6GNTN

D3.1 REPORT ON 3D MULTI LAYERED NTN ARCHITECTURE

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Abstract	This deliverable presents a first iteration of the NTN topology (type of UEs, type of NTN nodes and envisaged communication links), a preliminary network sizing via link budget analysis and some initial considerations 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

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DATA: Data sets, microdata, etc.

DMP: Data management plan

ETHICS: Deliverables related to ethics issues.

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EXECUTIVE SUMMARY

The goal of this deliverable is to provide an initial version of the 6G-NTN network topology, carry out an initial sizing of the communication links and perform a preliminary 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It is worth emphasizing that this deliverable will be superseded by D3.5, which will be released at the month 12 of the project. This summary as well as the conclusive section are nevertheless useful for a general understanding of the rationale behind the subsequent progress and investigations.

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 drones.
- Communication links between the above elements, namely service links, inter-node links (INL) or inter-satellite links (ISL), and feeder links.

As initial working assumption, 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) constellations with altitude between 400 km and 800 km for C-band and Q/V band connectivity, and an overlay layer of three GEO satellites have been retained. The possibility to split each LEO constellation into two sub-layers to achieve higher computational resources in space is currently under consideration.

Preliminary link budgets **focusing on LEO satellites** have been performed, leading to the following initial estimations:

- C-band LEO service uplinks (with omnidirectional UE antennas) allow a user rate between 100 kbps at Edge of Coverage (EOC) and 500 kbps at Center of Coverage (COC) in Line of Sight (LOS) conditions. Up to 6-10 dB additional losses would still allow to close the link budget at EOC/COC respectively. On the service downlinks, the link budget is somewhat more favorable so that even in the worst case of EOC and 10 dB additional losses, 200 kbps could be achieved.
- The corresponding aggregate data rate per LEO satellite would be a few Gbps for both up- and downlinks, assuming 5% uniform usage for all beams, and few tens of Gbps, assuming 30% uniform usage of all beams. This initial analysis could be refined assuming different loads for different beams based on traffic predictions.
- Feeder link budgets allow a data rate larger than 10 Gbps and the optical inter-satellite links can offer a data rate between 10 and 100 Gbps with telescope size and optical power compatible with State-of-the-Art technologies. **The preliminary conclusion is that no major bottlenecks are expected in the design of the C-band LEO constellation**.
- Q/V-band LEO service uplinks (with directive UE antennas) allow a user rate between 6 Mbps at EOC and 12 Mbps at COC in LOS conditions. Even for the worst-case scenario of 10 dB additional losses at EOC, the user rate remains above 1 Mbps. In the service downlinks, the link budget is somewhat less favorable so the user rate will drop below 1 Mbps at EOC in non-LOS (NLOS) conditions.

- The corresponding aggregate data rate per LEO satellite would be approximately 0.5 and 1 Tbps for the downlink and uplink, respectively, assuming 10% uniform usage for all beams, scaling up linearly for higher average load. This initial analysis could be refined assuming different loads for different beams based on traffic predictions.
- Given that the same data rates mentioned above for the feeder links and optical ISLs are available, **the preliminary conclusion is that the sizing and design of the Q/V-band LEO constellation shall be carefully addressed**. The aforementioned split of the constellation into two sublayers, separating service links, and transport networks (feeder links + ISLs) could improve the situation.

Note that all service link budgets calculations consider so far 5G New Radio (NR) systems. Improvements in the spectral efficiency arising from the work described in D4.1 '*Report on unified and data driven air interface for 6G-NTN*' will be considered in later deliverables. Moreover, the amount of data that the satellite will be able to process onboard and the amount of data which will have to be transferred to other satellites and/or to ground strongly depend on which RAN and CN functions will be available in space.

The preliminary 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**. Up to which point this flexibility could be implemented shall be subject of further analysis.

Two rather different scenarios have been addressed in detail, namely the different architectural options to enable direct NTN communications between UEs and a configuration in which only Radio Unit (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.

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ABBREVIATIONS

5G	Fifth Generation
6G	Sixth Generation
ACM	Adaptive Coding and Modulation
AF	Application Function
AMF	Access and Mobility Management Function
AP	Access Point
AR	Augmented Reality
ARQ	Automatic Repeat reQuest
AS	Access Stratum
ATN	Aggregation Transport Node
AUSF	Authentication Server Function
AWGN	Additive White Gaussian Noise
BBU	Base Band Unit
BER	Bit Error Rate
CN	Core Network
COC	Center of Coverage
COTS	Commercial Off-The-Shelf
CP	Control Plane or Cyclic Prefix
CU	Central Unit
DL	Downlink
DN	Data Network
DP-QPSK	Dual Polarisation Quaternary Phase Shift Keying
DU	Distributed Unit
E2E or e2e	End to end
EOC	Edge of Coverage
ETN	Edge Transport Node
FDD	Frequency Division Duplex
FE or F/E	Front End
FFT	Fast Fourier Transform
FiWi	Fiber Wireless
FL	Feeder Link
FSO	Free Space Optic
GA	General Assembly
GEO	Geostationary Earth Orbit
gNB	Next Generation Node B
GS	Ground Station
GSO	Geo-Synchronous Orbit
GUI	Graphical User Interface
GW	Gateway
HAP	High Altitude Platform

HARQ	Hybrid Automatic Repeat reQuest	**MAC**	Medium Access Control
HIBS	HAP station as IMT Base Station	**MEO**	Medium Earth Orbit
HMD	Head Mounted Display	**MIMO**	Multiple-Input Multiple-Output
HO	Handover	**NAS**	Non-Access Stratum
IEEE	Institute of Electrical and Electronics Engineers	**NF**	Noise Figure or Network Function
IFFT	Inverse Fast Fourier Transform	**NGSO**	Non-Geo-Synchronous Orbit
IMT	International Mobile Telecommunications	**NR**	New Radio
INL	Inter-Node Link	**NTN**	Non-Terrestrial Networks
IoT	Internet of Things	**OADM**	Optical Add/Drop Multiplexer
IP	Internet Protocol	**OCC**	Optical Camera Communication
IRIS²	Infrastructure for Resilience, Interconnectivity and Security by Satellite	**OFDM**	Orthogonal Frequency Division Multiplexing
ISL	Inter-Satellite Link	**OISL**	Optical ISL
ITU	International Telecommunication Union	**OLT**	Optical Line Terminal
LAN	Local Area Network	**ONU**	Optical Network Unit
LCT	Laser Communication Terminal	**OWC**	Optical Wireless Communication
LED	Light-Emitting Diode	**PCB**	Printed Circuit Board
LEO	Low Earth Orbit	**PCF**	Policy Control Function
LiFi	Light Fidelity	**PDCP**	Packet Data Convergence Protocol
LoS	Line of Sight	**PDU**	Protocol Data Unit
L*x*	Layer *x* of the OSI Protocol Stack (*x* = 1...7)	**PHY**	Physical Layer
PoC	Proof of Concept	**TDM**	Time Division Multiplexing

PON	Passive Optical Network	**TDMA**	Time Division Multiple Access
POS	Passive Optical Splitter	**TN**	Terrestrial Network
PPDR	Public Protection and Disaster Relief	**TX**	Transmission / Transmitter
PRB	Physical Resource Block	**U2U**	User Equipment to User Equipment
PSK	Phase Shift Keying	**UC**	Use Case
QPSK	Quaternary Phase Shift Keying	**UDM**	Unified Data Management
RAN	Radio Access Network	**UE**	User Equipment
RF	Radio Frequency	**UHD**	Ultra-High Definition
RLC	Radio Link Control	**UL**	Uplink
RNC	Radio Network Controller	**UP**	User Plane
RNTI	Radio Network Temporary Identifier	**UPF**	User Plan Function
RRC	Radio Resource Control	**Uu**	Interface between UE and RAN
RU	Radio Unit	**VLEO**	Very Lowe Earth Orbit
RX	Reception / Receiver	**VR**	Virtual Reality
SaaS	Software as a Service	**WDM**	Wavelength Division Multiplexer
SDAP	Service Data Adaptation Protocol	**WLAN**	Wireless Local Area Network
SFP	Small Factor Pluggable	**W-PON**	Wireless Passive Optical Network
SL	Service Link or Side Link	**Xn**	Network interface between NG-RAN nodes
SMF	Session Management Function	**ZED**	Zero Energy Device
TCP	Transmission Control Protocol		
TDD	Time Division Duplex		

1 6G-NTN NETWORK TOPOLOGY

Deliverable D3.1 is the first version of the '*Report on 3D multi layered NTN architecture*'. Three further versions of this deliverable are planned in the course of the project.

The topology 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 such initial configuration.

The architecture here proposed will be further analyzed and, if necessary, refined in the next issues of this deliverable throughout the project lifetime, taking also into account the progress of the ongoing initiative IRIS[2] (Infrastructure for Resilience, Interconnectivity and Security by Satellite) of the European Commission, which at the time of writing is still at the stage of proposals evaluation. Furthermore, preliminary inputs from D2.5 '*Report on regulatory requirements*', on the availability of frequency bands, are considered, as well as input from other deliverables produced in WP3 tasks regarding UE antennas, payload dimensioning, and LEO constellation sizing.

This chapter presents the initial 6G-NTN network topology in terms of type of terminals, here after referred to as User Equipment (UE), non-terrestrial nodes (namely HAPs and satellites), and the radio links between them.

A visual summary of the resulting 6G-NTN network topology is shown in Figure 1.

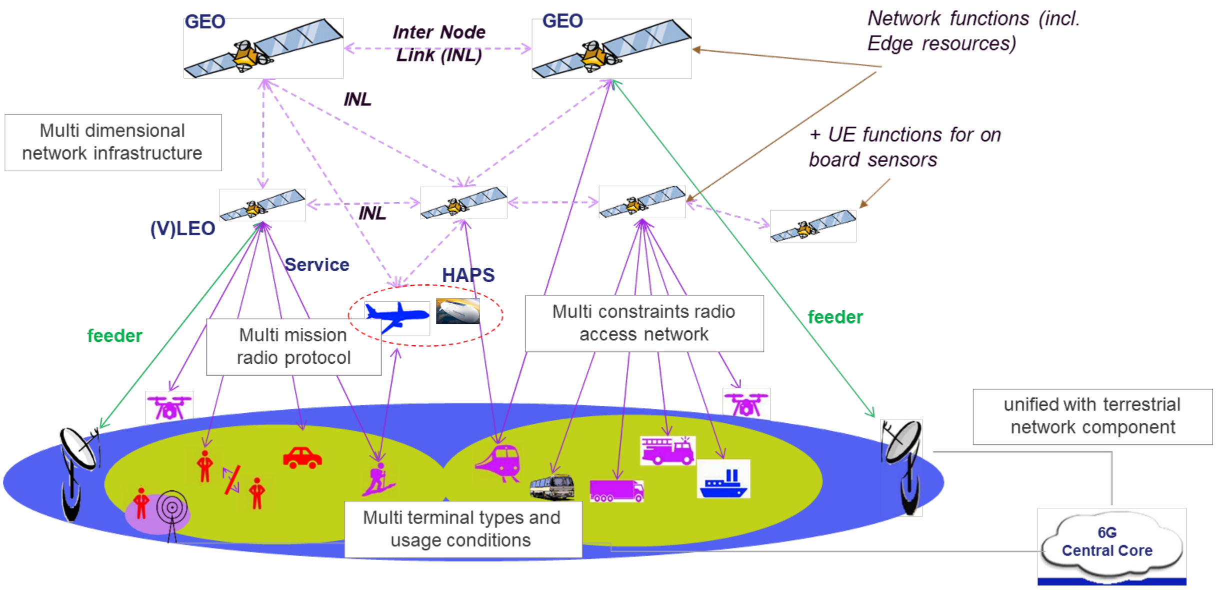

FIGURE 1: 6G-NTN 3D NETWORK TOPOLOGY.

