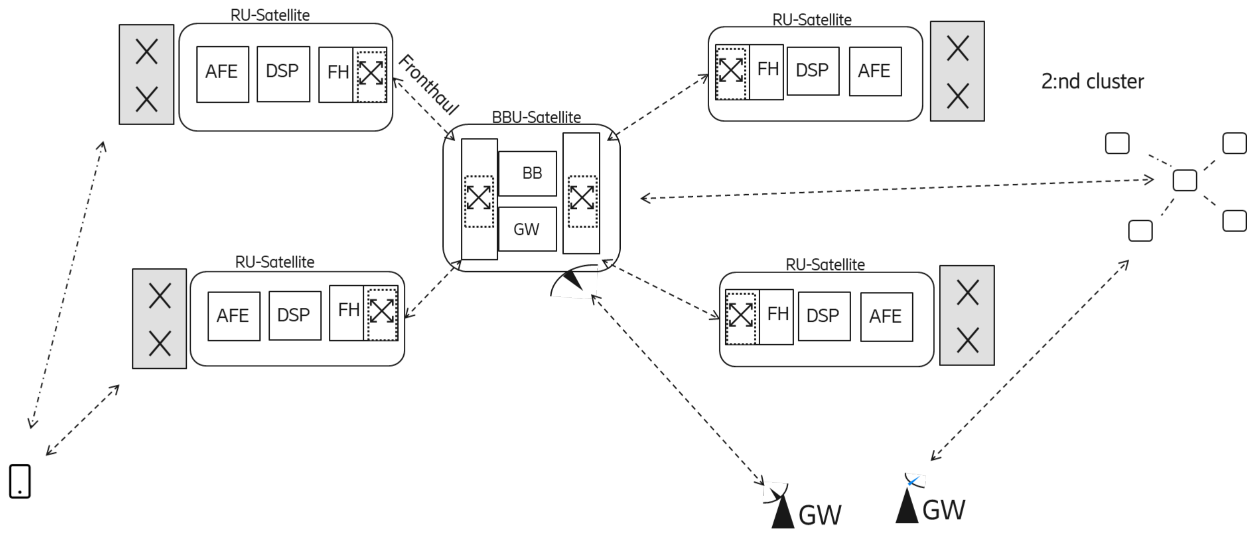

FIGURE 29: FEASIBILITY OF LLS BASED NTN ARCHITECTURE TO ALSO ENABLE ROUTING OF TRAFFIC BETWEEN BBU SATELLITES

4.2.1 Bandwidth Requirement Analysis

This section provides a quantitative analysis of Lower-Layer split architecture option, focusing on the bandwidth requirements for links (ISL, feeder link) between nodes. Please note that the analysis presented here is also relevant to the scenario in which the lower layer split is implemented for the conventional LEO constellation.

The analysis is divided in two parts. In Section 4.2.1.1we calculate the required bandwidth for serving a fully loaded cell (all resources allocated) in uplink direction, assuming an LLS architecture. Next that section describes how many cells could be served for a given fronthaul link bandwidth.

In general, for an LLS architecture, the uplink direction is the direction driving the bandwidth requirements for the interface. For that reason, a similar analysis as the one in Section 4.2.1.1 for downlink is not included here.

In Section 4.2.1.2 we present a comparative analysis between two architectures (full base station onboard and LLS architecture) considering the bandwidth requirement to transport a full slot of data. Here the focus is not so much on how many cells can be supported, but rather to give the reader a comparative notion between the two systems.

4.2.1.1 Bandwidth Requirements Analysis for the Uplink

In uplink (UL) direction, a system built with an LLS architecture will transmit the signals received from the UEs for processing in the baseband node. Since the transmit signals have traversed the channel, they will be affected by fading, noise and other impairments.

In this section we provide a quantitative analysis of the bandwidth cost for transporting UL frequency domain samples between a radio node and a baseband node. The analysis is valid for systems where baseband is deployed on the ground or in a satellite, given that the logical functional split is the same.

The following assumptions are made:

- **Air Interface**
  - The system operates in C-band. In general, if the SINR is better, that may lead to select a block floating point scheme with more bits per block
  - The channel is assumed to be line-of-sight, with at most rank 1 transmission.
  - The bandwidth corresponds to 273 physical resource blocks (3276 subcarriers). The underlying assumption here is that the cell is fully loaded in UL.
  - There are 14 OFDM symbols per slot.
  - There are 2000 slots per second.
  - Subcarrier spacing is 30 kHz.
  - FDD is used.
- **LLS Implementation**

- The radio node consists of analog and digital front-ends, receiver beamforming, removal of cyclic prefix, FFT transforms, optional multi-user processing and equalization (e.g. one tap frequency domain equalization for OFDM systems)
- Complex (in phase/quadrature) frequency domain samples are transmitted in UL
- The FFTs in the OFDM demodulator are performed in the service satellite.
- Receiver beamforming coefficients are pre-calculated and stored in the satellite. This assumption and its implications shall be subject of further analysis.
- No extra overhead for transmitting beamforming coefficients is considered.

IQ Sample Representation

- Each group of 12 contiguous IQ samples (1 physical resource block) is represented in block-floating point format, with 4 bits for the mantissa for each component (I, Q) and 8 bits for a shared exponent (valid for all 12 IQ samples). In total ((4+4) * 12) + 8 = 104 bits per physical resource block.
- This choice of block floating point representation is adequate for a system using QPSK and does not introduce relevant SINR degradation.

Fronthaul Implementation

- The maximum transmit unit (MTU) in the fronthaul link is 1500 bytes.
- The traffic from radio to baseband node in the fronthaul link contains only user plane packets.
- User plane packets are not allowed to carry content for more than one OFDM symbol (in time).
- Each user plane packet contains approximately 30 bytes of overhead.

Differently from downlink, the bandwidth requirements for an uplink interface do not vary with modulation and coding scheme (MCS) choice, in case the method for representing the frequency domain IQ samples is kept constant (e.g., block floating point encoding).

Similarly to DL, on the other hand, the bandwidth utilization depends on utilization of the air interface (grows with the number of allocated UEs).

To evaluate the required bandwidth, we propose to calculate the cost of transmitting the frequency domain IQ samples of a cell at maximum load (all physical resources allocated to UEs).

Next, the cost of servicing one cell (approximately 815 Mbps) is used to estimate how many cells could be supported for a given fronthaul link capacity. For the calculations, we account for the overhead in user plane fronthaul packets.

The results are collected below in Table 33. Note that this calculation assumes a quite harsh requirement that all cells are fully loaded simultaneously. In practice, the utilization of different cells fluctuates over time, so the actual numbers of cells that can be supported are higher than shown here. Additionally, the traffic is under control of the baseband scheduler, which can assure that no overload occurs and that there is fairness between different cells sharing the

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same link. It is also noted, due to satellite constraints (e.g. power limit), a satellite may not be able to support the communication to a large number of cells at the same time, which would reduce the required per-cell fronthaul capacity since a cell is only scheduled for a fraction of time.

It is possible to observe that for fronthaul links of around 100 Gbps, the interface could possibly support more simultaneous cells (active beams) than the satellite would serve (the assumption from D3.9 '*Report on software defined payload and its scalability*' is to have 100 simultaneous beams per satellite).

TABLE 33: NUMBER OF SUPPORTED CELLS AT PEAK LOAD, UPLINK LLS

Fronthaul Link Capacity	Supported cells at peak load
5 Gbps	6
10 Gbps	12
25 Gbps	30
50 Gbps	61
100 Gbps	122

4.2.1.2 Comparative Bandwidth Requirements Analysis for the Downlink

This section provides an illustrative comparison of the bandwidth requirements for two hypothetical systems, namely:

- Option 1 - where a full base station is placed in a satellite.
- Option 2 - where the physical layer is functionally split between a baseband node on the feeder satellite and a radio node on the service satellite.

Due to the high number of variables in a real implementation, the results should be taken as an example, rather than an exact evaluation. Unless otherwise specified below, most parameters refer to an NR system.

The following assumptions are made:

- **Air Interface**
  - The system operates in C-band. In general, if the SINR is better, the downlink average coding redundancy could be smaller, making the bandwidth requirement more favourable
  - The data to be transmitted fits in one NR slot.
  - The channel is assumed to be line-of-sight, with at most rank 2 transmission (due to use of left, right polarization).
  - The system operates with 2 antenna ports per cell.

- The bandwidth corresponds to 273 physical resource blocks (3276 subcarriers).
- There are 14 OFDM symbols per slot.
- There are 2000 slots per second.
- Subcarrier spacing is 30 kHz.
- FDD is used.
- The system operates at relatively low SNR, i.e. between MCS 0 and MCS 10 as defined in Table 5.1.3.1-2 of [19].
- The LDPC code operates with an average code rate of 0.42. This has been obtained by averaging the code rates from MCS 0 to MCS 10. In practice the average coding rate will depend on the channel conditions for each user/deployment.
- The coded transport blocks are on average 2.34 times larger than the input data (obtained by the reciprocal of average code rate).
- The system has an overhead (PDCP, RLC, MAC, physical control channels and reference signals) of 14%, as described in Section 4.1.2 of [20].

LLS Implementation

- Unmodulated data is transmitted in DL (QPSK, QAM modulation is performed in the radio node).
- The FFTs in the OFDM modulator are performed in the satellite.
- Beamforming coefficients are pre-calculated and stored in the satellite. This assumption and its implications shall be subject of further analysis.
- No extra overhead for transmitting beamforming coefficients is considered.

Fronthaul Implementation

- The maximum transmit unit (MTU) in the fronthaul link is 1500 bytes.
- The traffic in the fronthaul link is assumed to contain both control and user plane packets.
- For a given slot, one control plane packet per polarization per antenna port is sent.
- Each control plane packet has approximately 50 bytes.
- User plane packets are not allowed to carry content for more than one OFDM symbol (in time).
- Each user plane packet contains approximately 30 bytes of overhead.

We propose to compare both systems by a ratio of how much data needs to be sent over a link of interest for a full NR slot. For Option 1, the link of interest is a FL/OISL carrying the NG interface, while for Option 2 it is an OISL carrying the fronthaul LLS interface.

For a full base station onboard the satellite, the traffic sent over the link corresponds (except for packet headers) to what is to be sent over to the UE.

For option 2 (LLS), the data entering the base station is augmented by headers in PDCP, RLC, MAC (e.g., control elements), channel coding (LDPC for PDSCH). Besides that, there is overhead added for the fronthaul link itself.

To obtain the comparison metrics, we follow this procedure:

1. Calculate the maximum number of bits that fit in an NR slot (given all the assumptions stated above).
2. Calculate the amount of useful data in said slot (by subtracting the air interface overhead). The result obtained in in this step is used as the amount of data required by Option 1 (full base station onboard).
3. From the useful data, we obtain the user plane overhead in fronthaul. Calculate how many user plane fronthaul packets are needed, then calculate how many overhead bits for that number of packets.
4. The fronthaul control plane overhead is calculated directly from the assumptions.

The results are presented as a bar graph in Figure 30, where the capacity requirements are normalized by the requirements of the full base station onboard system (Option 1).

Option 2 requires around 2.8 times the bandwidth used for Option 1. The main contribution comes from the bandwidth expansion added by the channel coding (LDPC for NR).

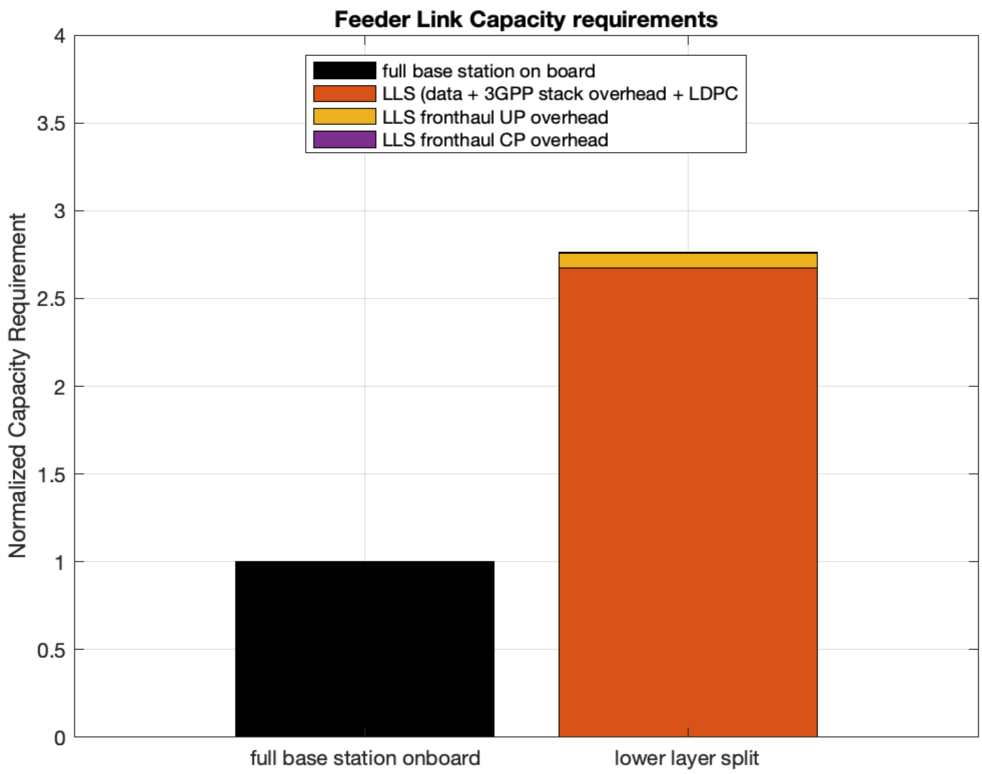

FIGURE 30: ILLUSTRATIVE COMPARISON OF SERVICE-FEEDER SATELLITE LINK CAPACITY REQUIREMENTS (NORMALIZED).

4.3 SPLIT OPTIONS FOR THE CONVENTIONAL LEO CONSTELLATION DESIGN

As already mentioned, for the conventional LEO constellation design in which each satellite implements service links, ISLs and feeder links as shown in Figure 31, potential bottlenecks are to be expected as far as the availability of resources in space (complexity, power, and mass) is concerned. Therefore, the different split options between space and ground listed Table 34 are compared and analysed. Please note they correspond to the split options considered for 5G TN, but in this context their pros and cons when applied to an NTN scenario are analysed in Appendix B.