1.1 TYPE OF USER EQUIPMENT

UEs are first classified according to their usage type into:

- Handheld
  - Consumer

  - Professional
- Automotive
- Drone-mounted
  - Light drones
  - Heavy drones
- 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 both 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 meaningful types of RF FEs are presented in Table 1. The detailed antenna design for UEs will be reported in D3.2 '*Report on antenna terminals*' and its updated versions.

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 (see also Figure 4)	Non-directive (hemispherical) antenna	9	23	-3	C_NTN_1
		7	26	-3	C_NTN_2
		7	26	0	C_NTN_3
Q/V (see also Figure 4)	Directive antenna	5	34	28	QV_NTN_1
		5	37	32	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 and drones have a double role in the 6G-NTN network since they can act both as UEs as well as Non-Terrestrial Nodes.

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 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 the following types of non-terrestrial nodes, namely deterministic nodes with a fixed and predictable orbit (both GSO and NGSO) and flexible nodes, namely HAPs, which might be present or not at different points in time and at different locations to extend coverage or enhance the network capacity.

The detailed payload and antenna design for non-terrestrial nodes will be carried out in D3.3 '*Report on software defined payload and its capability*' and its updated versions.

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 approximatelyapprox. 35.786 km. GEO satellites fly onfly in an equatorial plane with a constant angular speed equal to that of the Earth. Thus, for a user located on the Earth 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 regionsregion where the satellites areare not visible. 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 surface, as shown in Figure 2.

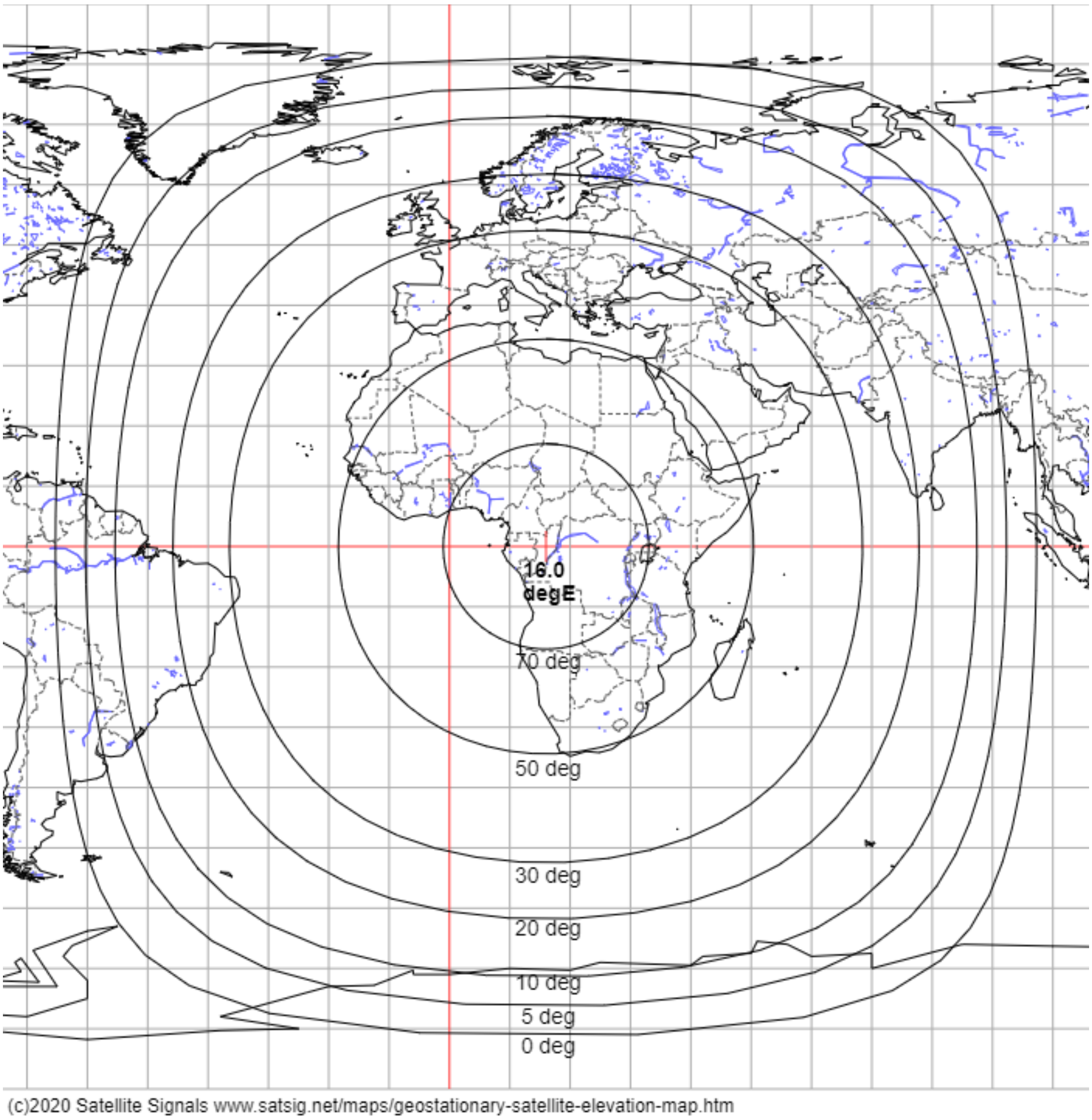

FIGURE 2: EXEMPLARY COVERAGE OF A GEO SATELLITE FOR DIFFERENT MINIMUM ELEVATION ANGLES.

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

1. broadcast & multicast mission, which is however not the primary focus of the 6G-NTN project
2. 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 (assumes dual steer/connectivity between GSO and NGSO links)
3. 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 presence of major disruption of the ground infrastructure.

➲ **A lower layer made on NGSO satellites**, where LEO encompasses Earth-centered 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. 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 switches 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 tradeoffs 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 will be reported in D3.3 '*Report on Software defined payload and its scalability*' and D3.4 '*Report on VLEO space segment'* and their updated versions. For the time being, the working assumption is to consider **LEO constellations with altitude between 400 and 800 km**. A preliminary constellation sizing is shown in Table 3.

TABLE 3: EXAMPLE OF LEO CONSTELLATION SIZING AT 600KM ALTITUDE

	User Elevation 30°	**User Elevation 45°**
1 sat visible	432 satellites with 16 orbital planed	1118 satellites with 26 orbital planed
2 sats visible	855 with satellites with 15 orbital planed	2225 satellites with 25 orbital planed

The main role of NGSO satellites is to provide broadband access to handhelds and to VSAT-like UEs (see also Table 2). **As of today, it is envisaged to have two separate LEO constellations, one with C-band connectivity and another one with Q/V connectivity.**

- The C-band constellation will use polar orbits, so to ensure truly global coverage even in the Arctic and Antarctic regions.
- The Q/V-band one might use inclined orbits, so to loosen the requirements and thermal management and heat dissipation.

However, according to the preliminary analysis carried out in Chapter 2 and attempting to figure out which RAN and CN functionalities shall be implemented in space to support the use cases identified, in D2.1 '*Use case report*', a first qualitative conclusion is that a remarkable amount of processing capabilities will be required. To make sure that this does not become the system bottleneck, two sub-layers of LEO satellites are currently being considered for further analysis, namely:

- **A lower NGSO sub-layer, aiming at providing global coverage to UEs on ground**. Most of the available payload mass and power will be devoted to enable the service up- and downlinks, so these satellites will connect via ISLs to the upper sub-layer but will have neither feeder links nor ISLs among them.

- **An upper NGSO sub-layer with less satellites implementing the transport network and providing additional processing capabilities in space**. These satellites will have no direct service links between space and ground but will be connected to the lower NGSO sub-layer with ISLs. Moreover, they will have ISLs between them and feeder links.

This innovative concept, exemplified in Figure 3, will be further investigated in the subsequent part of the project.

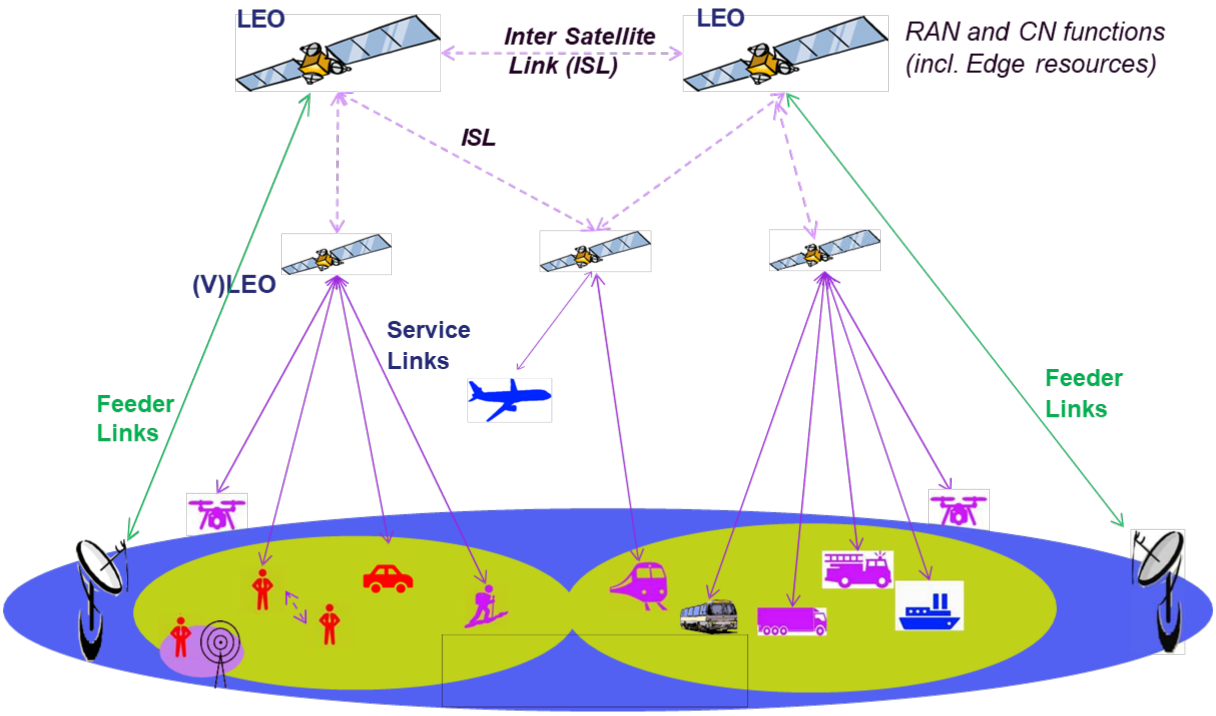

FIGURE 3: DOUBLE-LAYERED LEO CONSTELLATION.

Medium Earth Orbit (MEO) satellites, flying typically at an altitude around 10.000 km, will not be initially considered in order to limit the number of possible architectural options to be analysed. At a later stage in the project, it will be assessed whether the introduction of one additional layer between GSO and NGSO in low earth orbit could bring benefits justifying the remarkable increase in cost and especially complexity.

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 e.g., large concerts or sport events. Note that **it is not foreseen to have a permanent network of such nodes, rather they will be opportunistically deployed if and when needed**.

1.3 OVERVIEW OF COMMUNICATION LINKS

The following type 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 ground. GSs typically have large antennas and less stringent power limitations compared to UEs, therefore FLs have typically a very high availability in the range of 99.5% thanks to a number of 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.
- **Inter-Node Links (INLs)** connecting non-terrestrial nodes. When both nodes are satellites, the term **Inter-Satellite Links (ISLs)** can be also 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 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 4, including also the relevant frequency bands identified in D2.5 *'Report on Regulatory requirements*'.

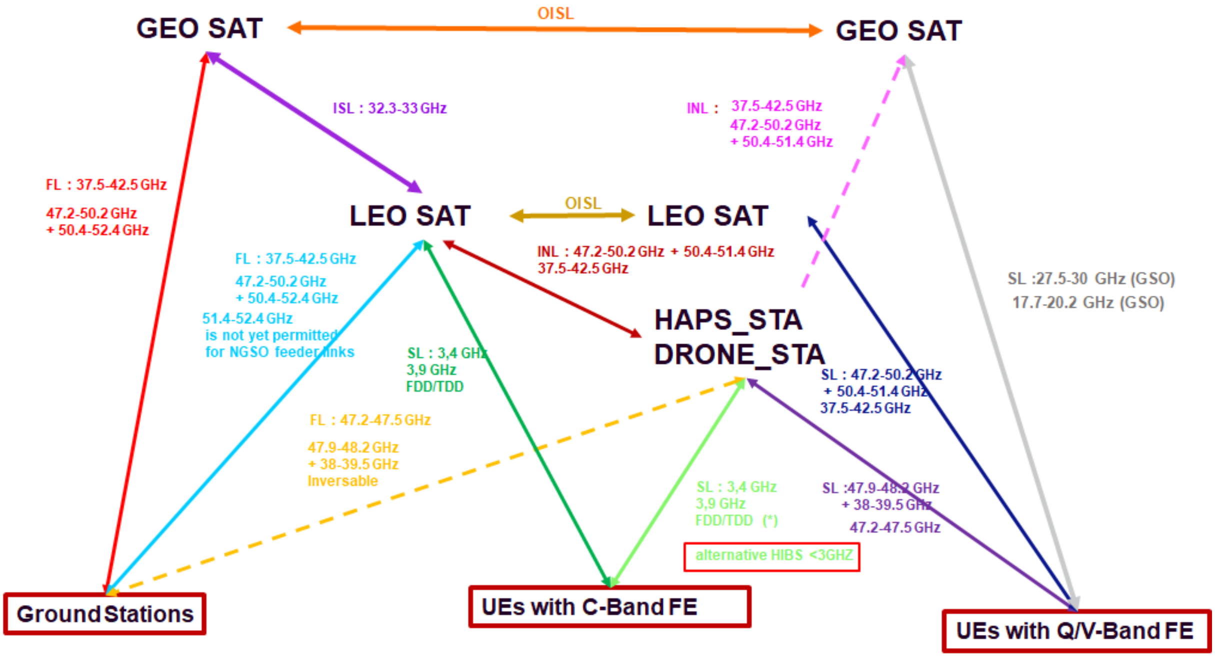

FIGURE 4: OVERVIEW OF RELEVANT COMMUNICATION LINKS AND FREQUENCY BANDS.

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1.3.1 Service Links

Service links will be either in C-band with hemispherical / omnidirectional antennas 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 baseline, but the feasibility of TDD will be investigated in WP4. For the Q/V-band links, FDD is the most logical approach, since the uplink and downlink are in separated 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 backup option.

It is worth emphasizing that Figure 4 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, which will be assumed to be part of the 6G-NTN system but not further analysed in the project and assumed to be based on Commercial Off-The-Shelf (COTS) equipment and technologies. Its presence 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 4, is also supposed to be part of the final 6G-NTN network and will be further investigated in the rest of the project.

1.3.2 Inter-Node Links

Five different types of INLs are potentially envisaged, namely:

1. Links between HAPs and LEO satellites, to be realized in Q/V-band. Since HAPs are mostly envisaged as standalone flexible network nodes, all HAPs shall be able to connect to the LEO constellation.
2. Links between HAPs and GEOs, to be realized also in Q/V-band. The preliminary link budget analysis in the next chapter shows however that the achievable data rate is pretty low, thus it shall be subject of further trade-off whether those INLs will be retained or dropped.
3. Links between LEOs and GEOs, to be realized in Ka-band. Whether all LEO satellites will be equipped with ISL capabilities towards GEO or only a subset, it’s subject of further trade-off analysis in the rest of the project.
4. Links between LEO satellites, to be realized with optical technology. As initial baseline, each LEO satellite should have four Laser Communication Terminals (LCTs), two of them for intra-plane connectivity, two of them for inter-plane connectivity.
5. 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), its technical feasibility and meaningfulness given the achievable data rate shall be subject of 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 and HAP-GEO in Q/V-band shall be subject of further analysis.**

1.3.3 Feeder Links

All feeder links are supposed to be in Q/V-band. HAPs will have feeder links only if they are in visibility of the ground station. The sizing of the ground network in terms of 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.

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2 INITIAL 6G-NTN NETWORK SIZING

This chapter contains the preliminary link budget analysis given the network topology, types of terminals, and links discussed in the previous chapter.

2.1 SERVICE LINK BUDGETS

The tables below show the achievable rate for both C-band and Q/V-band assuming different fading depths, elevation angles and 5G NR. This will be updated in the next issues taking into account the results of WP4 on waveform improvements.

For C-band, the UE rate is in the order of hundreds of kbps, whereas for Q/V-band, UE rate in the order of 1-10 Mbps can be achieved.

2.1.1 C-Band Link Budgets

In Table 4, UL means that the UE transmits and the satellite receives, while DL implies the contrary, i.e., the satellite transmits and the UE receives.

TABLE 4: 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	3.2	3.3	3.9	4	3.9	3.4	100	100	360	360	12	30	360	264

2.1.1.1 Uplink

TABLE 5: C-BAND UPLINK THROUGHPUT (1 PRB), AVAILABILITY 99.5%, 4 DB SHADOWING

Channel type	**Unit**	**Worst Case (El 30°)**	**Average Case (El 45°)**	**Best Case (NADIR)**
Band Name	-	C	C	C
Spectral Efficiency	bits/s/Hz	0,35	1,08	1,56
UE Rate	Mbit/s	0,125	0,389	0,561

TABLE 6: C-BAND UPLINK THROUGHPUT (1 PRB), AVAILABILITY 99.5%, 4 DB SHADOWING + 6 DB ADDITIONAL LOSSES

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Channel type	Unit	Worst Case (El 30°)	Average Case (El 45°)	Best Case (NADIR)
Band Name	-	C	C	C
Spectral Efficiency	bits/s/Hz	0,09	0,45	1,08
UE Rate	Mbit/s	0,032	0,162	0,389

TABLE 7: C-BAND UPLINK THROUGHPUT (1 PRB), AVAILABILITY 99.5%, 4 DB SHADOWING + 10 DB ADDITIONAL LOSSES

Channel type	Unit	Worst Case (El 30°)	Average Case (El 45°)	Best Case (NADIR)
Band Name	-	C	C	C
Spectral Efficiency	bits/s/Hz	#N/A	0,22	0,68
UE Rate	Mbit/s	#N/A	0,078	0,245

2.1.1.2 Downlink

TABLE 8: C-BAND DOWNLINK THROUGHPUT (1 PRB), AVAILABILITY 99.5%, 4 DB SHADOWING

Channel type	Unit	Worst Case (El 30°)	Average Case (El 45°)	Best Case (NADIR)
Band Name	-	C	C	C
Spectral Efficiency	bits/s/Hz	1,27	1,46	1,46
UE Rate	Mbits/s	0,46	0,52	0,52

TABLE 9: C-BAND DOWNLINK THROUGHPUT (1 PRB), AVAILABILITY 99.5%, 4 DB SHADOWING + 6 DB ADDITIONAL LOSSES

Channel type	Unit	Worst Case (El 30°)	Average Case (El 45°)	Best Case (NADIR)
Band Name	-	C	C	C
Spectral Efficiency	bits/s/Hz	1,01	1,27	1,46
UE Rate	Mbits/s	0,36	0,46	0,52

TABLE 10: C-BAND DOWNLINK THROUGHPUT (1 PRB), AVAILABILITY 99.5%, 4 DB SHADOWING + 10 DB ADDITIONAL LOSSES

Channel type	Unit	Worst Case (El 30°)	Average Case (El 45°)	Best Case (NADIR)
Band Name	-	C	C	C
Spectral Efficiency	bits/s/Hz	0,64	1,14	1,27
UE Rate	Mbits/s	0,23	0,41	0,46

2.1.2 Q/V-Band Link Budgets

In Table 11, UL means that the UE transmits and the satellite receives, while DL implies the contrary, i.e., the satellite transmits and the UE receives.

TABLE 11: 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-V1	47.2	50.4	37.5	40.5	50	40	800	800	5760	5760	12	480	5760	132

2.1.2.1 Uplink

TABLE 12: Q/V-BAND UPLINK THROUGHPUT (1 PRB), AVAILABILITY 99.5%, 3 DB SHADOWING

Channel type	Unit	Worst Case (El 30°)	Average Case (El 45°)	Best Case (NADIR)
Band Name	-	Q-V	Q-V	Q-V
Spectral Efficiency	bits/s/Hz	1,06	1,94	2,17
UE Rate	Mbit/s	6,095	11,198	12,474

TABLE 13: Q/V-BAND UPLINK THROUGHPUT (1 PRB), AVAILABILITY 99.5%, 3 DB SHADOWING + 6 DB ADDITIONAL LOSSES

Channel type	Unit	Worst Case (El 30°)	Average Case (El 45°)	Best Case (NADIR)
Band Name	-	Q-V	Q-V	Q-V
Spectral Efficiency	bits/s/Hz	0,254	1,33	1,94
UE Rate	Mbit/s	3,119	7,655	11,198

TABLE 14: Q/V-BAND UPLINK THROUGHPUT (1 PRB), AVAILABILITY 99.5%, 3 DB SHADOWING + 10 DB ADDITIONAL LOSSES

Channel type	Unit	Worst Case (El 30°)	Average Case (El 45°)	Best Case (NADIR)
Band Name	-	Q-V	Q-V	Q-V
Spectral Efficiency	bits/s/Hz	0,21	0,92	1,53
UE Rate	Mbit/s	1,215	5,326	8,788

2.1.2.2 Downlink

TABLE 15: Q/V-BAND DOWNLINK THROUGHPUT (1 PRB), AVAILABILITY 99.5%, 3 DB SHADOWING

Channel type	Unit	Worst Case (El 30°)	Average Case (El 45°)	Best Case (NADIR)
Band Name	-	Q-V	Q-V	Q-V
Spectral Efficiency	bits/s/Hz	0,49	0,96	1,57
UE Rate	Mbits/s	2,84	5,55	9,04

TABLE 16: Q/V-BAND DOWNLINK THROUGHPUT (1 PRB), AVAILABILITY 99.5%, 3 DB SHADOWING + 6 DB ADDITIONAL LOSSES

Channel type	Unit	Worst Case (El 30°)	Average Case (El 45°)	Best Case (NADIR)
Band Name	-	Q-V	Q-V	Q-V
Spectral Efficiency	bits/s/Hz	0,12	0,49	0,96
UE Rate	Mbits/s	0,72	2,84	5,55

TABLE 17: Q/V-BAND DOWNLINK THROUGHPUT (1 PRB), AVAILABILITY 99.5%, 3 DB SHADOWING + 10 DB ADDITIONAL LOSSES

Channel type	Unit	Worst Case (El 30°)	Average Case (El 45°)	Best Case (NADIR)
Band Name	-	Q-V	Q-V	Q-V
Spectral Efficiency	bits/s/Hz	0,05	0,19	0,61
UE Rate	Mbits/s	0,28	1,11	3,50

2.2 INTER-NODE LINK BUDGETS

2.2.1 Inter-Orbit Link Budgets

The inter-orbit links constitute the inter-node links between LEO and GEO satellites, HAPs and LEO satellites, and HAPs and GEO satellites. The inter-orbit link budgets have been calculated in accordance with the antenna sizing performed by TAS-F for the corresponding radio frequency (RF) bands, resulting in the preliminary definition of the antenna parameters for equivalent isotropic radiated power (EIRP) and Gain-to-noise Temperature (G/T). The achievable data rates for each of the inter-node links between HAP, LEO and GEO are presented below.