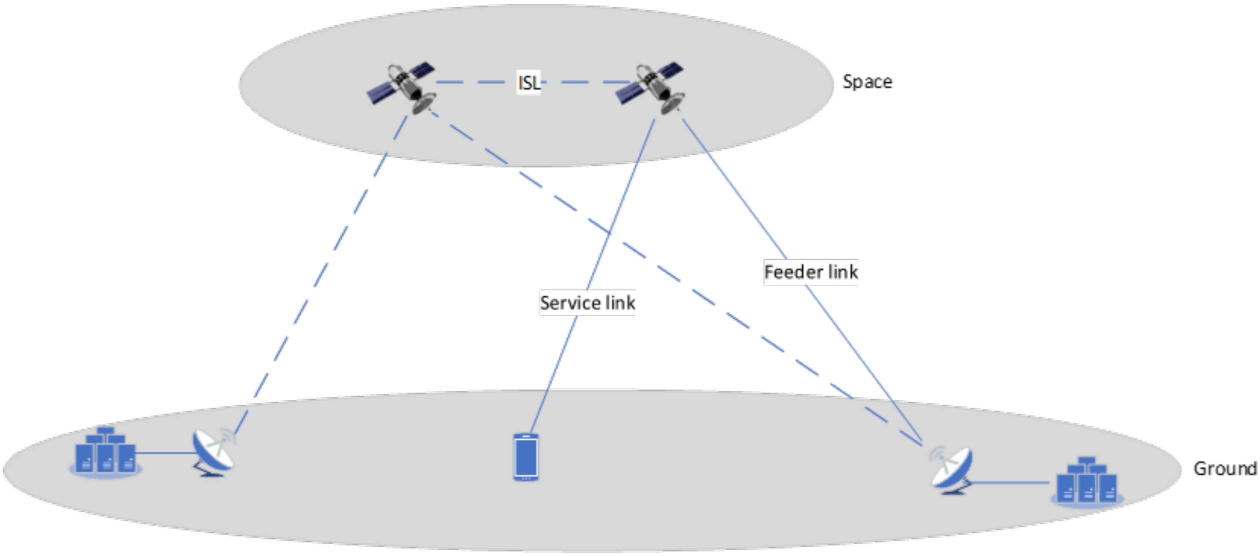

FIGURE 31: REFERENCE SCENARIO FOR THE LEO CONVENTIONAL ARCHITECTURE

TABLE 34: LIST OF SPLIT OPTIONS FOR THE LEO CONVENTIONAL CONSTELLATION

Option	Functions in space	Functions on ground
1	Complete gNB	Core network (CN) + data network (DN)
2	Complete AS layers for User Plane (UP) PDCP-and-below layers for Control plane (CP)	CN + DN for UP RRC + CN for CP
3	RLC + MAC + PHY + RU	PDCP + RRC + CN + DN
4	MAC + PHY + RU	RLC + PDCP + RRC + CN + DN

5	PHY + RU	MAC + RLC + PDCP + RRC + CN + DN
6	Lower PHY (cyclic prefix (CP) removal/addition + FFT/IFFT) + RF	Higher PHY + MAC + RLC + PDCP + RRC + CN + DN
7	RU	PHY + MAC + RLC + PDCP + RRC + CN + DN

4.3.1 Comparison of Split Options and Mapping to the 6G-NTN Use Cases

Based on the detailed analysis in Appendix B, a summary table is reported below, showing that different split options might have different advantages, where different colours are used to indicate if the considered split option shown in the row is desirable by considering the characteristic/feature shown in the corresponding column. In particular, the following comments are in order:

- Payload complexity decreases when moving from split option 1 to 7.
- Onboard edge computing requires typically CN functionalities, so it's feasible only with split options 1 and 2.
- Latency critical services might be especially problematic with split options 5 to 7.
- Dynamic resource sharing might be more difficult to support with split options 1 to 4.
- Centralized RRM may require either a central RRC entity or two very-tightly coordinated RRC entities serving neighbour/overlapping areas with ideal connection between them, in order to optimize the system level management and the system performance, e.g. to improve mobility support by collecting and considering more global information. Thus, such centralized RRM may not be easily supported with split option 1, since different neighbour/overlapping areas served by different NTN-NTN gNBs and/or different NTN-TN gNBs have different RRC entities that are located far away from each other.

It shall be noted once more that the split options are those currently defined in 5G. Up to which point and how these shortcomings could be mitigated or completely solved in 6G shall be subject of further investigation.

TABLE 35: ANALYSIS SUMMARY OF THE DIFFERENT SPLIT OPTIONS FOR THE LEO CONVENTIONAL CONSTELLATION

Split Option	Required feeder link and ISL data rate	Allowed feeder link latency	Required onboard CN	Existing design / baseline implementation for feeder link	Usage of ISL	Applicable mobility scheme	Latency for RRC, RLC re-TX, HARQ and RACH, CSI	Separation between CU-CP and CU-UP	Centralized scheduling	Centralized RRM
1	Low	High	Yes for CP/UP	NG	Xn	L3	Low for all	No	No	No

2	Low	High	Yes for UP	No	Xn-U	L2	Low for all except RRC	Yes	No	Yes
3	Low	High	No	F1/IAB	RLC context transfer	L2	Low for all except RRC	No	No	Yes
4	Medium	Low	No	No	Gateway coverage extension	L2	Low for HARQ and RACH, CSI	No	No	Yes
5	Medium	High	No	No	Gateway coverage extension	L2/L1	High for all	No	Yes	Yes
6	High	High	No	O-RAN 7-2x	Gateway coverage extension	L2/L1	High for all	No	Yes	Yes
7	High	High	No	No for onboard analog conversion; Yes for pure RF repeater	Gateway coverage extension	L2/L1	High for all	No	Yes	Yes

Since the analysis of the different split options in the previous section based on network considerations resulted in a scenario where no clear "winner" could be identified, a further comparative analysis is carried out in this section from a different angle, namely which split option could better support the 6G-NTN use cases defined in D2.1 '*Use case definition*'.

Table 36 provides such initial analysis with respect to the different UCs. In this table, as an example, "+++" implies a preferred option than an option with "++", which is further preferred than an option with "+". It is to be noticed that this analysis reuses the current 5G protocol stack layers and terminologies, as it is unknown how 6G will change and evolve comparing to the 5G at this moment. For example, a radio unit (RU) mainly contains the RF elements, a gNB L1-low contains the lower part of physical layer functions, (e.g., IFFT/FFT, and CP insertion/removal) of a 5G gNB, a gNB DU contains the radio layers below the PDCP layer, such as higher part of the physical layer functions together with MAC and RLC layers, while CU contains the PDCP+SDAP/RRC layers. In addition, the option of "RU+DU+CU+routing fun+AF" indicates to equip a routing function for the E2E link traffic at the space, e.g., on a satellite as illustrated in Section 4.3.2. Please note, this initial analysis is subject to further

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changes in the rest of the project duration, e.g., based on the progress and the technical solution developments on the relevant topics.

In certain scenarios of UC1 for maritime communication, it is important to support communication when the satellite cannot be directly connected to the on-ground gateway, e.g., when the satellite moves to a remote area or when the satellite is in the middle of an ocean. In this case, one option is to use ISLs to connect the satellite to the gateway, where the additional traffic load posed by the remote satellite on the ISLs and the feeder links of the satellite in visibility of the ground station needs to be accounted. In order to reduce these traffic burdens on the ISLs link and the feeder links, it may be preferred to use a higher layer split option, e.g., to equip the satellite with RU+DU, or even RU+DU+CU, which have the advantage of consuming less bandwidth of the backhaul link comparing to a lower layer split option. Another architectural option is to enable the direct NTN communication by implementing a routing function in the satellite(s), e.g., as illustrated in Section 4.3.2. With the direct NTN communication, the traffic can be routed directly from one UE to another, which can further avoid routing all traffic through the feeder links.

For UC2 and UC3, where drones are used for inspecting the power line or transporting goods and passengers, it may be preferred to have a lower layer split option to reduce the required computational capabilities in the satellite payload, since direct communications between drones are not relevant for these UCs. However, there are some considerations in UC2 and UC3 to enable edge computing technology such that certain processing can be performed at the satellite. In that case, in order to support edge computing, at least the User-plane (U-plane) core network function needs to be implemented in the satellites together with the application function to support edge computing, i.e., UPF+AF need to be carried by the satellites for directing the data of a considered Protocol data Unit (PDU) session to the proper edge entity, wherein the PDU session needs to be transported over the Access Stratum (AS) radio layers.

UC4 considers the coexistence between TN and NTN. In such a scenario, it may be preferred to have a centralized scheduler, e.g., for dynamic resource sharing and/or interference reduction/avoidance. Thus, a centralized MAC entity may be deployed on the ground to schedule both the coexisting TN and NTN cells, while the remaining lower layer functions can be moved to the space segment. The scenario where only RU and L1-low is implemented in the space and the rest of RAN functionalities as well as all CN functionalities are left on ground is analysed in detail in Section 4.3.3.

UC5 targets at improving the NTN coverage in 6G, while its impact from/on the desired functional split option is not clear at this moment.

The high mobility scenario investigated in UC6 requires an improved mobility support between TN and NTN, as well as between NTN and NTN. In addition, it also requires a low latency for supporting certain latency critical services such as gaming and even Virtual Reality (VR). In this case, to reduce the latency, it may be preferred to have an onboard MAC layer and an RLC layer at the satellite, such that the Hybrid Automatic Repeat Request (HARQ) process and ARQ process can be carried out between the UE and the satellite directly, which can avoid the impact of feeder link propagation delay on retransmission latency. Furthermore, to improve the mobility performance between TN and NTN, it may be preferred to have a centralized RRC layer on the ground, e.g., to achieve a centralized RRM. Regarding the NTN-NTN mobility, if ISL can be used to implement the Xn interface between two neighbour satellites, it may be preferred to have onboard RRC layers at the different satellites. In this manner, the feeder link propagation delay is not involved in some Handover (HO) steps and the corresponding signalling transmissions, such that the latency for HO can be reduced, which in turn reduces the service interruption time.

UC7 aims at reducing the dependency of the operability of NTN network on feeder link and in general ground segment availability, such that an E2E communication can be set up and supported even when a feeder link is unavailable. In this case, it is preferred to have onboard routing function equipped at the satellite. This scenario is analysed in detailed in Section 4.3.2.

What it turns out of this preliminary analysis is that different split options might be best suited for different UCs and that a "one size fits all" approach is not ideal. Therefore Section 4.3.3 analyses a novel concept named Adaptive Functional Split (AFS). Up to which point this flexibility could be implemented, will be subject of further analysis.

TABLE 36: INITIAL ANALYSIS ON FUNCTIONAL SPLIT OPTIONS VS. 6G-NTN USE CASES

Functional split Space - Ground		UC1	UC2	UC3
Space	Ground	Maritime Coverage for search and rescue coast guard intervention	Autonomous Power Line Inspection Using Drones	Urban Air Mobility
RU	DU+CU+Core	Can be discarded if no connection between Sat and ground segment	+++	+++
RU+L1-LOW	DU (w/o L1-Low)+CU+Core	Can be discarded if no connection between Sat and ground segment	+++	+++
gNB-DU processed payload: RU+DU	CU+Core	+	Can be discarded	Can be discarded
gNB processed payload: RU+DU+CU	Core	+	Can be discarded	Can be discarded
RU+DU+CU+routing fun+AF	Core	+++ (Routing function)	+++(UPF+AF: NTN edge computing enabler)	+++(UPF+AF: NTN edge computing enabler)
Requirements and scenarios to be supported		• Coast Guard Intervention with Seamless Handover to Different Feeder Links for NTN Network Connection • Coast Guard Intervention without Terrestrial Coverage and with only NTN coverage	Drones are intended to gather pictures and videos for Routine inspection.	Requires NTN edge computing.

Functional split Space - Ground		UC4	UC5	UC6	UC7
Space	Ground	Adaptation to PPDR or Temporary Events	Consumer Handheld Connectivity and Positioning Areas	Continuous Bidirectional Data Stream in High Mobility	Direct Communication over Satellites
RU	DU+CU+Core	+++	Less correlated w/ split opt	+	Can be discarded
RU+L1-LOW	DU (w/o L1-Low)+CU+Core	+++	Less correlated w/ split opt	+	Can be discarded
gNB-DU processed payload: RU+DU	CU+Core	Can be discarded	Less correlated w/ split opt	+++	Can be discarded
gNB processed payload: RU+DU+CU	Core	Can be discarded	Less correlated w/ split opt	++ (TN-NTN HO) +++ (NTN –NTN HO)	Can be discarded
RU+DU+CU+routing fun+AF	Core	Can be discarded	Less correlated w/ split opt	Can be discarded	+++(no need for AF)
Requirements and scenarios to be supported		6G TN and 6G NTN coexistence	Light indoor coverage	Requires performance increase (especially RTT)	Resiliency of 6G NTN communication, w/o a tight dependency on the feeder link availability. Latency reduction. Offloading the load on the feeder link.

4.3.2 Architectural Options for Direct NTN Communications

As can be seen from Figure 25, the legacy architectures require a connection between the NTN payload and the on-ground network, e.g., CN and DN.

It is noted that it might be not always possible and/or desirable to connect an NTN node (e.g., a satellite or HAP) with the ground network. For instance, when the UE needs to set up a communication with the peer UE, the gateway may become unavailable for the UE's serving satellite, e.g., during a natural disaster, which may destroy the gateway or causes power outage at the ground network. In such cases where the connection to the ground network

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becomes unavailable, a communication between two UEs via the ground network cannot be supported based on the legacy NTN architectures.

However, an NTN platform may serve a coverage area much larger than that of a legacy TN access point, e.g., a TN gNB. For example, the area covered by a LEO satellite may have a size of up to one thousand kilometres. Therefore, in many scenarios, a satellite may cover two communicating UEs with a high probability. In this case, a direct communication between two UEs can take place over the satellite without the need for the data to go through the ground network, e.g., as shown in Figure 32. In addition, ISLs can be used to further enlarge the coverage area of the direct NTN communication, e.g., as shown in Figure 33. More detailed information and use cases of the direct NTN communication can be found in D2.1 '*Use case definition*'.

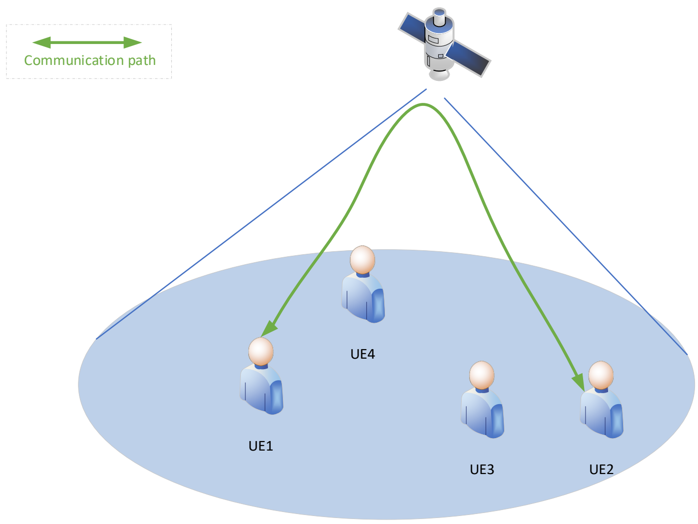

FIGURE 32: DIRECT NTN COMMUNICATION OVER A SINGLE SATELLITE.

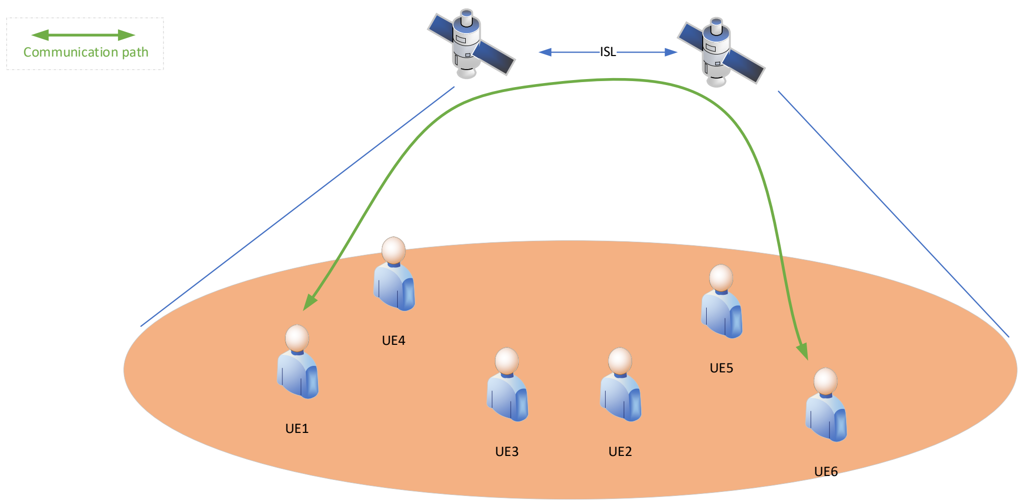

FIGURE 33: DIRECT NTN COMMUNICATION OVER TWO SATELLITES CONNECTED OVER ISL.

Based on the above description, the potential benefits of the direct NTN communications include:

- Latency reduction
- Feeder links and ISLs load reduction

- Support communication in case of ground network unavailability (natural or man-made disasters but also cyber-attacks)
- Enable future NTN NW to be decoupled from the ground network deployment

Therefore, in this section we analyse the different system architecture options where the feeder link to ground NW is not used for direct NTN communication, e.g., when the connection to the ground network is/becomes unavailable.

Please note, since 6G architecture has not been defined at the time of this report, the 5G system architecture and the terminologies for the corresponding functions are reused in this section as a baseline to describe the different options.

4.3.2.1 Option 1: NTN Node Equipped with gNB, CN Functions and even DN/AF/Server

In this option, the NTN nodes can be equipped with a RAN function/node, e.g., a gNB, together with one or multiple CN functions, e.g., UPF, AMF, SMF, AUSF, PCF, UDM, etc. If needed, even DN/AF/server can be deployed onboard the NTN platform to enable onboard data processing. To some extent, this option is similar to moving the complete TN network and the corresponding functions to the space, which allows the future NTN network to be independent from the legacy TN. With this option, the considered direct NTN communication can take place by using the available TN solutions, since all the needed functionalities would be available in the space.

An illustration of the control plane protocol architecture for this option is shown in Figure 34. As it can be seen, both the RRC layer used for AS layer control and the NAS layer are terminated at the UE and the satellite(s). For the sake of simplicity, Figure 34 shows that both RRC and NAS are terminated at the same satellite, e.g., a satellite is equipped with both RAN for RRC and CN functions for NAS. However, in a multi-layer 3D NTN architecture with distributed NFs, the gNB and the CN functions, e.g., AMF and SMF, can be distributed in different NTN nodes, e.g., on different satellites that are connected via ISLs. In that case, the RRC layer and the NAS layer of the UE can be terminated at different satellites.

Figure 35 shows the user plane protocol architecture for Option 1. As can be seen, the E2E data can be transmitted over the PDU sessions of the two UEs. Besides, the PDU session of a UE is supported and controlled by the CN functions deployed in the space segment, e.g., in satellite(s). With this architecture, the routing of the user traffic from one UE to another UE can be performed by the CN function, e.g., a UPF, which is controlled by another SMF onboard the same satellite or another satellite but with ISL connection to the satellite carrying the UPF. As another alternative, it is also possible to rely on an onboard AF to route the traffic, if the AF can be deployed on the satellite(s).

With this option, the UE may need less modifications at the AS layer, and the legacy TN solutions can be reused as the baseline. However, this solution may also face some technical challenges, such as:

- Increased complexity and power consumption at satellite, e.g., due to the deployment of various CN functions at a satellite, which can be a potential bottleneck impacting the success of 6G NTN.
- Potentially a large impact on CN due to moving CN nodes. In legacy network deployment, a CN node is normally static and deployed on the ground. However, if a CN node is deployed in the satellite, e.g. in a LEO satellite, the CN node can have high mobility, which can cause a dynamic CN topology change, as well as frequent CN node change for a serving UE. Thus, to support this option, the design of CN and system architecture in 6G would need to take account of the impacts caused by the moving CN nodes.

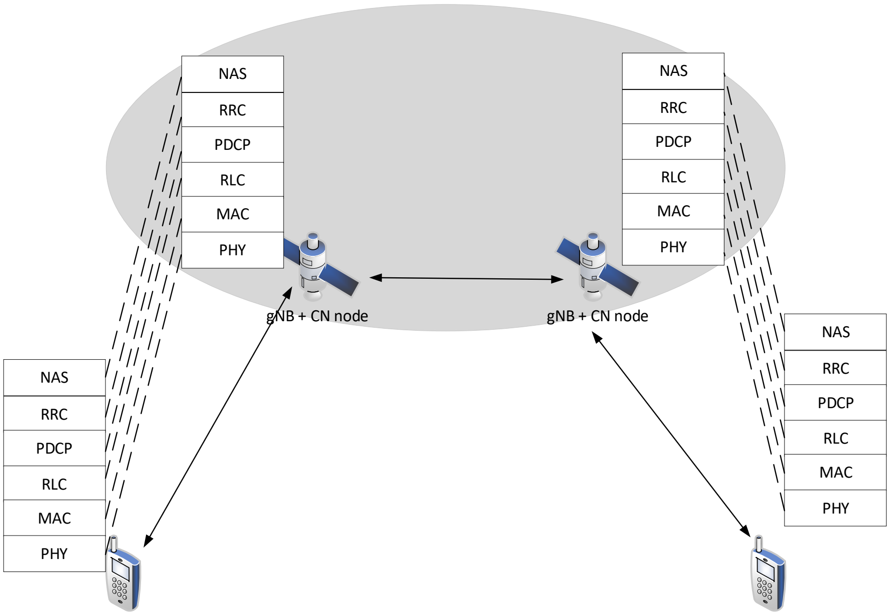

FIGURE 34: ILLUSTRATION OF CONTROL PLANE FOR OPTION 1.

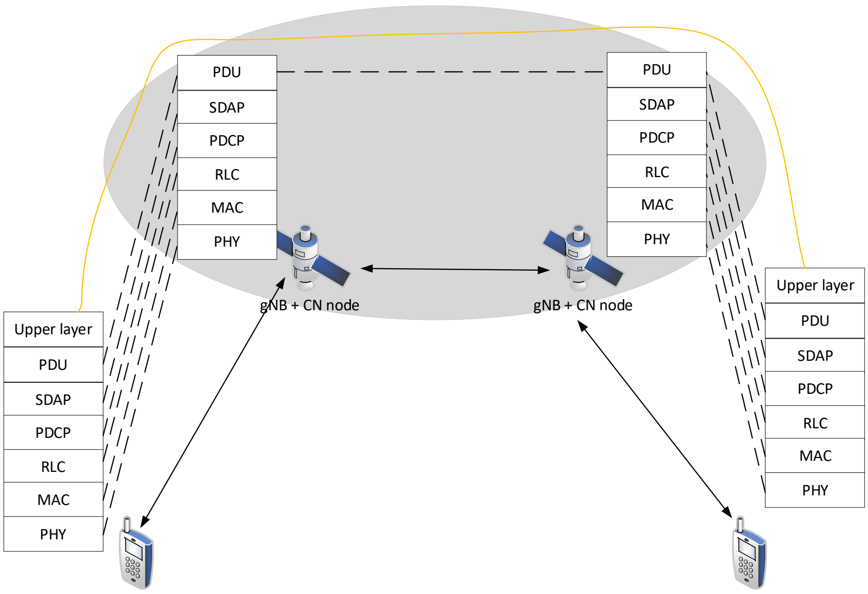

FIGURE 35: ILLUSTRATION OF USER PLANE FOR OPTION 1.

In 6G NTN, a multi-layer/multi-orbit 3D architecture is expected, where the integration between GEO satellites and LEO satellites can contribute to simplify the implementation of Option 1. For example, as shown in Figure 36:

- The GEO satellite may store and maintain the UE subscription and the corresponding policy information for the set of the UEs registered in a considered network operator(s) that are covered by the footprint of the GEO satellite. Thus, the (semi)static UE subscription and policy information is located in a fixed position, which is similar to TN.

- GEO satellites may carry and implement CN nodes, at least for supporting some of the control plane (CP) functions. For example, the GEO satellites can carry the UDM, UDR, AUSF for the purpose of authorization and authentication. In addition, SMF/AMF/PCF may also locate in GEO optionally, e.g. to offload the control plane tasks from LEO and avoid the need for relocating the CN node from one satellite to another. In this way, the context of a serving UE/session can be kept at a fixed GEO satellite, similar as in TN. However, it is noted, locating the CN nodes/functions onboard a GEO satellite may cause relatively a large CP latency, e.g. the CN message of a UE may be transmitted between the ground UE and the GEO satellite.
- A LEO satellite in the conventional architecture or a group (e.g. two) of LEO satellites in the distributed architecture, e.g. as shown in Section 1.4, may carry the RAN node/functions. Besides the RAN node/functions, it may carry certain CN nodes/functions. In one example, it may carry UPF, such that the data communication can be routed directly from one UE to another UE through the link UE1 <-> RAN@LEO <-> UPF@LEO <-> UPF@LEO <-> RAN@LEO <-> UE2 without involving the GEO satellite, which can support a low E2E latency in the user plane. In addition, SMF/AMF/PCF can also be implemented on the LEO constellation for the purpose of session and mobility management, e.g. if such a function is not contained in the GEO satellite. In this case, low latency can be even achieved for the CP procedures that do not require to contact the GEO satellite such as a CP procedure without the need for authorization and authentication. However, carrying SMF/AMF/PCF with LEO constellation implies a compromise of increased complexity for relocating the UE/session context from the leaving LEO satellite to the upcoming LEO satellite during the satellite switch.
- For inter-connecting the different nodes/functions located on LEO constellation and a GEO satellite to support CP procedures such as UE authorization and authentication, ISL can be used. Since a CP procedure normally does not consume a lot of data, the achievable data rate of the ISL between LEO and GEO should be enough for supporting this implementation option.

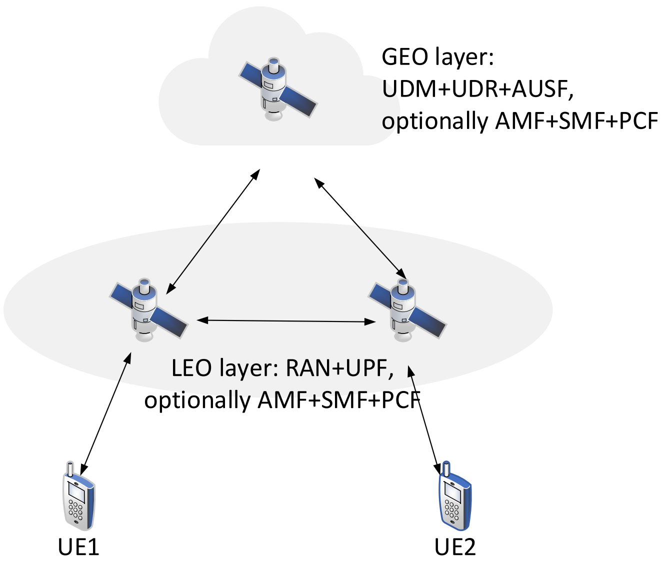

FIGURE 36: USING GEO SATELLITE TO SIMPLIFY THE IMPLEMENTATION OF OPTION 1

4.3.2.2 Option 2: NTN Node Equipped with an Onboard Relay-Like gNB

In this option, a RAN node, e.g., a gNB, is available at the NTN node. In order for this option to support an E2E link between two UEs without connectivity to the ground network, modifications may be needed at the onboard RAN node, comparing to the legacy RAN node. For example, since the legacy gNB does not support a direct routing between two UEs, the onboard RAN node needs an additional routing function to route the E2E traffic from one UE to another UE via one or multiple satellite(s).

Figure 37 and Figure 38 illustrate the control plane protocol architecture and the user plane protocol architecture for Option 2, respectively. As can be seen, the Uu air interface designed for NTN (e.g., the Uu interface designed in the legacy 5G NTN) can be used as the baseline for the direct NTN communication. It is noted the onboard NTN payload in Option 2 only terminates the RAN protocol stacks for a UE, which is different from Option 1, since the NTN node(s) in Option 1 carries the CN functions as well. In addition, the control plane in Option 2 can leverage the RRC layer to control the UE and, thus, it can handle the NTN mobility caused by the high mobility of the NTN node(s), e.g., with the help of Xn interface carried over the ISL.

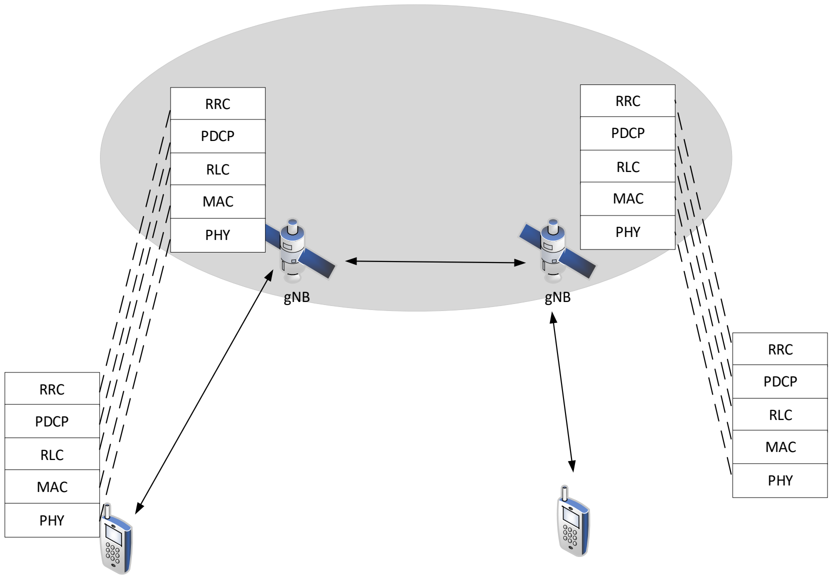

FIGURE 37: ILLUSTRATION OF CONTROL PLANE FOR OPTION 2.

In addition to the mentioned routing function, modifications may be needed for supporting additional upper layer protocols and procedures in Option 2. For instance, authorization, policy/parameter provision, and security/privacy protection may be desired for direct NTN communication. In order to do that, the similarity of direct NTN communication with sidelink (SL) UE-to-UE (U2U) relay is noted. For SL U2U relay, a UE can act as a relay UE to route the traffic between two remote UEs, even when the relay UE is out of the network coverage. Thus, as an example, the technical solutions in SL U2U relay can be considered as a baseline for authorization, policy/parameter provision, and security/privacy protection in direct NTN communication. It is further noted that, differently from the SL U2U relay that applies the PC5 interface to facilitate the proximity communication between the remote UE and the relay UE, the satellite in the considered direct NTN communication leverages the NTN Uu interface at AS layer to transport the upper layer data (e.g., application or service data) between the two end UEs. Moreover, if charging is required for direct NTN communication, offline charging may be applied, where the satellite and its payload may generate and keep a record of the amount of data consumed by a UE with the direct NTN communication.

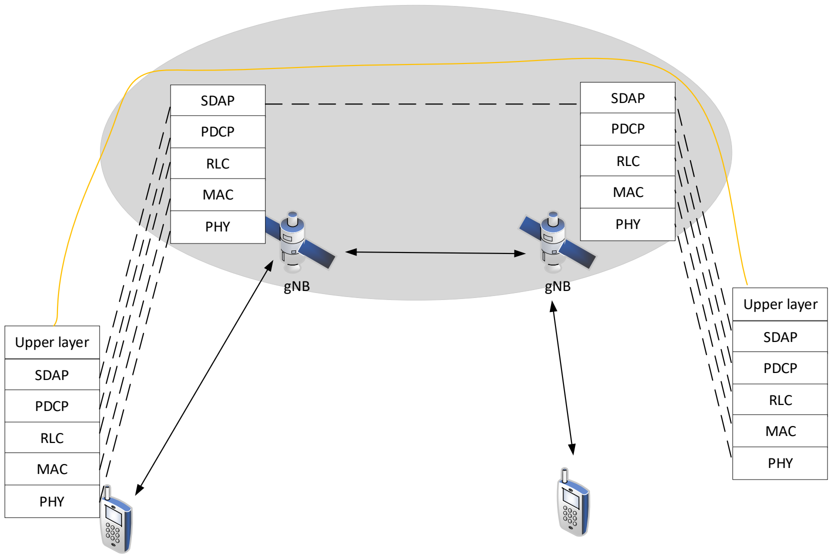

FIGURE 38: ILLUSTRATION OF USER PLANE FOR OPTION 2.