2.2.1.1 LEO-GEO Link Budgets

TABLE 18: LEO-GEO LINK BUDGETS

	LE-GEO	DL	UL
Parameters	Tx altitude [km]	36000.00	600.00
	Rx altitude [km]	600.00	36000.00
	Frequency [GHz]	32.425	32.875
	Symbol rate [MBaud]	250.00	250.00
	TX EIRP [dBW]	60.40	60.40
	RX G/T [dB/K]	14.10	14.10
	Path loss [dB]	213.64	213.76
	Margin [dB]	3.00	3.00

Results	SNR [dB]	2.48	2.36
	Spectral efficiency [bits/s/Hz]	1.47	1.44
	Data Rate [Mbps]	367.55	361.23

The link budgets for the downlink and the uplink of the inter-node link between a LEO and a GEO satellite are presented in Table 18. The link is realized in the Ka band between 32.3 GHz and 33 GHz with 200 MHz spacing between the downlink and the uplink. It is shown that carrier symbol rates of up to 250 MBaud are achievable with resulting data rates of up to 367.55 Mbps and 361.23 Mbps in the downlink and the uplink, respectively.

2.2.1.2 HAP-LEO Link Budgets

TABLE 19: HAP-LEO LINK BUDGETS

	HAP-LEO	DL	UL	DL	UL	DL	UL
Parameters	TX altitude [km]	600.00	20.00	600.00	20.00	600.00	20.00
	RX altitude [km]	20.00	600.00	20.00	600.00	20.00	600.00
	Frequency [GHz]	40.00	50.00	40.00	50.00	40.00	50.00
	Symbol rate [MBaud]	80.00	40.00	80.00	40.00	80.00	40.00
	TX EIRP [dBW]	51.50	24.60	51.50	24.60	51.50	24.60
	RX G/T [dB/K]	-11.00	11.00	-11.00	11.00	-11 .00	11.00
	Elevation [deg]	30.00	30.00	45.00	45.00	90.00	90.00
	Slant range [km]	1075.48	1075.48	814.92	814.92	600.00	600.00
	Path loss [dB]	185.12	187.05	182.71	184.64	180.05	181.98

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	Margin [dB]	3.00	3.00	3.00	3.00	3.00	3.00
Results	SNR [dB]	1.95	-1.87	4.36	0.54	7.02	3.20
	Spectral efficiency [bits/s/Hz]	1.36	0.72	1.90	1.09	2.59	1.63
	Data Rate [Mbps]	108.86	28.88	151.98	43.67	207.54	65.05

The link budgets for the downlink and the uplink of the inter-node link between a HAP and a LEO satellite are presented in Table 19 for three cases of the elevation angle: 30 degrees elevation (worst case), 45 degrees elevation (average case) and 90 degrees elevation (best case). The link is realized in the Q/V band where the downlink is between 37.5 GHz and 42.5 GHz and the uplink is between 47.2 GHz and 50.2 GHz, as well as 50.4 GHz and 51.4 GHz. It is shown that carrier symbol rates of up to 80 MBaud and 40 MBaud are achievable in the downlink and the uplink, respectively. Depending on the elevation angle, the data rates in the downlink range between 108.86 Mbps and 207.54 Mbps, whereas the data rates in the uplink range between 28.88 Mbps and 65.05 Mbps.

2.2.1.3 HAP-GEO Link Budgets

TABLE 20: HAP-GEO LINK BUDGETS

	HAP-GEO	DL	UL
Parameters	Tx altitude [km]	36000.00	20.00
	Rx altitude [km]	20.00	36000.00
	Frequency [GHz]	40.00	50.00
	Symbol rate [MBaud]	0.10	0.10
	TX EIRP [dBW]	51.50	24.60
	RX G/T [dB/K]	-11.00	11.00
	Path loss [dB]	215.60	217.54
	Margin [dB]	3.00	3.00
Results	SNR [dB]	0.50	-6.34

	Spectral efficiency [bits/s/Hz]	1.08	0.30
	Data Rate [Mbps]	0.11	0.03

The link budgets for the downlink and the uplink of the inter-node link between a HAP and a GEO satellite are presented inTable 20. The link bandwidth is allocated in the Q/V band where the downlink is between 37.5 GHz and 42.5 GHz and the uplink is between 47.2 GHz and 50.2 GHz, as well as 50.4 GHz and 51.4 GHz. Because of the low EIRP and G/T values for the HAP antenna due to payload constraints, only low data rates in the kbps range are achievable.

2.2.2 Intra-Orbit Link Budgets

Optical inter-satellite links provide a reliable and high-throughput communication link between two satellites. There are two scenarios investigated:

1. LEO-LEO OISL at various altitudes (400 km, 600 km and 800 km)
2. GEO-GEO OISL assuming three equally spaced GEO satellites

In the following we are presenting link budgets for the individual scenarios including justification for choice of system and channel parameters. 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

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) formats. State-of-art coherent communications systems with DP-QPSK modulation, pre-amplification and robust coding are capable of achieving sensitivities as low as 5 photons per bit (value used in calculations below).

In general, channel is modelled as loss-less AWGN (additive white Gaussian noise) channel. 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 fiber-coupling subsystem

Last, we add coding gain obtained by implementing channel codes.

2.2.2.1 LEO-LEO Link Budgets

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

TABLE 21: ORBITAL PARAMETERS LEO (ALL VALUES IN KM

Altitude	ISL Range (in-plane)	ISL Range (adjacent plane)
400	1059	1074
600	1567	1572
800	2065	2039

TABLE 22: LINK BUDGET LEO OISL 400KM WITH 30MM APERTURE

Parameter	Units	LEO-LEO at 400 km	LEO-LEO at 600 km	LEO-LEO at 800 km
Link Distance	km	1070	1570	2060
Tx Aperture	cm	0.03		
Rx Aperture	cm	0.03		
Tx Power	dBm	37.0		
Tx Gain	dB	92.6		
Tx Optical Loss	dB	-0.7		
Tx Pointing Loss	dB	-2.0		
Free Space Loss	dB	-258.8	-262.1	-264.5
Rx Gain	dB	95.7		
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	-41.7	-45.0	-47.4
Effective Power	dBm	-37.7	-41.0	-43.4
Detector Sensitivity	PPB	10		
Req. Power at 10G	dBm	-49.0		
Link Margin at 10G	dB	11.3	8.0	5.6
Req. Power at 100G	dBm	-39.0		
Link Margin at 100G	dB	1.3	-2.0	-4.4

From the provided link budgets for 30 mm aperture we can observe that whilst 10G OISL is feasible, 100G OISL is only feasible for lowest altitudes (400 km). By increasing the aperture size to 80 mm (e.g., TESAT SCOT-80), the 100G OISL is feasible even with one tenth of the optical power (500mW) compared to the case with small aperture.

TABLE 23: LINK BUDGET LEO OISL 400KM WITH 80MM APERTURE.

Parameter	Units	LEO-LEO at 400 km	LEO-LEO at 600 km	LEO-LEO at 800 km
Link Distance	km	1070	1570	2060
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	-258.8	-262.1	-264.5
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		
Total Transmission	dBm	-34.6	-37.9	-40.3
Effective Power	dBm	-30.6	-33.9	-36.3
Detector Sensitivity	PPB	10		
Req. Power at 10G	dBm	-49.0		
Link Margin at 10G	dB	18.4	15.1	12.7
Req. Power at 100G	dBm	-39.0		
Link Margin at 100G	dB	8.4	5.1	2.7

The dependency of the achievable capacity relative to the optical terminal aperture diameter and launch (transmit) power is also shown in following graphs (reported as Figure 5) for 400km and 800km LEO OISL scenarios.

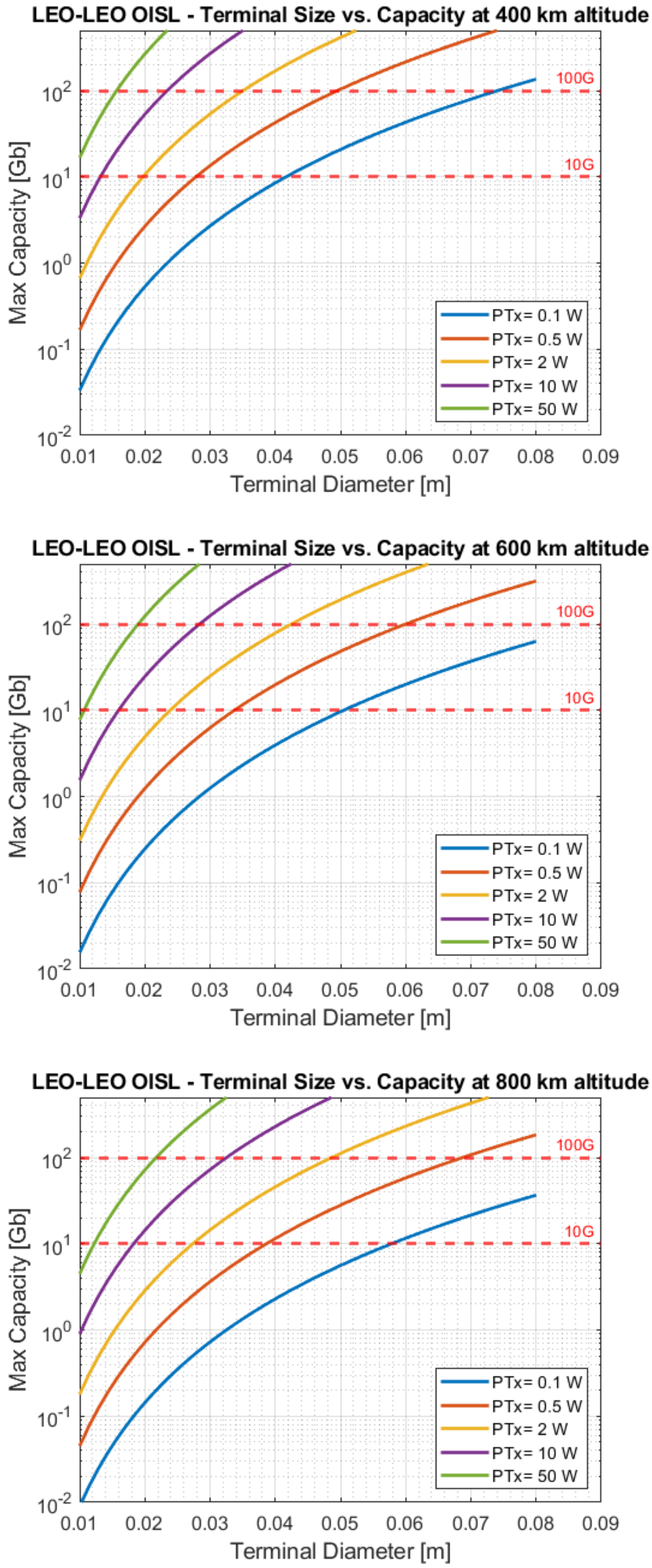

FIGURE 5: CAPACITY ASSESSMENT OF A LEO OISL AS A FUNCTION OF THE USED TERMINAL DIAMETER FOR VARIOUS TRANSMITTED OPTICAL POWER LEVELS AND DIFFERENT ALTITUTDES

2.2.2.2 GEO-GEO Link Budgets

TABLE 24: LINK BUDGET GEO OISL FOR TWO DIFFERENT APERTURE SIZES

Parameter	Units	GEO-GEO	GEO-GEO
Link Distance	km	70000	
Tx Aperture	m	0.07	0.25
Rx Aperture	m	0.07	0.25
Tx Power	dBm	37.0	
Tx Gain	dB	100.0	111.1
Tx Optical Loss	dB	-0.7	
Tx Pointing Loss	dB	-2.0	
Free Space Loss	dB	-295.1	
Rx Gain	dB	103.0	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	-63.3	-41.1
Effective Power	dBm	-59.3	-37.1
Detector Sensitivity	PPB	10	
Req. Power at 10G	dBm	-49.0	
Link Margin at 10G	dB	-10.3	11.9
Req. Power at 100G	dBm	-39.0	
Link Margin at 100G	dB	-20.3	1.9

Assuming 70 mm aperture (e.g., SmartLCT), the link budget cannot be closed. In order to reach 10G GEO OISL, the optical power would need to be increased to 100W (50dBm) – such technology is not yet available for space applications, but is under development in an ESA contract.

Alternatively, the aperture size would need to be increased to 250 mm (currently not commercially available, but under development) 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 6.

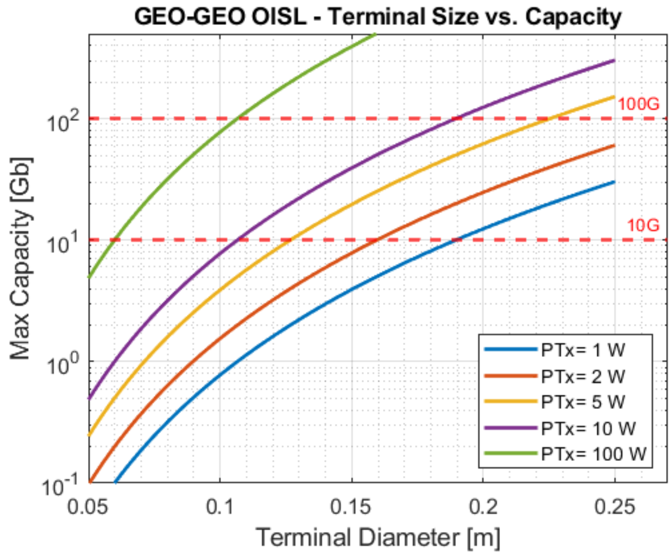

FIGURE 6: CAPACITY ASSESSMENT OF A GEO OISL AS A FUNCTION OF THE USED TERMINAL DIAMETER FOR VARIOUS TRANSMITTED OPTICAL POWER LEVELS.

2.3 FEEDER LINKS

The feeder link budgets for LEO satellites assuming 99.5% availability and clear sky conditions and a ground station located in Toulouse. The data used for the simulation are reported in Table 25 and Table 26.

TABLE 25: FEEDER UPLINK BUDGET IN Q/V-BAND

		Unit	UL: GW → SAT
Global	Band name	-	Q-V
	UL frequency	GHz	50.00
	Useful Bandwidth	MHz	4500.00
Gateway - TX	Elevation angle to sat	Deg	10.00
	Slant range	km	1931.64
	Antenna view angle	Deg	64.16
	Polarization mismatch loss	dB	3.00
	EIRP	dBW	86.53
Satellite - RX	Altitude	km	600.00
	G/T	dB/K	10.50

Losses	Free space propagation	dB	192.15
	UE location	-	Toulouse
	Weather condition	-	Clear sky
	Propagation tool atmospheric loss computed	dB	3.76
	Zenith attenuation	dB	1.80
	Atmospheric path loss	dB	9.40
	Ionospheric scintillation loss	dB	0.0
	Tropospheric scintillation loss	dB	0.61
	Scintillation loss	dB	0.61
	Atmospheric loss	dB	10.01
	Shadowing margins	dB	0.0
	Body loss	dB	0.0
	Scan loss	dB	0.0
	Additional loss	dB	0.0
Global losses	Calibration mismatch loss	dB	1.00
	System margin	dB	1.00
Intermediate Results	C/N_0	dBHz	120.5
	C/N	dB	53.9
	C/I_0	dBHz	84.53
	C/I	dB	18.00
	$C/(N_0+I_0)$	dBHz	84.53
	Overall $C/(N_0+I_0)$ Including Global losses	dBHz	82.53
Results	Obtained C/N	dB	16.00

	Nearest C/N	dB	15.12
	Residuals Margins	dB	0.8832
	Spectral efficiency	Bits/s/Hz	2.6748
	Rate	Mbit/s	12036.623

TABLE 26: FEEDER DOWNLINK BUDGET IN Q/V-BAND

		Unit	**DL: SAT → GW**
Global	Band name	-	Q-V
	DL frequency	GHz	40.00
	Useful Bandwidth	MHz	4500.00
Gateway - RX	Elevation angle to sat (seen from the UE)	Deg	10.00
	Slant range	km	1931.64
	Antenna view angle	Deg	64.16
	Polarization mismatch loss	dB	3.00
	G/T	dB/K	41.50
	Effective G/T	dB/K	38.50
Satellite - TX	Altitude	km	600.00
	EIRP	dBW	51.70
Losses	Free space propagation	dB	190.21
	UE location	-	Toulouse
	Weather condition	-	Clear sky
	Propagation tool atmospheric loss computed	dB	1.20
	Zenith attenuation	dB	0.40
	Atmospheric path loss	dB	8.00

	Ionospheric scintillation loss	dB	0.0
	Tropospheric scintillation loss	dB	0.54
	Scintillation loss	dB	0.54
	Atmospheric loss	dB	8.54
	Shadowing margins	dB	0.0
	Body loss	dB	0.0
	Scan loss	dB	0.0
	Additional loss	dB	0.0
Global losses	Calibration mismatch loss	dB	1.00
	System margin	dB	1.00
Intermediate Results	C/N_0	dBHz	120.05
	C/N	dB	53.52
	C/I_0	dBHz	84.53
	C/I	dB	18.00
	$C/(N_0+I_0)$	dBHz	84.53
	Overall $C/(N_0+I_0)$ Including Global losses	dBHz	82.53
Results	Obtained C/N	dB	16.00
	Required C/N	dB	15.12
	Residuals Margins	dB	0.88
	Spectral efficiency	Bits/s/Hz	2.4370
	Rate	Mbit/s	10966.70

2.4 THROUGHPUT/CAPACITY ESTIMATION

This chapter provides an initial throughput/capacity estimation for a LEO multi-beam satellite. More precisely, we estimate the achievable aggregate data rates of the C- and Q/V band service links of a LEO multi-beam satellite. For this, we assume that the satellite is power-limited with a maximum downlink beam usage of 5%, 10% up to 30%. Furthermore, we assume a geographically uniform distribution of the users and traffic load. In such a scenario the available spectrum is only partially used in each of the satellite beams so that inter beam interference is avoided.

For user uplinks, a LEO satellite could in principle support a higher beam usage and thus higher aggregated data rates than for user downlinks, but many applications are characterized by higher or similar data rates in the downlink and might not need higher data rates in the uplink.

2.4.1 Throughput/Capacity Estimation for C-Band

Following parameters have been assumed for the C-band service links of a LEO multi-beam satellite:

- Beam size: 50 km
- Number of beams: 1058 beams (EL 30°)
- Geographically uniform distribution of users and traffic load
- Uplink and downlink beam usage: 5%, 10%, 20% and 30%
- Frequency reuse / interference avoidance: achieved with low uplink and downlink beam usage
- Available bandwidth: 100 MHz up, 100 MHz down (FDD)
- Number of PRBs: 264 up, 264 down
- PRB bandwidth: 360 kHz
- Total bandwidth of all PRBs: 95.04 MHz up, 95.04 MHz down
- Spectral efficiency (shadowing 4 dB, average case - EL45°):
    - 1.08 bit/s/Hz up (see Table 5)
    - 1.46 bit/s/Hz down (see Table 8)

With these parameters we get a maximum aggregate data rate of 102.64 Mbit/s in the uplink beam and of 138.76 Mbit/s in the downlink beam, if we assume that all PRBs are active in the uplink and downlink beam. With the assumed uniform geographical user distribution and low beam usage of a LEO multi-beam satellite, only a subset of the available PRBs is used in a beam and following aggregate data rates per LEO multi-beam satellite (shown in Table 27) are achieved.

TABLE 27: AGGREGATE USER DATA RATE PER LEO MULTI-BEAM SATELLITE (C-BAND)

Beam usage	Up (Gbit/s)	Down (Gbit/s)
5%	5.43	7.34

10%	10.86	14.86
20%	21.72	29.36
30%	30.79	41.63

The aggregate downlink data rate is a bit higher than the aggregate uplink data rate, which might be suitable for most of the user applications.

The aggregate data rate per beam of a LEO multi-beam satellite is shown in Table 28.

TABLE 28: AGGREGATE USER DATA RATE PER BEAM OF A LEO MULTI-BEAM SATELLITE (C-BAND)

Beam usage	Up (Mbit/s)	Down (Mbit/s)
5%	5,13	6,94
10%	10,26	13,88
20%	20,53	27,75
30%	30,79	41,63

2.4.2 Throughput/Capacity Estimation for Q/V-Band

Following parameters have been assumed for the Q/V-band service links of a LEO multi-beam satellite:

- Beam size: 20 km
- Number of beams: 6626 beams (EL 30°)
- Beam usage: 10%, 20% and 30%
- Frequency reuse / interference avoidance: achieved with low uplink and downlink beam usage
- Available bandwidth: 800 MHz up, 800 MHz down
- Number of PRBs: 132 up, 132 down
- PRB bandwidth: 5760 kHz
- Total bandwidth of all PRBs: 760,32 MHz up, 760,32 MHz down
- Spectral efficiency (shadowing 3 dB, average case - EL45°):
    - 1.94 bit/s/Hz up (see Table 12)
    - 0.96 bit/s/Hz down (see Table 15)

With these parameters we get a maximum aggregate data rate of 1.475 Gbit/s in the uplink beam and of 0.73 Gbit/s in the downlink beam, if we assume that all PRBs are active in the uplink and downlink beam. With the assumed uniform geographical user distribution and low beam usage of a LEO multi-beam satellite, only a subset of the available PRBs is used in a beam and the aggregate data rates per LEO multi-beam satellite shown in Table 29 are achieved:

TABLE 29: AGGREGATE DATA RATE PER LEO MULTI-BEAM SATELLITE (Q/V-BAND)

Beam usage	Up (Gbit/s)	Down (Gbit/s)
10%	977.35	483.64
20%	1954.70	967.27
30%	2932.05	1450.91

Due to the higher spectral efficiency in the uplink, the aggregate data rate in the uplinks is higher than in the downlinks. Since these higher uplink data rates might be not needed for most of the applications, the transmit power and uplink spectral efficiency of the Q/V band user terminals could be reduced to achieve similar data rates in the uplinks than in the downlinks.

The aggregate data rate per beam of a LEO multi-beam satellite is shown in Table 30.

TABLE 30: AGGREGATE USER DATA RATE PER BEAM OF A LEO MULTI-BEAM SATELLITE (Q/V-BAND).