Furthermore, in order to support the onboard routing function for the E2E link, an additional layer/function may be added on top of the user plane architecture shown in Figure 38. The additional function/layer is not shown in Figure 38, since it may have different design options. For example, Figure 39 shows an example of using layer-3 (L3)-based routing function, where the additional routing function/layer for the E2E link may be added on top of the SDAP layer. In another example, Figure 40 gives an example of using layer-2 (L2)-based routing function, where the additional routing function/layer for the E2E link may be added on top of the RLC layer.

For the L3-based solution shown in Figure 39 the onboard gNB manages/updates the routing by using an additional layer/function above the AS layer, e.g. based on IP, QoS flow, radio bearer, RNTI, peer UE's location, and/or a header at an additional layer/function. In case a UE in the considered direct NTN communication is restricted with only one peer UE, i.e., a 1-to-1 mapping between the TX UE and the RX UE, routing can be performed based on the TX UE identity. Moreover, additional layer/function may be optionally needed at the UE, e.g., depending on if one UE is restricted to communicate with only one peer UE. In addition, two UEs of an E2E link may set up an E2E control layer, e.g., an E2E RRC/NAS layer as shown in Figure 41, where the E2E RRC/NAS layer is transported over NTN node(s) and Uu PDCP-and-below layers. The E2E RRC/NAS layer can be used for optimizing E2E and joint link control. In one example, the E2E RRC/NAS layer at the UE can be used to initiate the setup/release of the E2E link and/or store the status information of the E2E link.

As shown in Figure 40, for the L2-based solution, onboard gNB implements an additional layer (AL)/function above the RLC layer to route data packets, wherein layers below PDCP terminate at each UE and the satellite but the PDCP-and-above layers terminate at two end UEs. It is noted, though both Uu and PC5 may be considered for the PDCP-and-above layers, the PDCP and SDAP layers of PC5 may need to be modified, e.g., to handle the large propagation delay in NTN. In this solution, comparing to the L3-based solution, the satellite is not involved in E2E UP security since the PDCP layer is terminated at both UEs. Similar as to the L3-based solution, an optional E2E control layer, e.g., an E2E RRC/NAS layer, can be transported over NTN node(s) and leveraged for the E2E link control, as shown in Figure 42.

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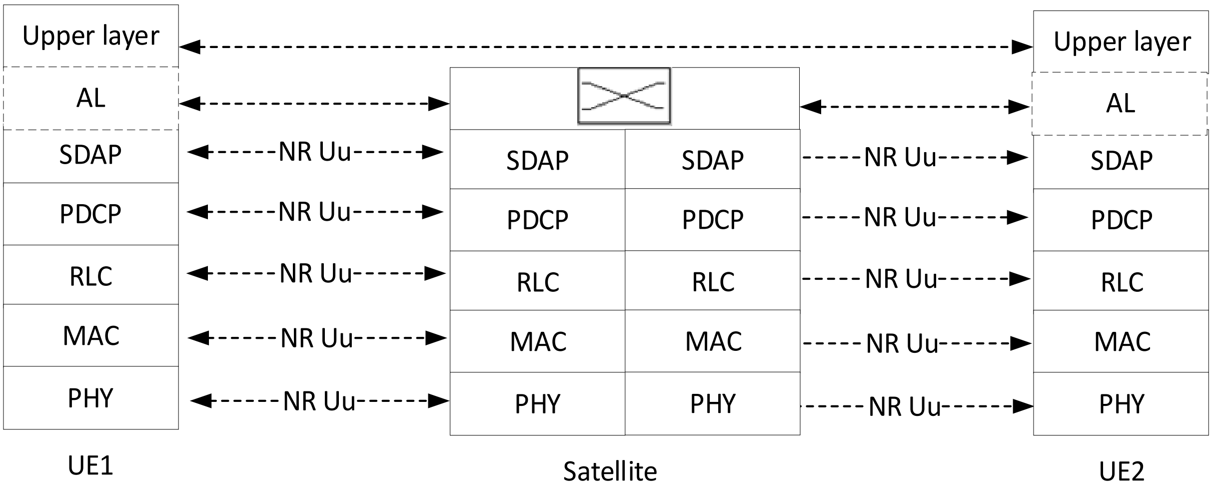

FIGURE 39: ILLUSTRATION OF LAYER-3-BASED ROUTING ON USER PLANE WITH A SINGLE SATELLITE.

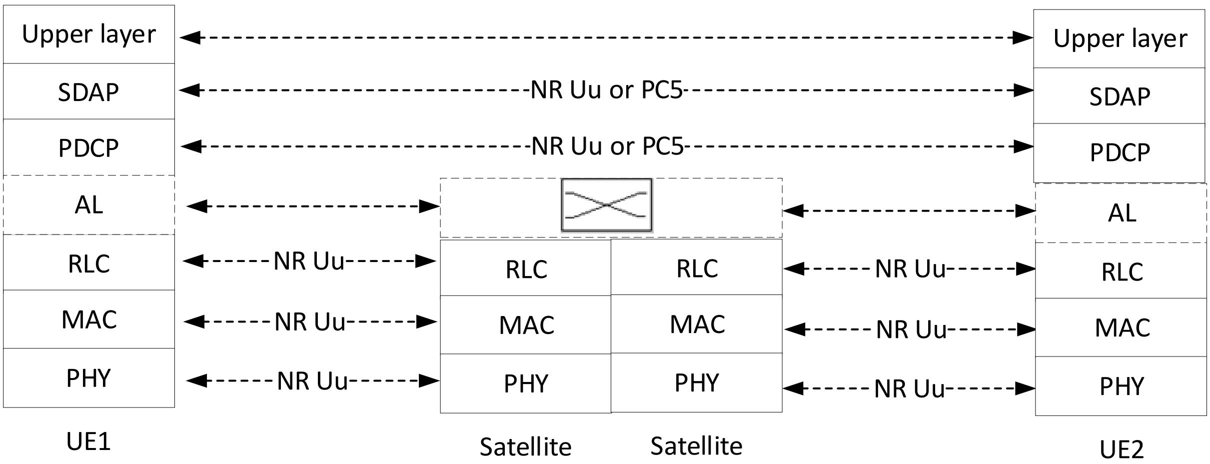

FIGURE 40: ILLUSTRATION OF LAYER-2-BASED ROUTING ON USER PLANE WITH A SINGLE SATELLITE.

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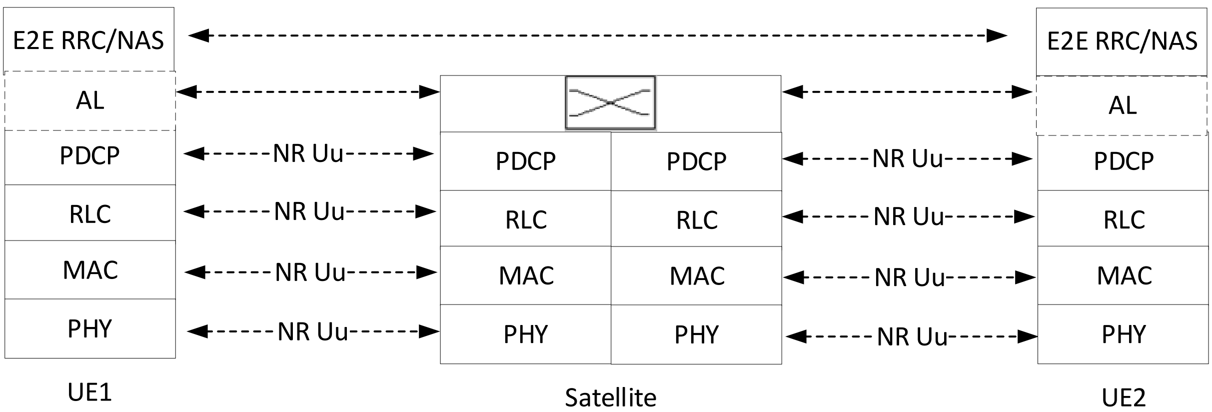

FIGURE 41: E2E LINK CONTROL-PLANE FOR L3-BASED SOLUTION.

As described above, since Option 2 does not require CN deployment on the NTN platform(s), the amount of satellite complexity and power consumption can be expected to be lower than that in Option 1. However, Option 2 would have impact on the RAN specifications, e.g., to implement the required modifications. In addition, due to the special way of handling authorization and security, Option 2 may experience more limitation for general service support comparing to Option 1.

It is noted that the additional complexity and specification effort for Option 2 may depend on the considered use case. For instance, some use cases may not require a mobility support, e.g., when the direct communication is used for a one-time short message transmission. While in some other use cases, the direct communication may be used to relay a broadcasted message from one transmitter UE to other users in the proximity of the transmitter UE, which may impact the routing function design at the onboard gNB.

Please note, Option 2 can be applicable for in the conventional architecture and the distributed architecture described in Section 1.4, though the conventional architecture has been used so far for illustrative purposes. In case of a distributed architecture, two LEO satellites may be grouped and concatenated to form a complete RAN node. Thus, the only difference for supporting Option 2 from a conventional architecture is on the detailed function split between the two LEO satellites. For example, if the service satellite carries a DU, then the UP of the E2E link between the two UEs served by the same service satellite may not need to go through the feeder satellite in case of L2-based solution, since the service satellite may directly route the data from one UE to another. i.e. UE1 <-> DU @ service satellite <-> UE2. However, if the service satellite carries only lower PHY layer, then the E2E link has to be routed through the feeder link, i.e. UE1 <-> service satellite <-> feeder satellite <-> service satellite <-> UE2, no matter whether L2-based or L3-based solution is used.

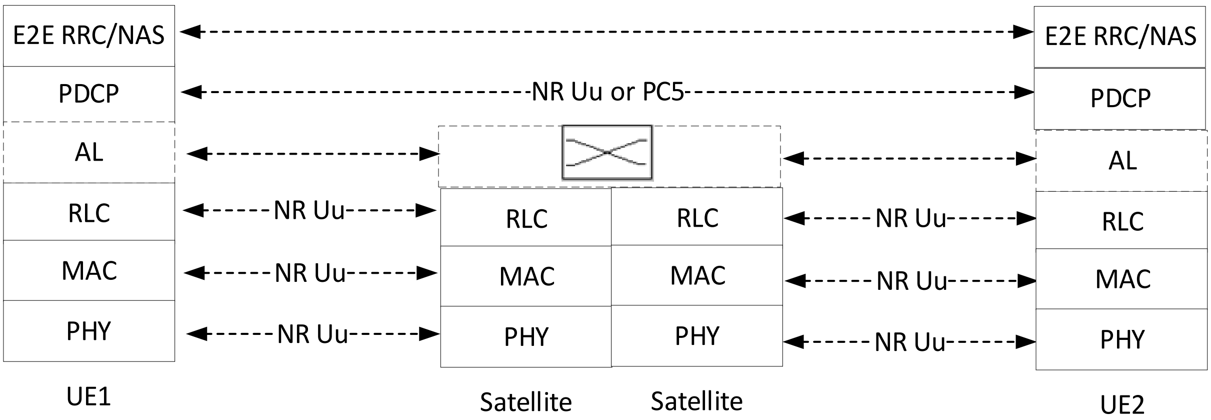

FIGURE 42: E2E LINK CONTROL-PLANE FOR L2-BASED SOLUTION.

4.3.2.3 Option 3: NTN Node Acting as a Sidelink Relay

It is noted, that the considered direct NTN communication may leverage the SL U2U relay design, whose design is currently ongoing in 3GPP Rel-18. The SL U2U relay technology is able to use a UE as a relay UE between two remote UEs and, thus, the E2E traffic between the two remote UEs can be relayed over the relay UE. The communication between a remote UE and the relay UE takes place over the PC5 interface, and the SL U2U relay can work even when all the involved UEs (i.e. including the relay UE and the remote UEs) are out of ground network coverage. Similarly, in Option 3, an NTN node (e.g., a satellite) may act as a SL relay to forward the traffic between two end UEs, as shown in Figure 43.

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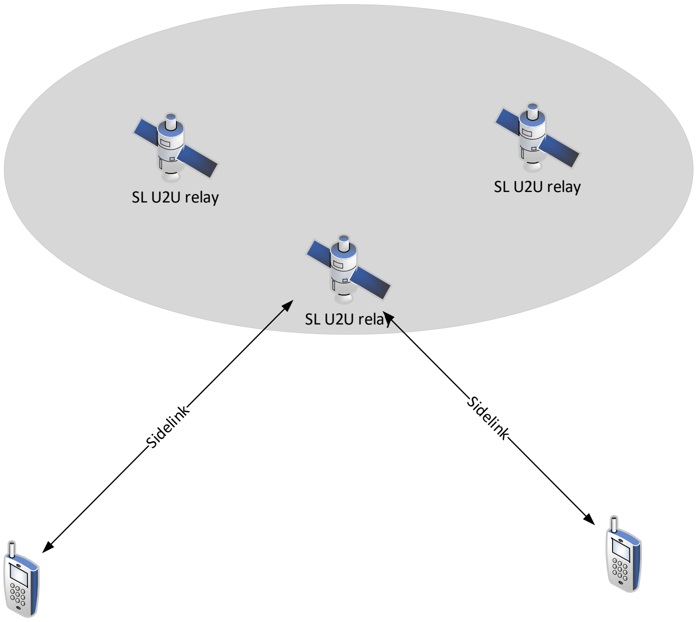

FIGURE 43: NTN PLATFORM ACTS AS A SL U2U RELAY.

In this option, the architecture design of SL U2U relay can be largely reused to support the considered use case. However, more modifications may be needed on the SL air interface design (e.g., PC5 PHY/MAC) to handle the NTN-specific characteristics, since SL was not designed for supporting the long-distance communication between a UE and a satellite. Thus, it means that a UE supporting TN SL operation, e.g., a vehicle, may need to implement an additional capability for supporting SL operation in the considered SL U2U relay over a satellite. In addition, both the UE and the NTN payload may need to use different air interfaces for:

- regular NTN communications by going through the ground network, e.g., via Uu air interface, and
- direct NTN communication without going through the ground NW, e.g., via PC5 air interface.

Thus, this option may increase the complexity at both the UE and the satellite. In addition, since the current SL U2E U2U relay is designed for being equipped at a UE, it has less capability than a gNB. Thus, it may provide less efficiency and robustness than Option 2, e.g., for handling satellite switch due to NTN mobility.

Similar as the two options mentioned before, Option 3 can also be applicable in both the conventional architecture and the distributed architecture described in Section 1.4. In addition, similar to Option 2, the E2E link between two UEs under the same service satellite in the distributed architecture may also be relayed via the single service satellite, e.g. if the service satellite implements the relay UE function as in the Layer-2-based SL UE2UE relay solution.

Based on the above analysis, Table 37 summarizes the differences among the three options in supporting the considered direct NTN communication. As it can be seen, an integrated 3D network in 6G NTN allows to deploy a complete but distributed CN architecture in space by using both LEO and GEO satellites in Option 1, which is a promising technology for supporting the considered direct NTN communication.