Beam usage	Up (Mbit/s)	Down (Mbit/s)
10%	147.50	72.99
20%	295.00	145.98
30%	442.51	218.97

3 INITIAL 6G-NTN FUNCTIONAL ARCHITECTURE

During the development of 5G NTN, multiple architectural options were studied and captured in [1], for example:

- Transparent satellite as sketched in Figure 7
- Regenerative satellite with full gNB on board, as sketched in Figure 8
- Regenerative satellite with RU and gNB-DU on board, as sketched in Figure 9.

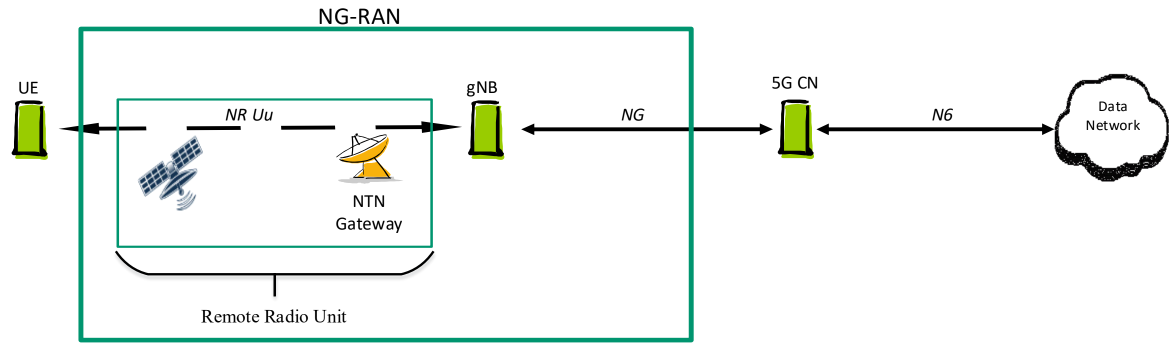

FIGURE 7: TRANSPARENT PAYLOAD [1]

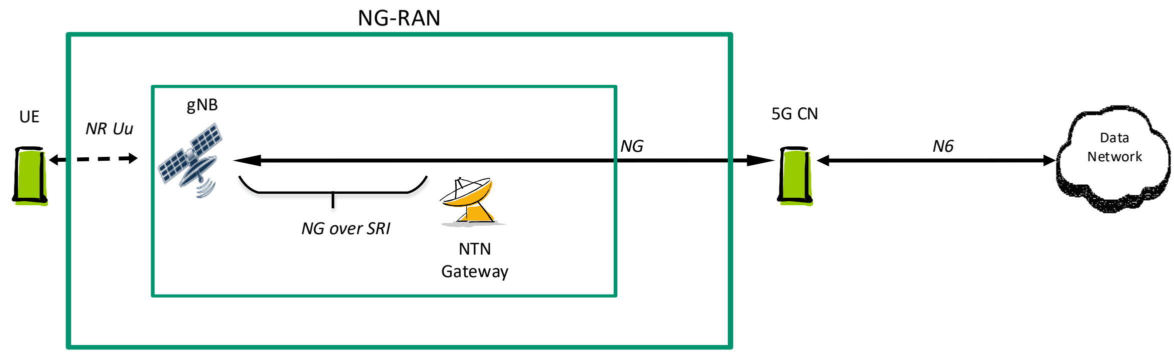

FIGURE 8: GNB PROCESSED PAYLOAD [1]

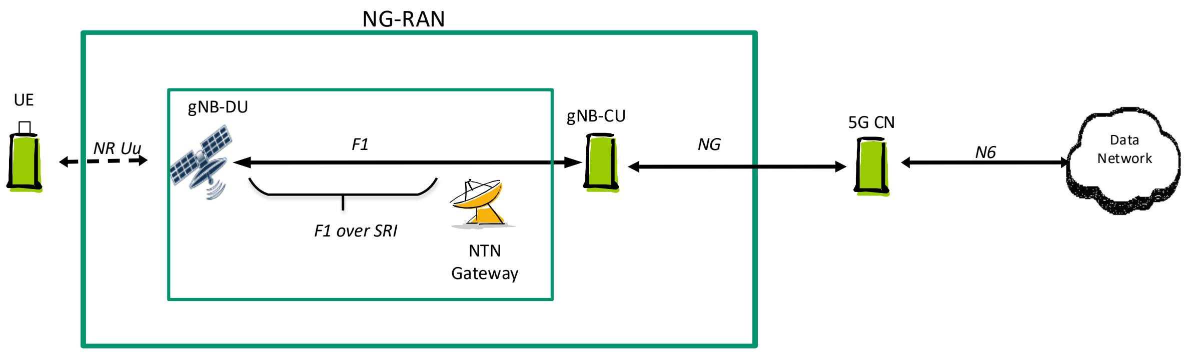

FIGURE 9: GNB-DU PROCESSED PAYLOAD [1]

It shall be mentioned that transparent payload is the only fully standardized option in Release 17 NTN. Regenerative payloads will be addressed, most likely, in Release 19+.

In 6G-NTN the objective is that the satellite payload will be based on a regenerative architecture meaning that data can processed and routed based on the properties of the data. Currently, 3GPP is still defining the package of topics to be addressed in the framework of Release 19 (to be frozen in December 2023), but it is expected that the support of regenerative payloads will be included. This time plan is perfectly aligned with the schedule and objectives of the 6G-NTN Project. This means that for the functional split option analysis no transparent (repeater like) architecture as in Figure 7 will be studied.

The 6G-NTN architecture foresees in turn 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, there will be constellation of satellites so the functionality of 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.

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)
- **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)
- **Satellite HW/SW impact**: payload complexity, power consumption, and memory requirements for satellites
- **Impact on Standard**: estimation and strategic consideration on the standard impact / required modifications when an option is adopted

3.1 OVERVIEW OF SPLIT OPTIONS

3.1.1 Full Base Station / gNB Onboard

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. In combination with User Plane Function (UPF), this allows for routing in between base stations with a dedicated network for that interconnection.

With full base station onboard, the complete radio protocol stack must be implemented in the satellite, assuming 5G terminology in the lack of a better alternative as 6G is not yet standardized, 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 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. Alternatively, the Xn interface may also be possible between two satellites over ISL, if an ISL exists between the two satellites. All RRC signaling between the UE and gNB would be terminated in the satellite. The required capacity of feeder link would scale with requested user data.

One observation, however, is that NG was not specified to be mobile such as how the NG/Xn will be connected/disconnected due to moving base station that will be required when a new NG need to be setup from ground station to the next satellite whenever a satellite need to change feeder link. When gNB on a satellite disconnects the NG, the users must also be handed over to a new satellite. Two types of handovers need to be handled 1) UE to a cell set up by a new satellite 2) Satellite to ground station. In future standardization of 6G, base station mobility capability should also be addressed.

3.1.2 Full Base Station and Some / All Core Functions Onboard

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.

The core network is defined in logically independent functions and the placement is a matter of implementation. Adding functionalities in the satellites shall be evaluated regarding cost, complexity, power consumption, and its relation to use cases.

One of the functions of the core that could facilitate the use case of UE-to-UE link over one satellite where the ground station is not working any more could be the UPF), which is for the routing of data packets in the core network.

The options to allow direct NTN connectivity between UEs are analysed in detail in Section 3.3.

3.1.3 gNB-DU Onboard

This option is following the logic that either the network node (satellite or HAPS) is very power and resource limited and may include only the necessary gNB-DU baseband processing including the physical layer and MAC layer processing.

We acknowledge however that most power consumption is occurring in the DU unit versus the CU unit consuming a fraction of that for a given bandwidth processed.

A slightly modified version of this option in order to partly circumvent this problem is to move part of the DU on ground keeping on board only the lower part of the PHY. This sub-option, hereafter referred to as Low Layer Split (LLS), is analysed in detail in Section 3.4.

3.2 MAPPING OF FUNCTIONAL SPLITS VS 6G-NTN USE CASES

Table 31 provides an initial analysis on the function split options, with respect to the different UCs defined in D2.1 [2]. 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

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traffic at the space, e.g., on a satellite as illustrated in Section 3.3. Please note, this initial analysis is subject to further changes in the rest of the project duration, e.g., based on the progress and the technical solution developments on the relevant topics.

TABLE 31: 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.

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 a 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 3.3. 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 3.4.

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 neighbor 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 3.3.

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. Up to which point this flexibility could be implemented, will be subject of further analysis. The next two sections focus on two scenarios, namely different architectural options to enable direct NTN communications (Section 3.3) and a configuration in which 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 (Section 3.4).

3.3 ARCHITECTURAL OPTIONS FOR DIRECT NTN COMMUNICATIONS

As can be seen from Figure 7, Figure 8, and Figure 9, the legacy architectures require a connection between the NTN payload and the on-ground network, e.g., CN and DN.

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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 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 kilometers. 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 10. In addition, ISLs can be used to further enlarge the coverage area of the direct NTN communication, e.g., as shown in Figure 11. More detailed information and use cases of the direct NTN communication can be found in [2].

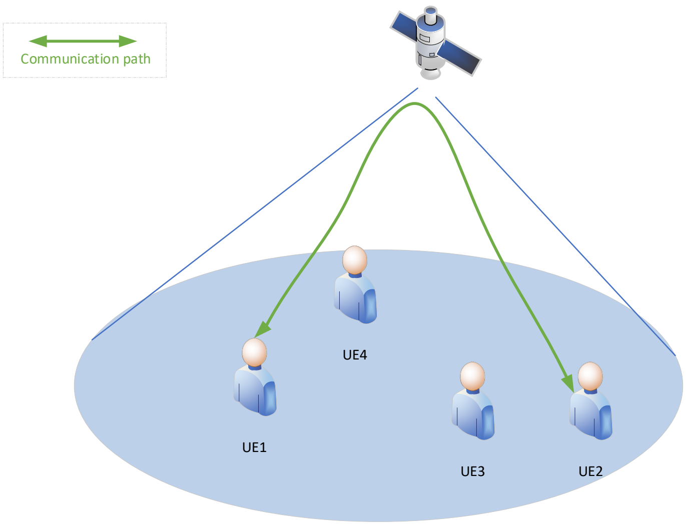

FIGURE 10: DIRECT NTN COMMUNICATION OVER A SINGLE SATELLITE.

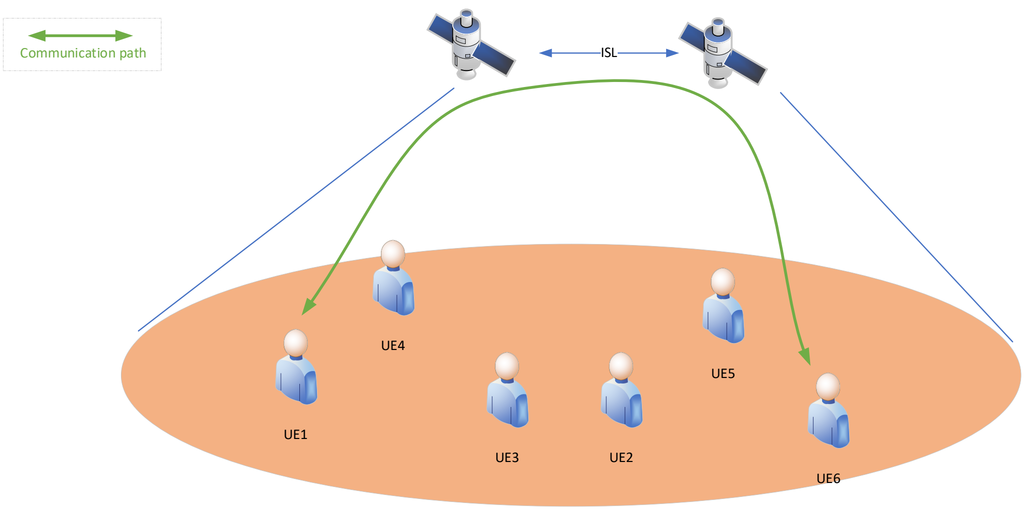

FIGURE 11: DIRECT NTN COMMUNICATION OVER TWO SATELLITES CONNECTED OVER ISL.

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 subsection as a baseline to describe the different options.

3.3.1 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 12. 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 12 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 13 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.

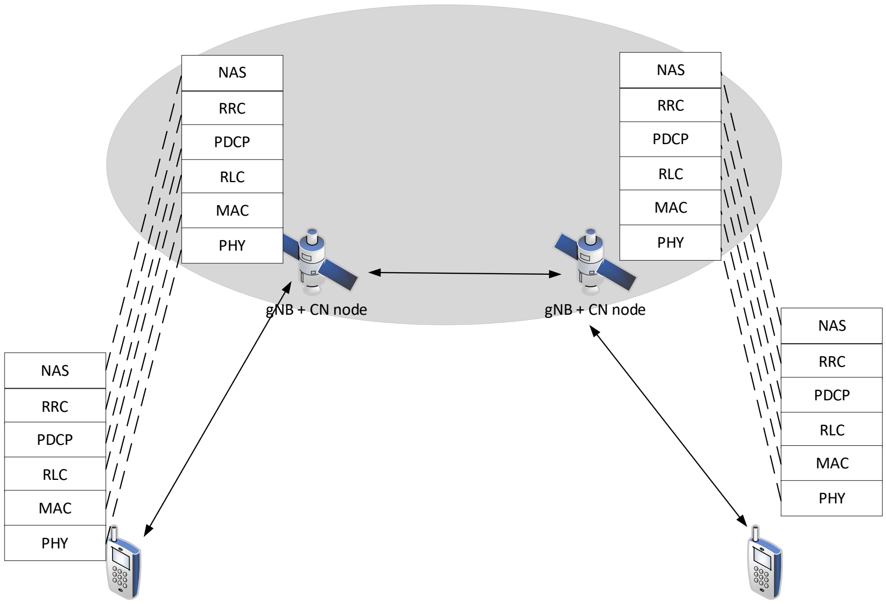

FIGURE 12: ILLUSTRATION OF CONTROL PLANE FOR OPTION 1.

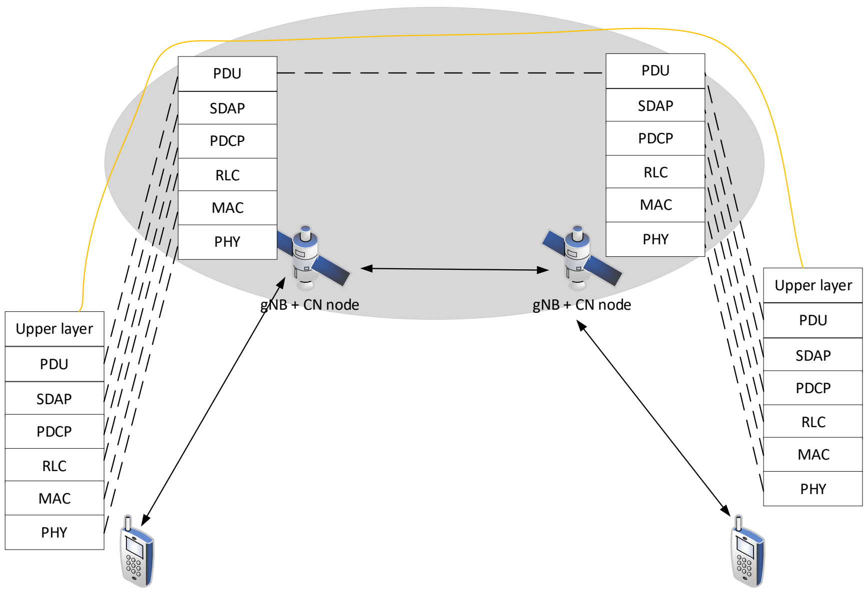

FIGURE 13: ILLUSTRATION OF USER PLANE FOR OPTION 1.-

3.3.2 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 14 and Figure 15 illustrate the control plane protocol architecture and the use 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 or in the future 6G 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.

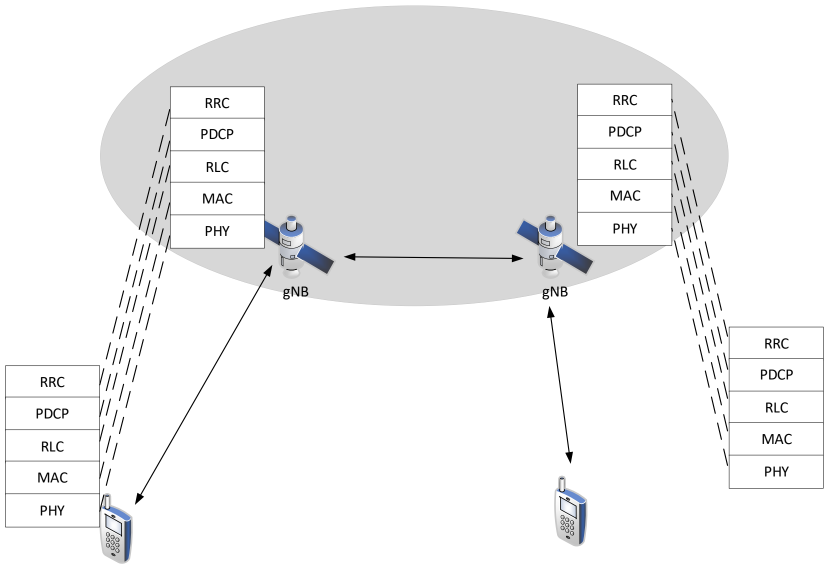

FIGURE 14: ILLUSTRATION OF CONTROL PLANE FOR OPTION 2.

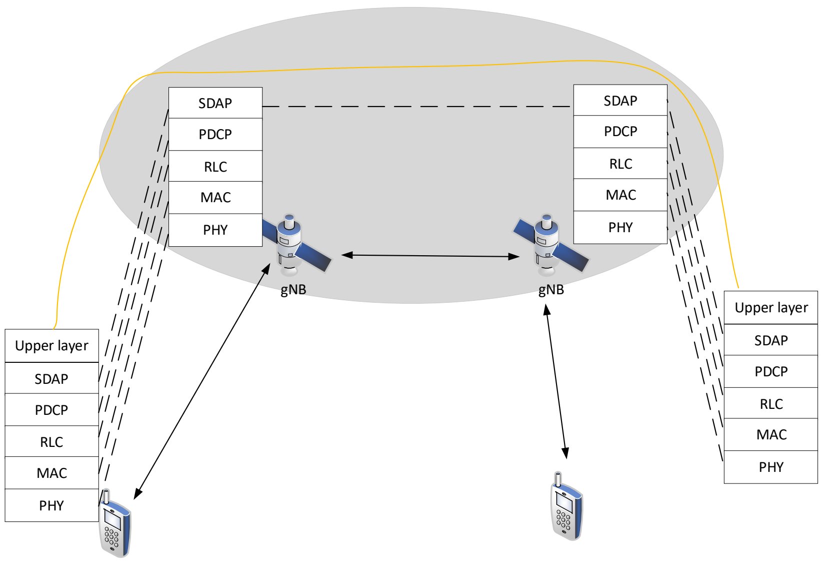

FIGURE 15: ILLUSTRATION OF USER PLANE FOR OPTION 2.

In addition to the mentioned routing function, modifications may be needed for supporting additional upper layer protocols and procedures in Option 2. For instance, aauthorization, 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.

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 15. The additional function/layer is not shown in Figure 15, since it may have different design options. For example, Figure 16 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 17 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 16 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 18, 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.

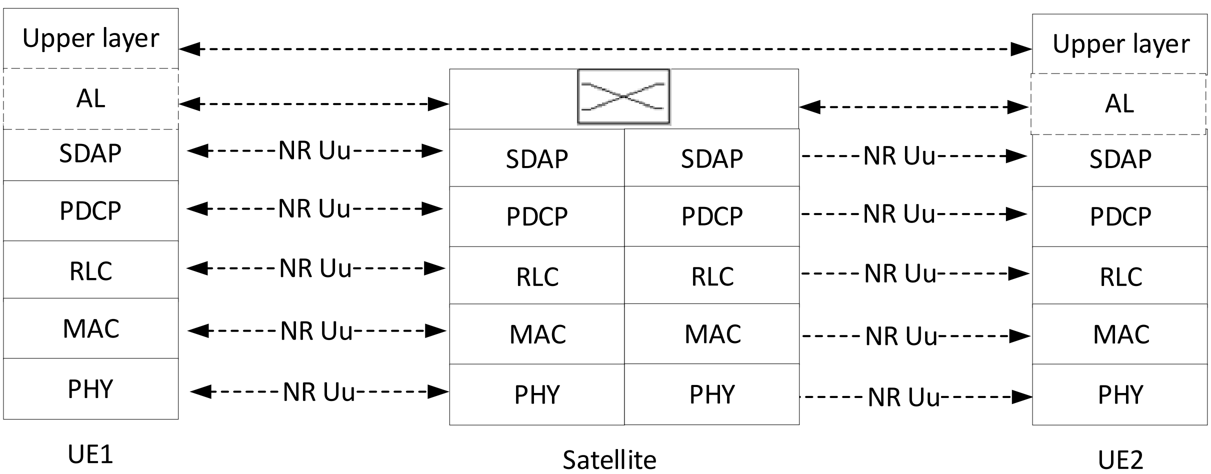

FIGURE 16: ILLUSTRATION OF LAYER-3-BASED ROUTING ON USER PLANE WITH A SINGLE SATELLITE.

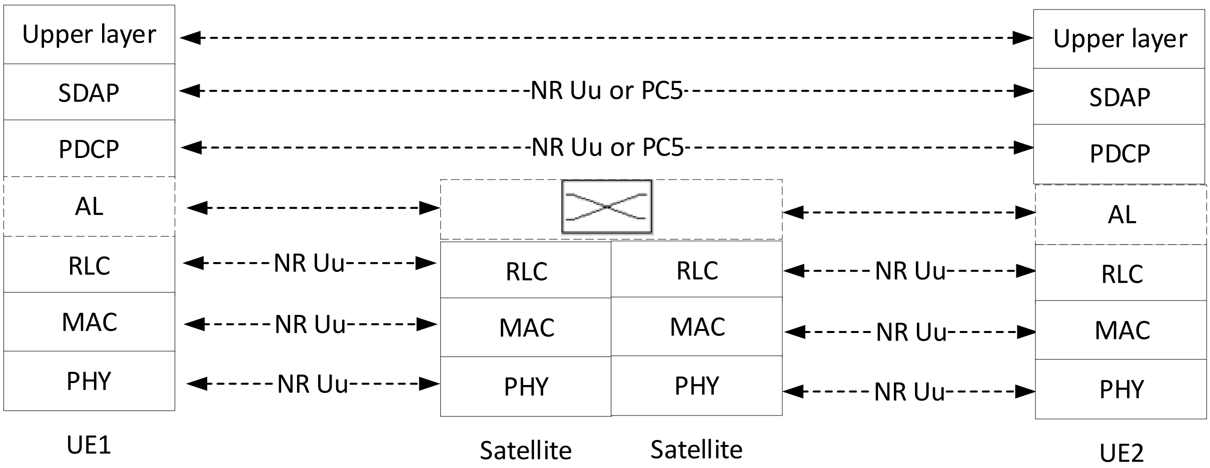

FIGURE 17: ILLUSTRATION OF LAYER-2-BASED ROUTING ON USER PLANE WITH A SINGLE SATELLITE.