TABLE 37: COMPARISON AMONG DIFFERENT OPTIONS FOR DIRECT NTN COMMUNICATIONS

	Option 1: Satellite equipped with RAN and CN	Option 2: Satellite equipped with RAN	Option 3: Satellite equipped with Sidelink Relay
Routing the E2E traffic	Supported by CN	Need to add new function/layer at RAN	Yes (TBC)
Impact on the onboard CN nodes	Large impact if LEO constellation needs to carry the complete CN, e.g. to handle moving CN nodes; Small impact if GEO constellation is used to carry the CN nodes	No	No
Added satellite complexity and power consumption	High if LEO constellation needs to carry the complete CN; Relatively small if GEO constellation is used for offloading certain CN tasks from LEO constellation	Medium	Medium
PHY/MAC support	Yes (R-17/18 or 6G NTN solutions)	Yes (R-17/18 solutions)	No (Need additional RAN1/RAN2 work)
Mobility and service continuity support	Less efficient if LEO constellation needs to carry the complete CN , e.g. to handle CN node switch; Good if GEO constellation is used to carry the CP CN functions.	Good (RAN node switch by reusing Uu RRC)	Middle (RAN node switch by SL signalling)
RAN impact	No/Minimum	Yes	Yes
Added UE complexity	Small	Medium	High

Architecture impact	Yes (Mostly on CN)	Yes (Mostly on RAN)	Little (Reuse SL U2U architecture)

4.3.3 Adaptive Functional Split

As discussed in Section 4.3.1, different use cases (UCs) are associated to different requirements and, thus, a "one size fits all" approach is not ideal. For example:

- Higher layer split is preferred for:
  - Traffic load reduction over ISL and the feeder link (UC1)
  - Equipping onboard MEC (UC2 and UC3)
  - Achieving lower latency (UC6)
  - Supporting direct NTN communication without feeder link (UC7)
- Lower layer split is preferred for:
  - Onboard complexity/power reduction (e.g. in drones in UC2 and UC3)
  - Central scheduling for dynamic resource sharing (UC4)
  - Enabling lower layer mobility (UC6)

It is noted, that different from a TN platform in the legacy design, an NTN platform (e.g. a satellite) may have to support different scenarios/use cases at different times and/or different areas, due to the special characteristics in NTN, such as:

- High mobility of a satellite, which is much higher than that of a TN platform, which implies that the satellite may move from one area to another area, e.g. from one country/continent to another country/continent, where conditions in the different areas may be much different, which poses the need for satellite to support different use cases at different times
- Large coverage area of a satellite, which is much larger than that of a TN platform, may imply a high possibility for the satellite to cover different areas with different scenarios and different technical requirements at a considered time instance

Therefore, in order to better support the different use cases in future 6G NTN, it is proposed to consider an adaptive functional split (AFS) technology, which enables the satellite to adapt the functional split in time and/or space domain.

In this section, four options for AFS are provided for their initial analysis in this deliverable. Please note, more detailed analysis, such as impact on technical specifications and/or implementation options, may be provided in the future deliverables.:

- Cell/area-specific AFS: Different functional split options for different cells/areas
- Scenario-specific AFS: Different functional split options in different scenarios
- UE-specific AFS: Different functional split options for different UEs
- Service-specific AFS: Different functional split options for different services

Please note, to illustrate the different AFS options in the rest of this section, a lower layer functional split option, which splits the PHY layer to a lower PHY sub-layer and a higher higher-

PHY sub-layer, is used as an example, while a higher layer functional split option, which contains the entire gNB protocol layers, is used as another example. However, these options are only used for illustration purposes, and they should not be interpreted as the only options for supporting the proposed AFS.

4.3.3.1 Cell/Area-Specific AFS

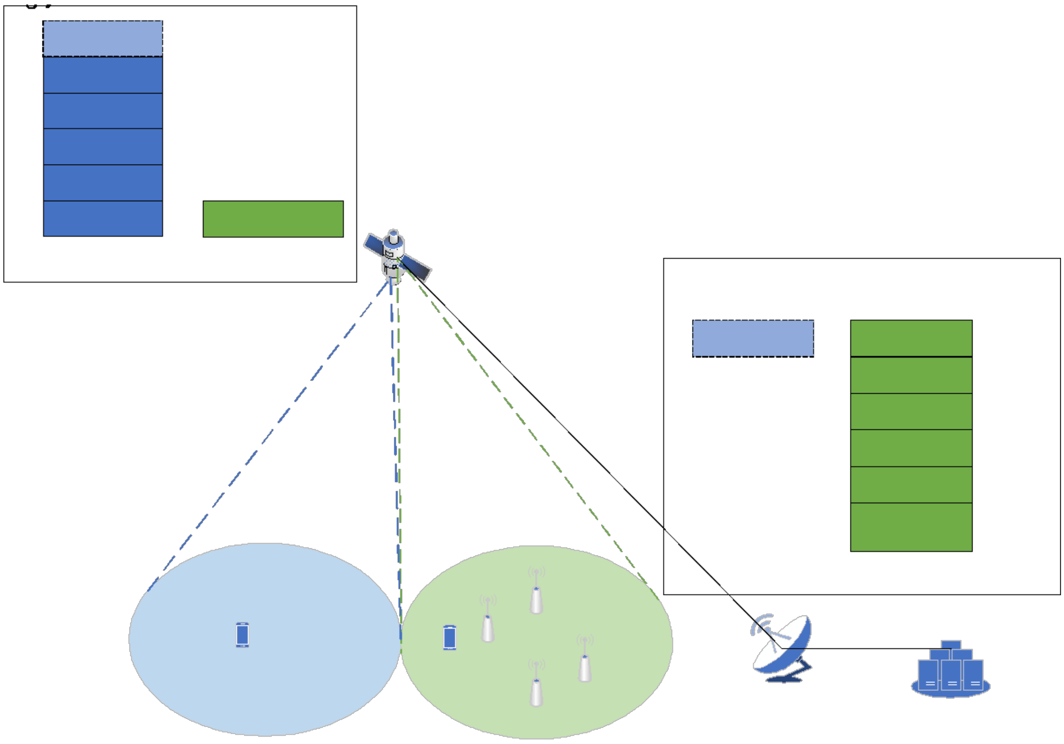

FIGURE 44: ILLUSTRATION FOR THE CELL/AREA-SPECIFIC AFS

Figure 44 shows an example for the cell/area-specific AFS scheme. In this scheme, a satellite may serve different cells or different areas by using different functional split options at the same time. For example, TN and NTN NW may coexist in the area covered by cell #m, e.g. along a seashore, which may prefer to deploy a lower layer function split such that more AS protocol layers can be centrally located on the ground, which enables to apply a central scheduling for handling TN-NTN coexistence and lower layer mobility solutions for TN-NTN mobility. In contrast, cell #n may cover an area without TN coverage, e.g. in the deep sea. In this case, cell #n may benefit from using a higher layer function split, which can help to achieve a lower latency in the AS layer and support onboard MEC in 6G NTN.

Please note, cell #n and cell #m may use the same physical lower PHY entity onboard the satellite, and they are logically separated in Figure 44 for illustration purpose only. Please also note, the same note applies for the rest of the figures in this section.

In the cell/area-specific AFS scheme, movement of a UE from one cell/area to another, e.g. from cell #m to cell #n, may cause handover, which can be supported with the legacy standards. The handover procedure can relocate the serving AS/NAS entities of the UE between space segment and ground segment, which effectively changes the split options for the UE.

In addition, since the satellite implements multiple split options for different areas/cells, feeder link needs to transport multiple interfaces. For example, if the low layer split option implements an lower PHY layer onboard the satellite, a fronthaul interface (e.g. the one defined in Open

RAN) needs to be transported over the feeder link. In addition to the fronthaul interface, the feeder link may also need to transport the interface used for the high layer split option. For instance:

- If only (part of) the AS layers are onboard the satellite for the high layer split option, while the NAS and PDU layers are on the ground, feeder link may need to carry the Xn interface for connecting the two base stations located onboard the satellite and on the ground as well as the NG interface for connecting the onboard base station with the ground CN nodes such as AMF and UPF.
- If AS + PDU layers are onboard the satellite for the high layer split option, but the NAS layer (e.g. AMF, SMF) terminates on ground, feeder link may need to carry the NG-C interface for connecting the onboard RRC with the on-ground AMF, the N9/N6 for connecting the onboard UPF with on-ground UPF/AF, and the Xn interface for connecting the onboard base station with the on-ground base station.
- If all of the AS, PDU, and NAS are onboard the satellite, feeder link needs to carry the N9/N6 interface for connecting the onboard UPF with on-ground UPF/AF.

It is noted, the need for carrying multiple interfaces over feeder link is also applicable for the other AFS schemes that will be described in the following of this section. In addition, due to the satellite movement, there is a need to support dynamic interface setup, removal, and reconfiguration over the feeder link.

4.3.3.2 Scenario-Specific AFS

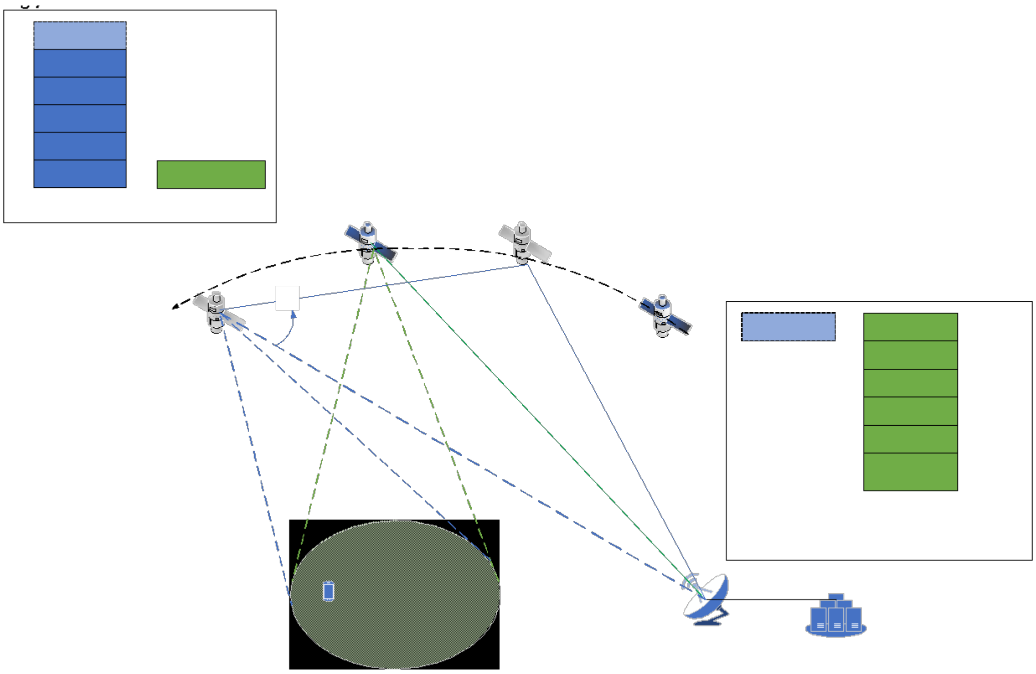

FIGURE 45: ILLUSTRATION FOR THE SCENARIO-SPECIFIC AFS

Figure 45 illustrates an example for the scenario-specific AFS, where the satellite may determine to adapt its functional split based on the real time scenario, e.g. if an ISL is needed. As shown in this figure, satellite 1 at time t1 may have a direct feeder link connection to the gateway and ground network, and it may apply a lower layer split function. However, afterwards, satellite 1 may move away from the gateway. And at time t2, satellite 1 has to establish an ISL towards another intermediate satellite (e.g. satellite 2) for its connection towards the ground network, since satellite 1 has moved out of the gateway's reachability. In this case, in order to reduce the load posed by the data of satellite 1 on the ISL and/or the feeder link of satellite 2, it may be preferred for satellite 1 to switch from lower layer split to higher layer split.

In one solution, NW may use two different cells for serving the considered area before and after adapting the onboard functional split, as shown in Figure 46. For instance, satellite 1 may use a cell #m to serve the UE at time t1, while switch to use a cell #n at time t2. In this solution, since the UE is served by the same satellite but different cells before and after adapting the onboard functional split, legacy mobility scheme (e.g. HO, RRC reestablishment procedure) may be applied for the UE to switch its connection to the target cell of the same satellite but with a different function split after the function split adaptation. This solution is simple to implement and has no spec impact, but it may introduce additional signalling overhead as well as service interruption time due to the HO procedure.

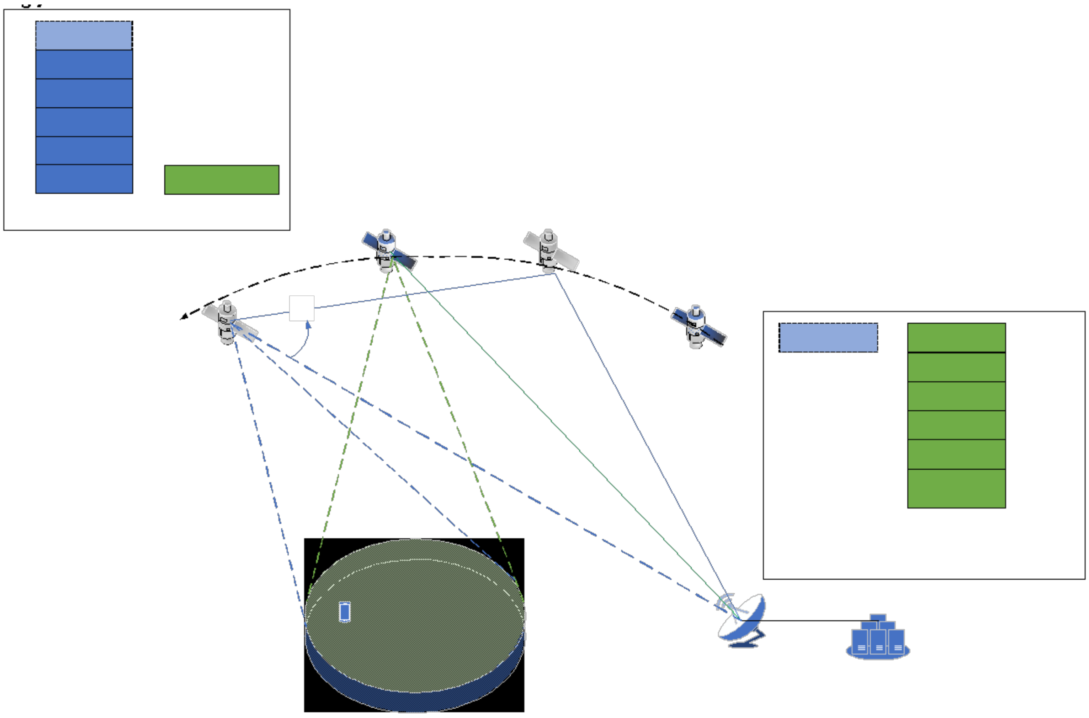

FIGURE 46: SCENARIO-BASED AFS BASED ON MULTIPLE CELLS

In another solution, NW may implement a virtual cell concept by interconnecting the different hardware located in the ground and space segments and, thus, the UE can be served by the same cell before and after the function split adaptation. For example, before the function split adaptation, the layers above lower PHY at the UE are terminated in the ground entity Thus, upon or right before the function split adaptation, the UE's radio context (e.g. radio link measurement, MAC/RLC/PDCP status, RRC configuration) can be transferred from the ground entity to the onboard entity. Thus, upon switching to the high layer split option, the onboard entity can directly take over and continue serving the considered UE and, thus, there is no need for L3 mobility such as HO. However, this solution implies a high implementation complexity between space segment and ground segment to realize the proposed virtual cell concept. In addition, there may be potential spec impact. For example, in order to achieve a smooth transition, the UE may need to be provided with additional assistance information to modify its behaviour properly, such as:

- The location change of the peer protocol stacks, e.g. for handling propagation delay. In one example, since the MAC layer is moved from ground to the serving satellite, the random access procedure will terminate onboard the satellite after the function split adaptation and, thus, the feeder link delay does not need to be accounted/compensated during the UE's RACH procedure anymore. In addition, other timers/window settings may also need to be reconfigured, e.g. the RLC/PDCP timers and NAS timers, to account for the E2E delay change due to the relocation of the corresponding protocol stack involved during the function split adaptation.

- Synchronization-related information, such as SFN timing offset before and after adaptation. In one example, if the same GNSS/UTC timing is used by both the onboard gNB and the on-ground gNB to determine the timing for transmitting a DL SFN #n towards the UE, the DL SFN will arrive at the UE with a time offset equal to the feeder link delay. Thus, the SFN timing offset can help the UE to accurately locate the time window for receiving a signal (e.g. synchronization signal) from the satellite after the function split adaptation.

4.3.3.3 UE-Specific AFS

Due to the complexity/resource/power constraint at satellite, a satellite may only be able to support some of the UEs with additional onboard protocol layers and computing resource, but the other UEs may only be supported with lower protocol layers onboard the satellite. Thus, in Figure 47, a UE-specific AFS scheme is shown, where different function split options may be applied for serving different UEs. For example, UE1 may be consuming a low latency service, but not UE2. Thus, in this example, the satellite may apply a higher layer split for UE1 but not UE2, which allows to use the precious onboard resource in a smart manner by taking account of each UE's specific requirement.

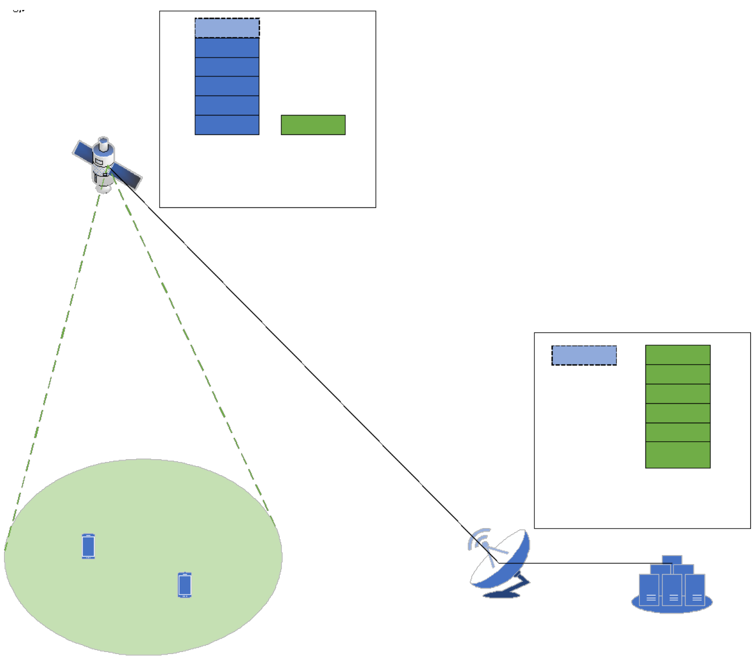

FIGURE 47: ILLUSTRATION FOR THE UE-SPECIFIC AFS

Applying different split option to serve different UEs may introduce the need for UE-specific time/delay compensation, since a considered protocol layer of different UEs may terminate at different physical locations, e.g. satellite vs. ground. This is different from the legacy 5G solution, where the protocol layer of different UEs will terminate at the same physical location and, thus, the time/delay compensation is rather cell-specific and common to all the UEs served by the same cell, e.g. the use of *K_mac* and common TA parameters are the same for all UEs served by the same cell. Thus, to support this proposal, there may be two options, which will be described in the following.

In the first option, NW deploys a single cell to cover the UE-located area, but with two different function split options such that the UE can be configured by the cell with the proper setting for operating with its configured split option. This solution requires implementing a radio cell, where a single radio layer associated to the considered cell may be distributed in different places, e.g. in space and on ground. Accordingly, the radio layer of a considered UE can only be terminated at on place, i.e. either in satellite or in the on-ground entity, based on the specific function split option configured to the UE. Thus, this solution requires a high implementation complexity, such as the need for a tight integration and interaction between different physical entities to implement a single radio protocol layer without confliction. In addition, it may also require additional enhancement on the UE's split option selection:

- In one option, NW may select the proper split option and determine the corresponding configuration for the UE, e.g. based on the UE-specific context/condition. However, before the UE-specific config/re-config (e.g. for time/delay compensation based on a RRC message) is received by the UE from NW, the UE may need to apply a configured/default split option to access and communicate with NW.
- In another option, UE may autonomously select the proper split option by itself. Afterwards, the UE may send its selection decision to NW, which helps NW to determine the proper UE configuration. In one example, a specific PRACH resource may be reserved for the UE to indicate its split option selection and, thus, the UE can apply its selected split option for its communication with NW from the beginning. In another example, it is also possible for the UE to use a default/configured split option until the indication of its selection has been sent to NW.
- In a third option, it is possible to apply both the NW-based option and UE-based option described above, e.g. an initial split option selection may be selected by the UE autonomously, while NW may decide to change the split option selection and the corresponding configuration for the UE after the UE's initial selection.

In the second option, NW may use multiple overlapping cells to cover the same area, where each cell is associated to a different split option. In this case, a UE is configured with the rule to determine a proper split option and access the cell associated to the selected split option. As shown in Figure 48, UE1 may select the higher layer split option and access cell #m, which applies a higher layer split option. Different from UE1, UE2 may select a lower layer split option and access cell #n. In this scheme, the UE needs to be aware of the association between different split options and different cells in the same area. The UE may apply the proper AFS configuration to communicate with the satellite, starting from the initial access procedure by acceding the corresponding cell. However, due to the coexistence of multiple cells in the same area, this solution may require an efficient way to handle the inter-cell interference, e.g. by time-and/or-frequency separation.

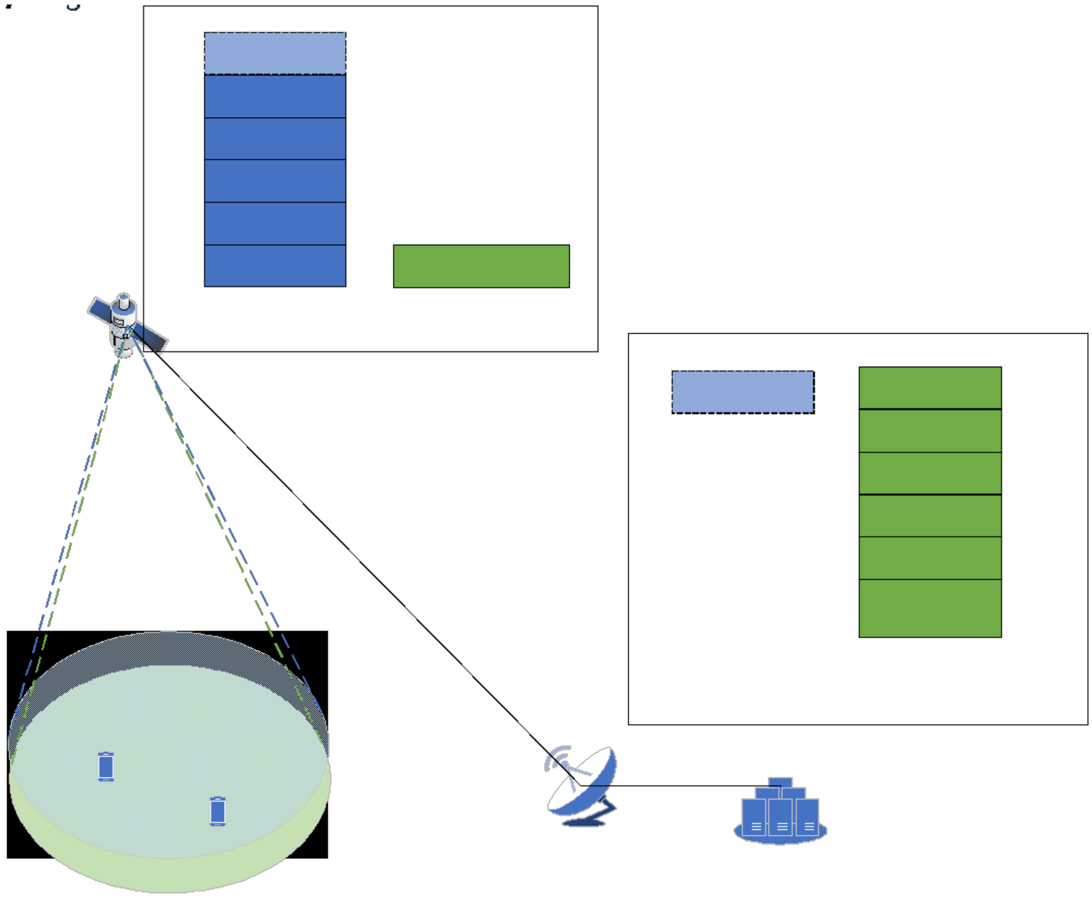

FIGURE 48: UE-BASED AFS BASED ON MULTIPLE CELLS

4.3.3.4 Service-Specific AFS

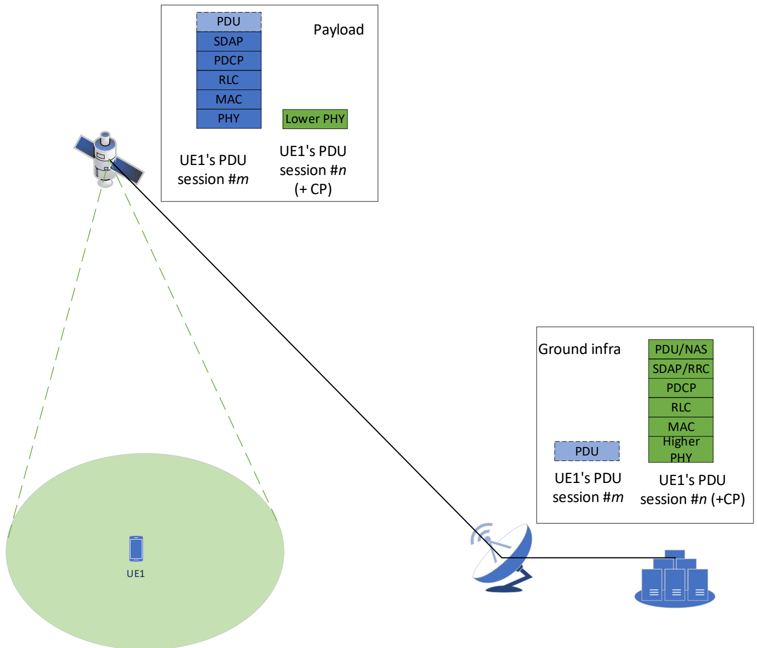

FIGURE 49: ILLUSTRATION FOR THE SERVICE-SPECIFIC AFS

In Figure 49, an example for supporting the service-based AFS is illustrated. In this example, the different services or PDU sessions of the considered UE may be served by using different split options. For example, the UE's session requiring an onboard MEC or low latency (e.g. UE1's PDU session #m) may be served by a high layer split, but lower layer split may be preferred for serving another session (e.g. UE1's PDU session #n) and the control plane of the UE to save the precious onboard resources. This scheme provides a finest granularity level for NTN NW to adapt its functional split function, based on the UE's service-specific requirements.

For the service-based AFS within a single cell, the onboard payload has to identify a proper split option for a received data block from the UE in UL, such that it can use the correct split option for processing. For example, as shown in Figure 49, a data associated to UE1's PDU session #m should be processed locally at the onboard payload, while a data associated to UE1's PDU session #n should be forwarded to the ground entity for processing in the layers above lower PHY. To do that, there are at least two solutions:

- Transport block (TB)-based solution - a resource allocation is associated to a particular split option. For example, when the UE is allocated with a communication resource for transmission, the UE may also be indicated regarding which split option is associated to the allocated resource. Based on that, the UE only multiplexes the data from the services associated to the indicated split option into the TB and transmits it in the allocated resource. Once the onboard payload receives the TB in the allocated resource, the onboard payload determines the proper processing path based on the indicated split option associated to the allocated resource. To implement this solution, there is a need for coordination between different MAC entities located in different places, e.g. to partition the resource pool and associate each partitions resource pool with the corresponding split option.
- LCH/RB/QoS flow-based solution - an LCH/RB/QoS flow is associated to a configured split option. In this solution, upon successful decoding of a received TB, the onboard payload can determine the LCHs/RBs/QoS flows multiplexed in the TB. Thus, the onboard payload can determine the proper split option for each of the multiplexed LCHs/RBs/QoS flows, based on the split option configured for the considered LCH/RB/QoS flow. It is noted, this solution requires the onboard payload to carry at least PHY and MAC layers and, thus, it cannot support lower layer split option with an onboard entity containing only below-MAC layer(s).

In an alternative solution, multiple overlapping cells can be used to serve the same area, e.g., as shown in Figure 50. In this scheme, the two different cells, e.g. cell #n and cell #m, are associated to the same footprint area, but different functional splits, e.g. one onboard RRC entity/cell to support the PDU session #m, while another on-ground RRC entity/cell for the PDU session #n. Accordingly, at the UE, it has to set up two RRC connections for two PDU sessions over the same service link, where the two PDU sessions are served by different cells and different protocol stacks at the UE. In addition, the UE may be (pre)configured with the rule to select the proper split option for a PDU session. This scheme can support TB-based functional split determination with less spec impact than using a single cell. Last but not least, there is a need to enabling coexistence and/or mutual interference handling between the overlapping cells.

Please note, the condition(s) used for describing the proposed adaptive function split is only for illustration purpose in Sections 4.3.3.1 to 4.3.3.4, and they should not be considered as an exclusive set of triggers in real implementation. As one example, in the next section, AFS may be triggered and applied by NTN to enable satellite-sharing.

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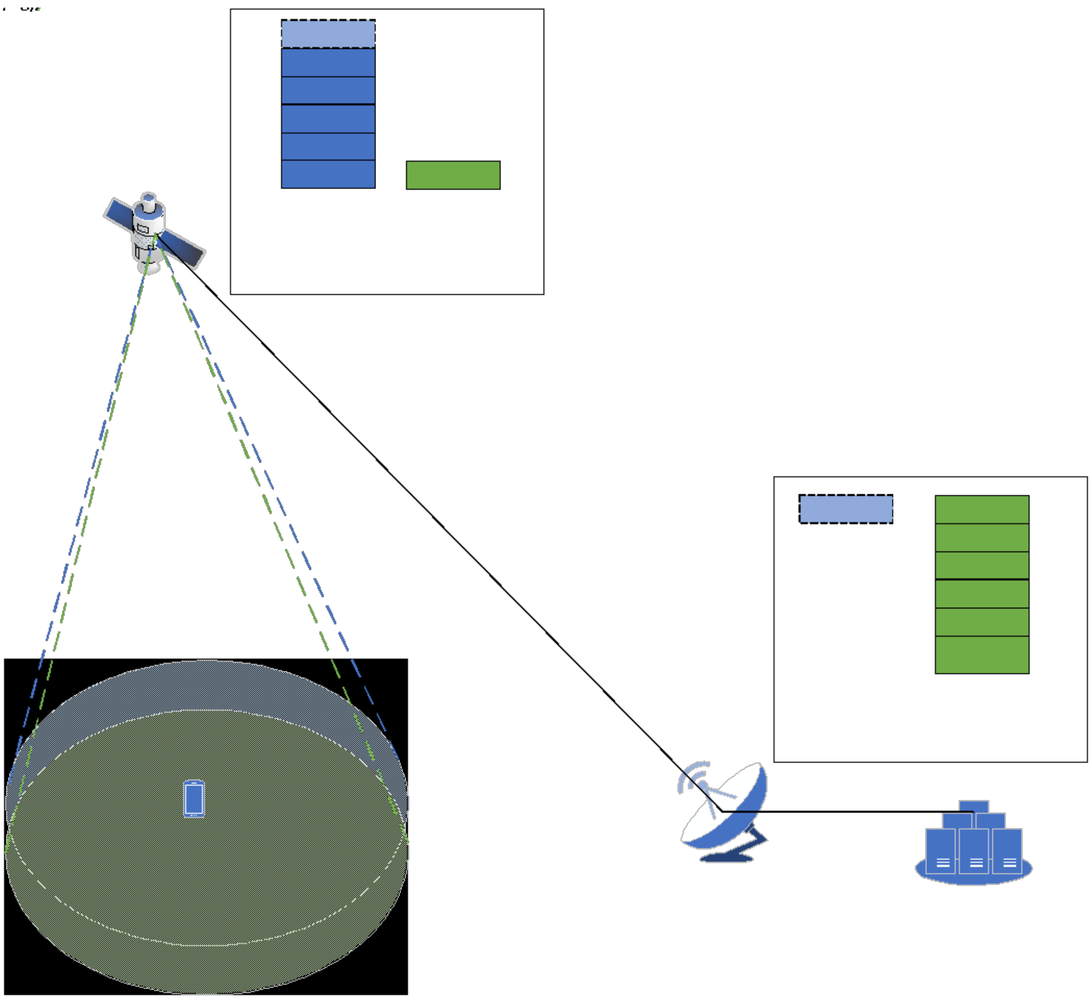

FIGURE 50: SERVICE-BASED AFS BASED ON MULTIPLE CELLS

4.3.3.5 Native Support for Satellite Sharing by AFS

The mobility of an NTN node (e.g. LEO/MEO satellite) that causes the NTN node to move across continent and ocean makes NTN much different from TN, since it is possible for the coverage area of one satellite to move from one operator's network to another operator's network, e.g. from one country to another. In this case, an important design target for 6G NTN is to enable satellite sharing among different network operators. In one example, a moving satellite provided and controlled by one satellite network operator (SNO) may be shared by two or multiple different mobile network operators (MNOs) to provide communication coverage to their subscribers.

However, different MNOs may face different conditions, which make them:

- Prefer different functional split options
- Sign different agreements with one satellite network operator (SNO) wrt. the applied functional split option
- Face different local regulation requirements

Thus, a critical issue is how to natively support satellite sharing and meet the requirements of the different operators. Based on the initial analysis, the AFS scheme discussed before can support satellite-sharing for multi-operators natively, e.g. by leveraging the cell/area-specific AFS and the scenario-specific AFS.

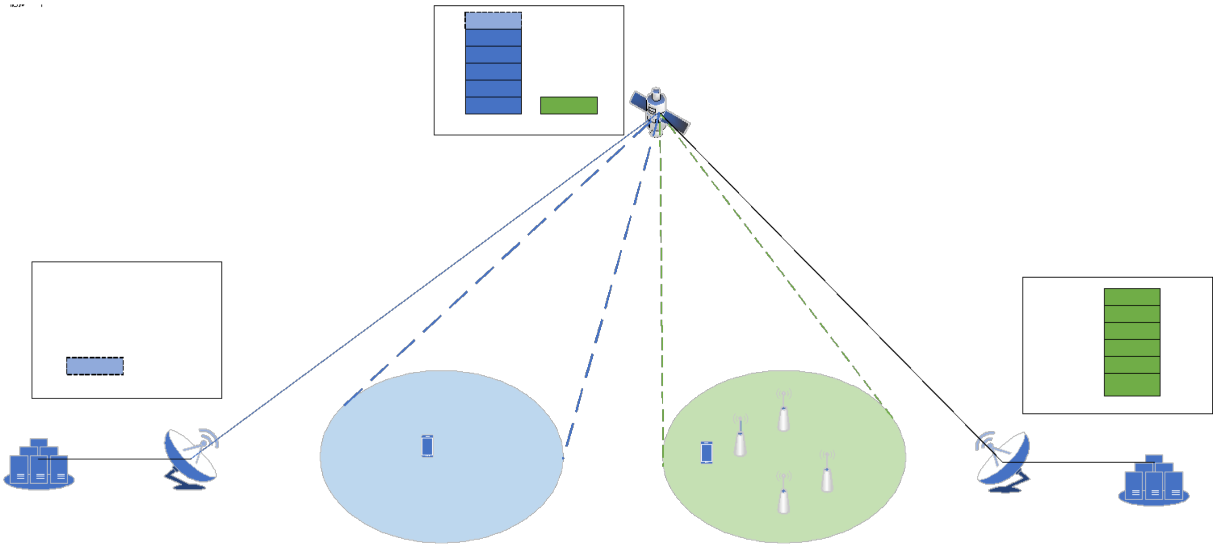

FIGURE 51: ILLUSTRATION ON THE NATIVE SUPPORT FOR SATELLITE-SHARING BY CELL/AREA-SPECIFIC AFS

In Figure 51, the cell/area-specific AFS described in Section 4.3.3.1 is used to support satellite sharing with different functional split options for different operators at the same time. As it shows, when the satellite moves to a position and covers the areas of the two different network operators, e.g. Operator A and Operator B, the satellite may use different functional splits for serving the coverage areas of the different operators, e.g. based on the agreements/configurations between the SNO and each individual MNO, correspondingly.

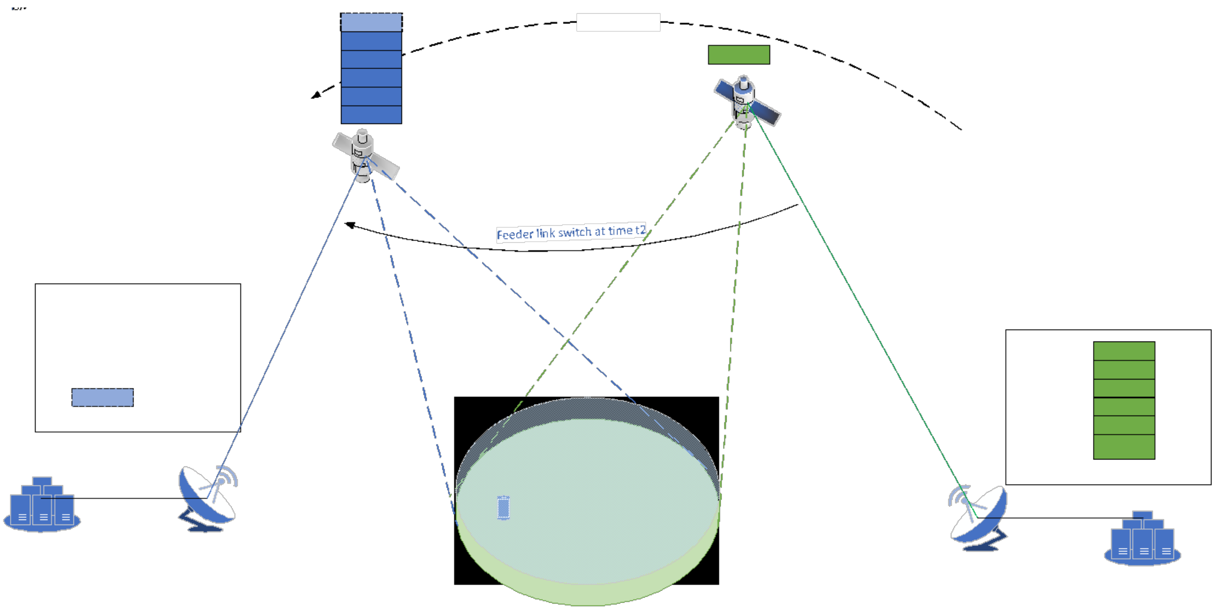

FIGURE 52: ILLUSTRATION ON THE NATIVE SUPPORT FOR SATELLITE-SHARING BY SCENARIO-SPECIFIC AFS

Figure 52 shows how to enable the satellite to switch its functional split options for connecting to different operators' networks. For example, at time t1, satellite 1 may apply a lower layer function split to connect to Operator B's ground infrastructures, based on the agreement/configuration between SNO and Operator B. Later on, at time t2, satellite 1 may move closed to Operator A and, thus, it switches its feeder link and connects to the Operator A's ground infrastructures by adapting to a higher layer split option, based on the agreement/configuration between SNO and Operator A.

5 CONCLUSIONS

The main outcomes of this deliverable are already summarized in the executing summary. This brief conclusion therefore takes a slightly different angle and focuses on the main innovations that this document contains, namely:

- A distributed architecture for the LEO constellation separating service link payloads from transport network (ISLs and feeder links) with enhanced processing capabilities in space (joint activity with Tasks 3.3 and 3.4) has been conceived and compared with a conventional approach in which all satellites are identical. Its feasibility in terms of delay performance as well as power and mass budgets have been assessed. Moreover, an initial cost analysis has been carried out, determining the conditions under which such distributed architecture could be meaningful from a cost perspective.
- An analysis of the support for full gNB in space within the aforementioned distributed architecture has been carried out, contributing to the resulting mass and power budget and to the sizing of the inter-satellite links.
- The design of the adaptive (use-case-based or service-based) function split to efficiently distribute network functions has been proposed for the conventional architecture, in order to optimally support the different use cases defined in the project. Its actual suitability for an implementation in space shall be subject of further studies.
- Different options for the support of direct NTN communication without the need of an available feeder link has been analysed at architectural level.

Important aspects to be further analysed are:

- **Interfaces:** which interfaces are carried over the feeder link, service link or inter-satellite link.
- **UE mobility:** how UE context is managed and whether legacy solutions are enough
- **Relationships between equipment / functions:** implication of maintaining connections between entities while satellites move (End-to-end depends on interfaces, underlying transport may also have an impact)
- **Transport through satellite network:** how to handle routing through the inter-satellite network (depends on multi-hop). Initial simulations have been performed assuming source routing, however a two layers routing scheme seems the most appropriate solution.
- **Capacity:** bottlenecks, traffic scalability with the number of UEs, cells or hops (depends on multi-hop), compression or bandwidth saving techniques for ISLs and feeder links traffic (depends on interfaces). Our preliminary assessment has not identified any major showstopper, however further and more detailed investigation is needed.
- **Satellite HW/SW impact**: payload complexity, power consumption, and memory requirements for satellites shall be subject of more detailed analysis. In particular, the estimation of the gNB power consumption is based on existing products designed for terrestrial networks and neither conceived nor optimised for usage in space.
- **Impact on standard**: estimation and strategic consideration on the standard impact / required modifications when an option is adopted which could be fed to the upcoming 6G standardisation effort.

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APPENDIX A: LLS IN TERRESTRIAL NETWORKS

In terrestrial networks it is common to separate RAN functionality in different nodes that implement a subset of the physical layer functionality. Historically, base stations were monolithic, containing both Digital Signal Processing (DSP) equipment and RF in the same node. Antenna panels (and power amplifier) were mounted on masts and connected to the base station via coaxial cables.

Over time, the building practices shifted to separating DSP and RF equipment in two nodes (baseband and radio) and mounting the radio node closer to the antennas. This reduces the thick coax cable runs used to connect radio to antenna panels, which were then substituted by fibre. The main enabler for this type of construction was the Common Public Radio Interface (CPRI). CPRI is a digital TDM interface that allows the transmission of time-domain samples between baseband and radio, besides control information and timing reference signals. It allowed the link between baseband node and radio node to become longer, in the range of a few tens of kilometers. This range extension also allowed operators to start installing baseband processing nodes in centralized locations, in more controlled environments, not necessarily close to the sites or exposed to the elements.

Another outcome of this architectural change was that split base stations have the advantage of decoupling the life cycles of the units. It is possible and common to upgrade baseband features and capacity and while reusing the radio, which is already deployed in the field.

With the introduction of 5G-NR, the number of antennas managed by each base station grew substantially, due to the Radio Access Technology (RAT) taking advantage of beamforming and multi-user massive Multiple Input Multiple Output (MIMO). The increase in number of antennas made a fronthaul interface carrying time-domain samples, such as CPRI, less advantageous. The bandwidth requirements for such a fronthaul link were too demanding, in the tens or hundreds of gigabits per second.

The industry and academia started considering alternative physical layer splits, by moving more functionality from baseband node to radio node. In an Orthogonal Frequency Division Multiplexing (OFDM) based RATs, a relevant change is to move the Fast Fourier Transform (FFT) to the radio node. That provides a reduction in overall required bandwidth, while also enabling the traffic on the fronthaul interface to be proportional to the user traffic instead of the bandwidth of the cell.

The variable traffic in the fronthaul interface allows for statistical multiplexing in the fronthaul infra-structure. That in turn, led to the adoption of high-volume Ethernet transceivers to implement packet based intra-PHY split base stations.

Connecting the baseband and radio nodes over a packet-switched fronthaul network allows the operators to leverage statistical multiplexing in their transport infra-structure but also enables simplified deployment and maintenance due to remote connectivity and configuration of the interconnects between the nodes.

A survey of functional-split related research for 5G is presented in [21]. A subset of the paper covers the intra-PHY split options [22] and [23] proposes adaptations for uplink receiver algorithms in a PHY-split base station. The authors develop specific formulations for zero forcing and interference rejection combining taking into consideration what operations shall be executed in each node. They develop the adaptations with the intent of minimizing traffic demands on the fronthaul interface while taking into consideration restrictions in the compute resources in the radio node.

Co-funded by the European Union

7 APPENDIX B: COMPARISON OF DIFFERENT SPLIT OPTIONS

- **Option 1**

Pros	Cons
- Less restriction on latency and BW requirements for the feeder link - Support onboard CN function - Support direct Xn interface via ISL between satellites/onboard gNBs (e.g. for latency reduction, feeder link traffic offload) - Lower latency for RRC configuration - Available NG interface design with implementation over feeder link	- Fast moving gNB from CN perspective - Frequent NG interface modification/reestablishment (e.g. gateway switch for satellite) - (Frequent) satellite switch implies a (frequent) L3 mobility - Highest complexity and power consumption onboard the satellite

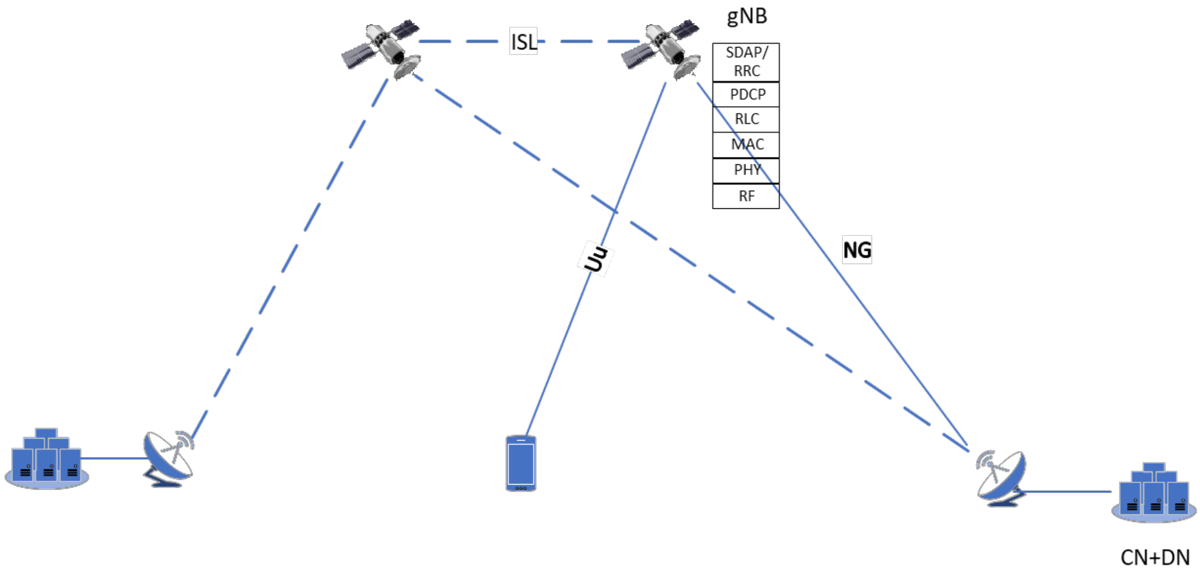

FIGURE 53: SPLIT OPTION #1 APPLIED TO THE CONVENTIONAL LEO CONSTELLATION

- **Option 2**

Pros	Cons
- Less restriction on feeder link latency and BW requirements - Support onboard user-plane (UP) CN function, e.g. UPF and MEC - Static N2 interface during satellite switch - Separation between CU-CP and CU-UP - Support L2 mobility for UE during satellite switch	- Frequent N3 interface modification/reestablishment - If CN CP network functions (NFs) are deployed in space, additional RRC entity may be needed in space as well - No baseline implementation for feeder link to support this split option

- ISL for supporting UP during satellite switch(Xn UP), e.g. data forwarding, UE PDCP/RLC context transfer	

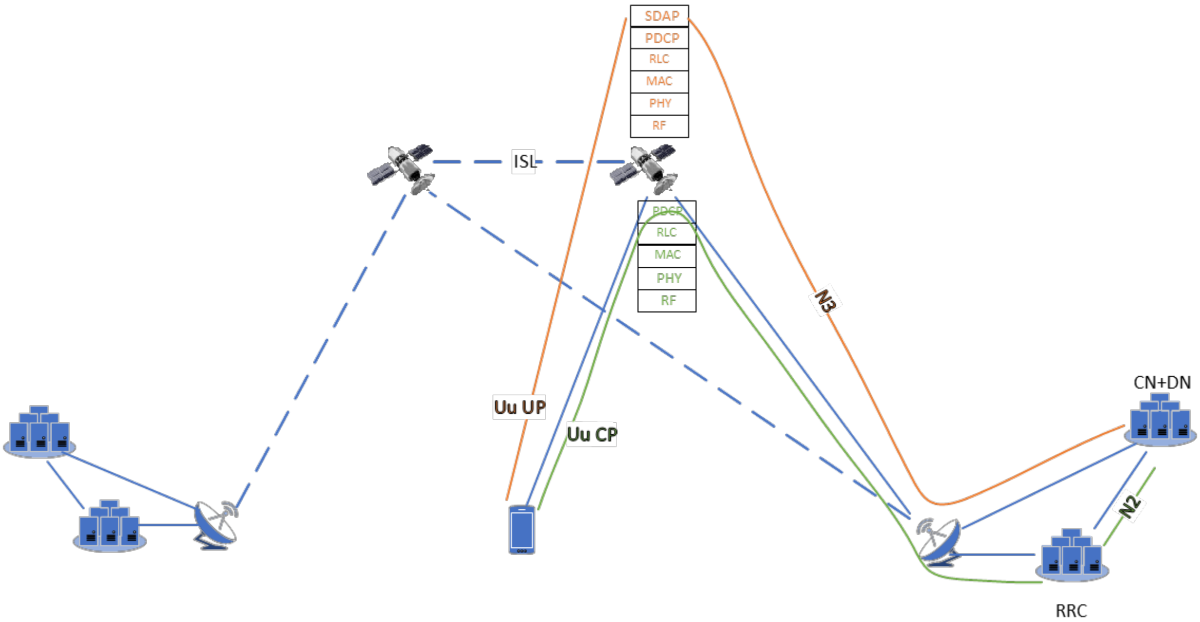

FIGURE 54: SPLIT OPTION #2 APPLIED TO THE CONVENTIONAL LEO CONSTELLATION

- **Option 3 (Onboard IAB could be a sub-option)**

Pros	Cons
- Less restriction on feeder link latency and BW requirements - Legacy F1 can be reused as a baseline for the feeder link - Static NG interface during satellite switch - L2 mobility during satellite switch - Centralized PDCP during satellite switch - ISL may be used for transferring the UE RLC context during satellite switch (e.g. UE's RLC remains during mobility) - Fast RLC re-Tx	- Dynamic F1 reestablishment and DU context transfer due to NTN mobility

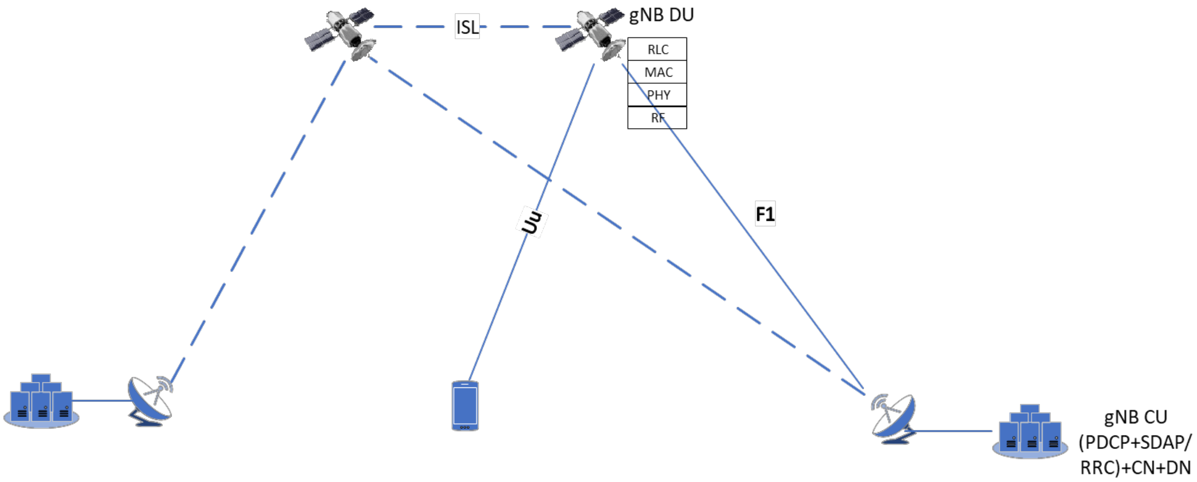

FIGURE 55: SPLIT OPTION #3 APPLIED TO THE CONVENTIONAL LEO CONSTELLATION

- **Option 4**

Pros	Cons
• Increased but moderate BW requirement on feeder link • L2 mobility with centralized RLC and PDCP for UE context (e.g. RLC and PDCP at the UE may remain during satellite switch) • Feeder link error can be handled by RLC re-TX • Smaller buffer is needed onboard the satellite • Flow control	• Low latency requirement on feeder link to support interaction between MAC and RLC • High RLC re-TX latency • No baseline implementation for feeder link to support this split option

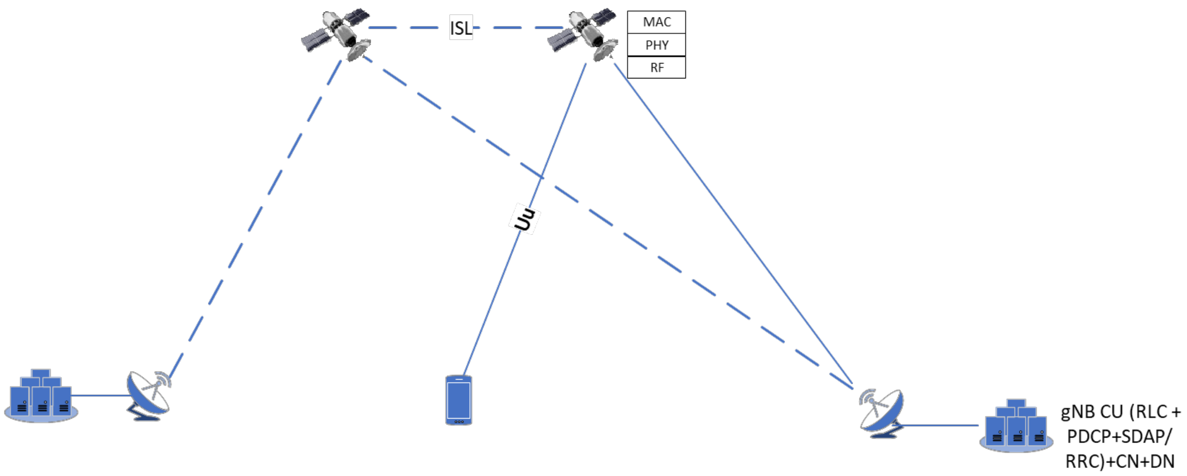

FIGURE 56: SPLIT OPTION #4 APPLIED TO THE CONVENTIONAL LEO CONSTELLATION

- **Option 5**

Pros	Cons
- Increased but moderate BW requirement on feeder link - High feeder link latency between PHY and MAC can be handled by timer/window extension as in NR NTN - Centralized scheduling for performance improvement - L2/L1 mobility during satellite switch - Feeder link error can be handled by HARQ re-Tx	- High HARQ re-Tx latency - High RACH latency - High CSI latency - No baseline implementation for feeder link to support this split option

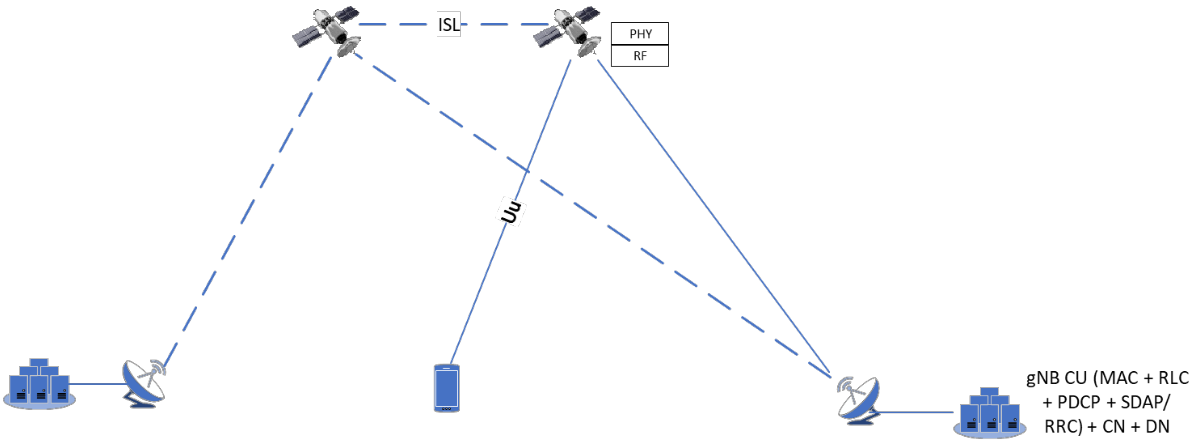

FIGURE 57: SPLIT OPTION #5 APPLIED TO THE CONVENTIONAL LEO CONSTELLATION

- **Option 6 (Low Layer Split)**

Please note that this split option is conceptually the same proposed in Section 4.2 for the distributed LEO constellation, however in this case only the RU is placed in space and the rest of the gNB and CN functionalities on ground. Therefore, the same analysis regarding the bandwidth requirements carried out in Section 4.2.1 is still valid in this case, but it will affect the link between the satellite and the ground, which depending on the satellite position could be a simple feeder link or the combination of a certain number of OISL(s) with one feeder link. In the latter scenario, data might aggregate during each hop in space, leading to potentially very demanding bandwidth requirements especially for the feeder link.

Pros	Cons
- O-RAN 7-2x interface can be considered as a baseline - Centralized scheduling - High feeder link latency can be handled by timer/window extension as in NR NTN - L2/L1 mobility during satellite switch	- High HARQ re-Tx latency - High RACH latency - High CSI latency - High BW requirement on ISL and feeder link

- Digital beamforming and waveform generation can be done onboard the satellite	

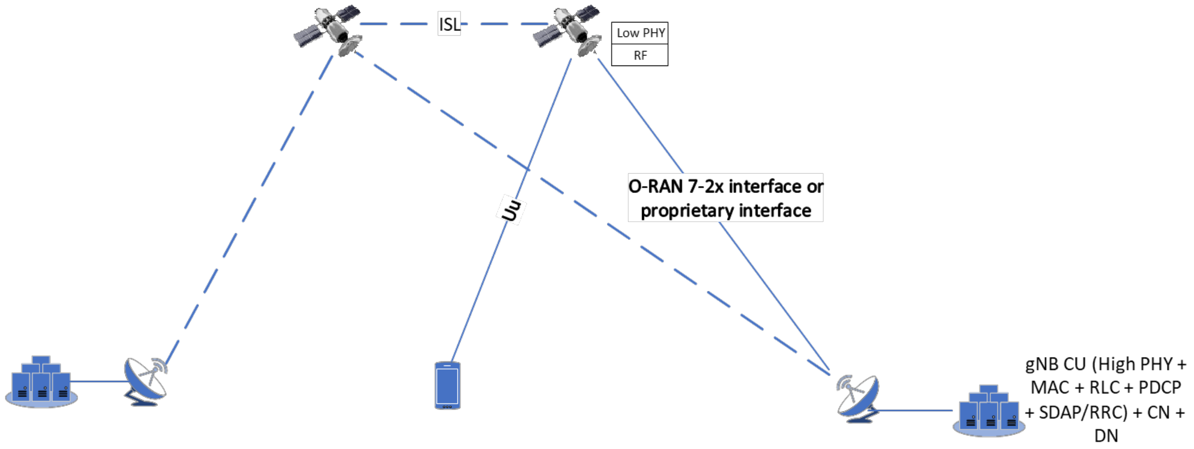

FIGURE 58: SPLIT OPTION #6 APPLIED TO THE CONVENTIONAL LEO CONSTELLATION

- **Option 7**

Pros	Cons
- Centralized pooling for the entire set of RAN protocol stacks - High feeder link latency can be handled in NR NTN already - L2/L1 mobility during satellite switch - Low complexity and power consumption onboard the satellite	- High radio layer E2E latency - High BW requirement on feeder link if digital-to-analog conversion (DAC) is performed in RF

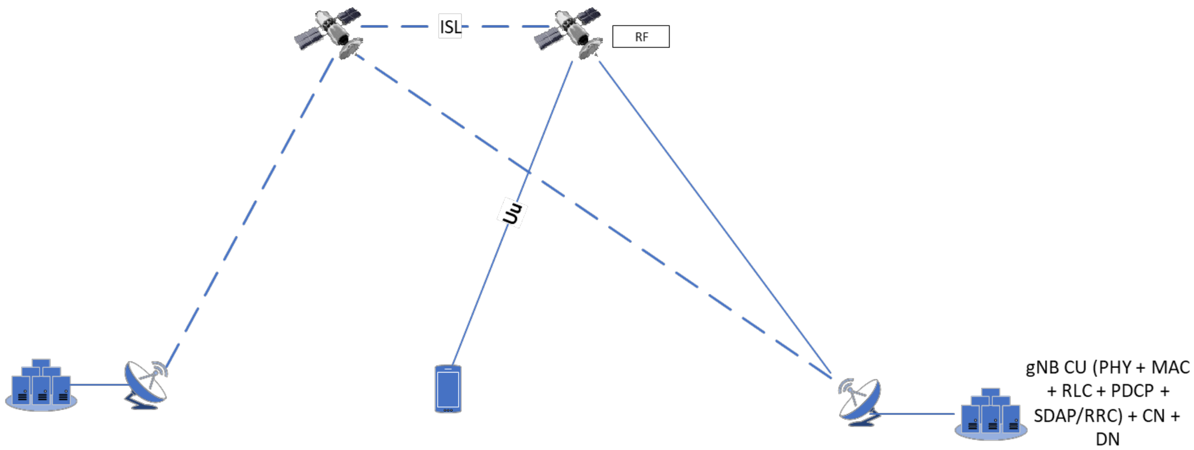

FIGURE 59: SPLIT OPTION #7 APPLIED TO THE CONVENTIONAL LEO CONSTELLATION.