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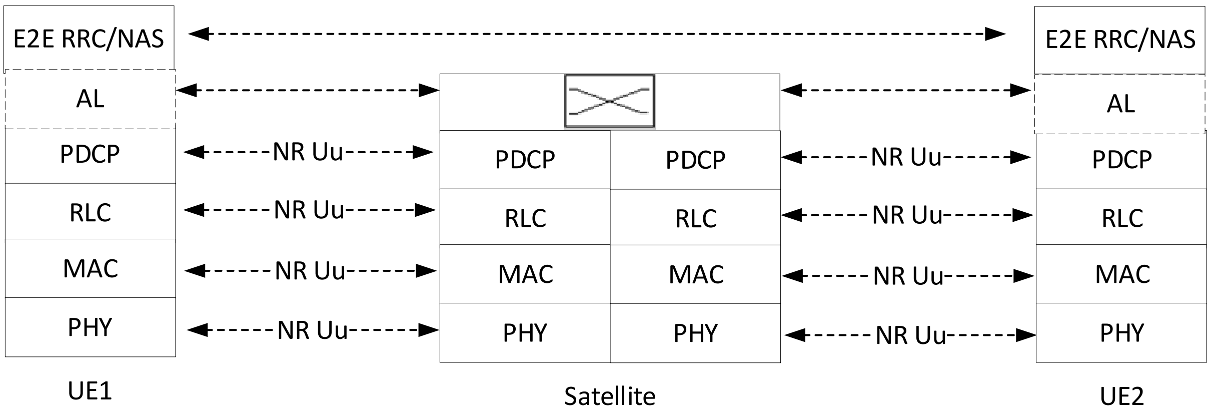

FIGURE 18: E2E LINK CONTROL-PLANE FOR L3-BASED SOLUTION.

As shown in Figure 17, 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, satellite is not involved in E2E UP security since the PDCP layer is terminated at both UEs. Similar as 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 19.

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.

It is noted, 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.

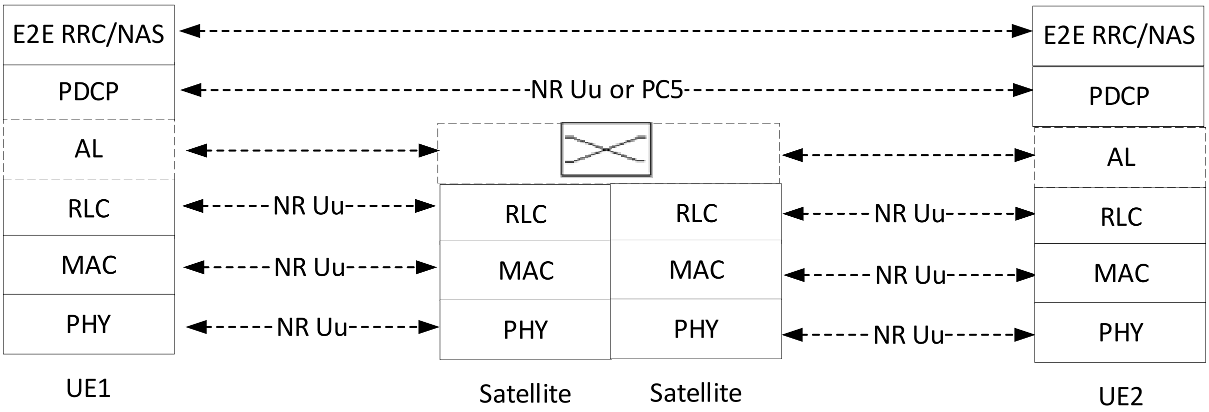

FIGURE 19: E2E LINK CONTROL-PLANE FOR L2-BASED SOLUTION.

3.3.3 Option 3: NTN Node Acting as a Sidelink Relay

It is noted, the considered direct NTN communication may leverage the SL U2U relay design, whose design is currently ongoing in 3GPP release 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 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 20.

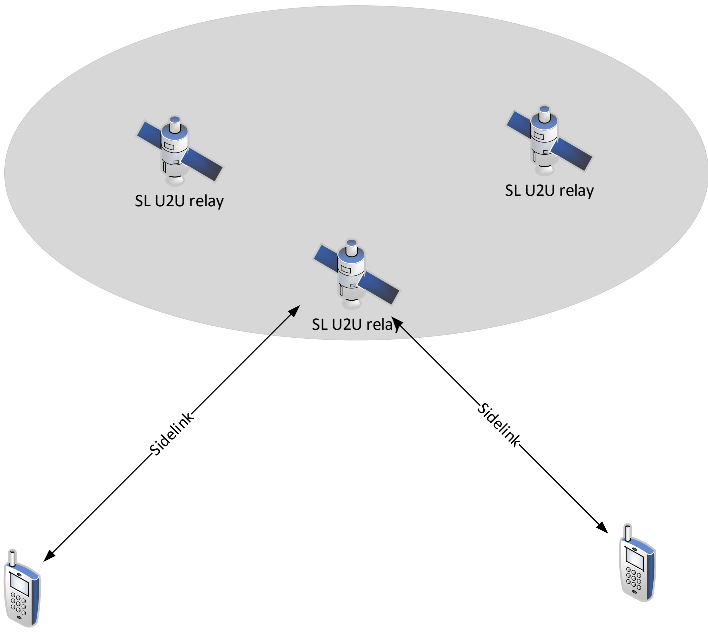

FIGURE 20: NTN PLATFORM ACTS AS A SL U2U RELAY.

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 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.

Based on the above analysis, Table 32 summarizes the differences among the three options in supporting the considered direct NTN communication.

TABLE 32：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	Yes (To handle mobile CN nodes)	No	No
Added satellite complexity and power consumption	High	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 (CN node switch)	Good (RAN node switch by reusing Uu RRC)	Middle (RAN node switch by SL signaling)
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)

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3.4 LOW LAYER SPLIT ANALYSIS

3.4.1 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 fiber. 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 [3]. A subset of the paper covers the intra-PHY split options. [4] and [5] propose 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.

3.4.2 LLS on NTN

When considering the specificities of NTN systems, a LLS base station is an attractive alternative. Here, an NTN LLS base station would have a baseband node on the ground and the radio on a flying node (e.g., satellite).

In the case of a radio node in a satellite, the fronthaul interface could be transported either over the feeder link or an inter node link (i.e., more than one hop to the ground). The fact that LLS can be implemented over traditional Ethernet / IP, indicates that one flying node could be used to forward LLS traffic to other nodes.

When comparing with the option of having a full (monolithic) base station on the flying node, implementing only the radio node would require less resources in terms of power consumption, volume, mass, and computational capacity.

A second benefit for such an architecture is that for the ground stations, the baseband processing nodes could be the same as the ones for terrestrial 6G. The development cost for baseband processing equipment, including all requirements for hardening such hardware against the environmental conditions and radiation aboard a satellite would be eliminated.

Compared to having a full base station on the satellite, the main drawback of such a system is the higher requirement on bandwidth for the feeder / inter node links. That extra cost usually comes from the transport of uplink signals. Here, the balance may be reached by careful consideration on where and how to implement receiver algorithms such as indicated in [4] and [5].

A detailed division of functions between nodes in such an architecture is subject to the choice of the waveform technology to be implemented.

4 CONCLUSIONS

Given the main outcomes of this preliminary network analysis and sizing already summarized in the executing summary, the following next steps and main lines of innovation can be identified.

4.1.1 Next Steps (towards Deliverable D3.5)

- Consolidate service and feeder link budgets considering the progress in Task 3.2 and 3.3, especially for Q/V bands.
- Refine the functional split analysis with inputs from Task 3.3 regarding payload capabilities (how much mass and power is available for implementing RAN and CN functions)
- Review the topology of the LEO constellations and dimensioning of the transport network in space (ISLs and feeder links) to avoid bottlenecks. This is an interactive process with Task 3.4.
- Provide further insights on the role of GEOs and HAPs

4.1.2 Main Potential Innovations at Architectural Level

- Q/V band antenna for UEs (carried out in Task 3.2) and for NTN nodes (carried out in Task 3.3)
- Double-layered LEO Constellation separating service link payloads from transport network (ISLs and feeder links) with enhanced processing capabilities in space (joint activity with Task 3.4)
- Support for gNB and CN functions mobility with distributed architecture in space (à potential contribution to 3GPP)
- Adaptation of Xn interfaces to work over concatenation of error prone links with high delay (→ potential contribution to 3GPP)
- Support for use-case-based or service-based function split to efficiently distribute network functions
- Support for direct NTN communication without the need for an available feeder link (→ potential contribution to 3GPP)

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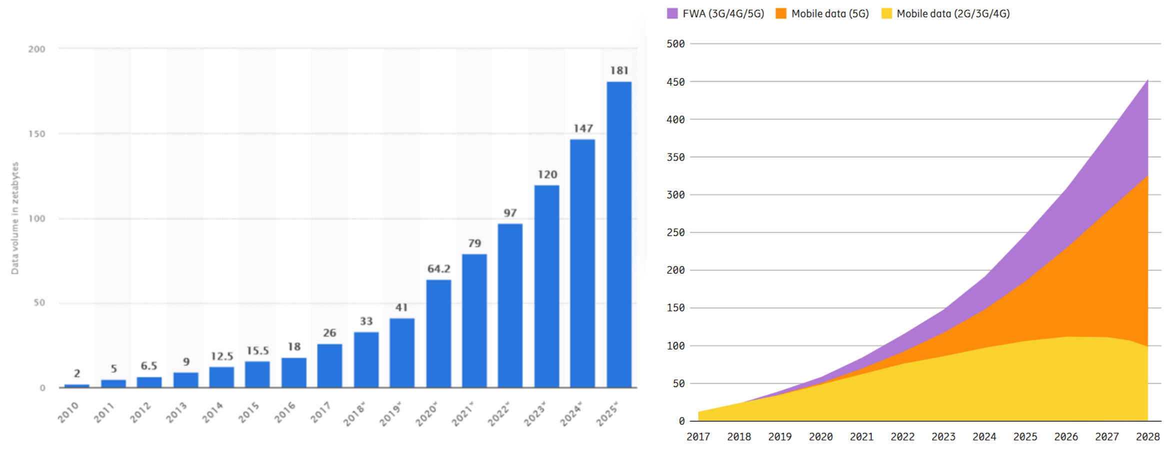
5 APPENDIX A: OPTICAL SATELLITE COMMUNICATION (OSC)

5.1 INTRODUCTION

Inter-satellite links between LEOs and between GEOs are supposed to be based on optical communications. This technology, which has proven its full technological maturity in the Earth Observation domain with the European Data Relay System (EDRS), is still at prototyping / pre-operational stage for telecom applications. Therefore, a thorough review is provided in this Appendix for interested readers.

5.1.1 Data Communication

The expected evolution of data traffic volumes (Figure 21 A) has a potential large impact on the energy consumption of ICT infrastructure, including Non-Terrestrial-Network segment. This forces the scientific community to propose a new vision for the network of tomorrow. Roughly every 10 years, the mobile communication ecosystem engages in designing a system using the most up-to-date techniques to answer to increased traffic (Figure 21 B). This periodicity stems from the time needed for research, standardization, international spectrum harmonization, and industrialization.



(A) (B)

FIGURE 21: TRAFFIC EVOLUTION: (A) GLOBAL DATA VOLUME [6], (B) MOBILE NETWORK DATA TRAFFIC EVOLUTION [7]

The percentage of energy required for operating the global ICT infrastructure could be between 20% and 30% by 2030 (depending on certain assumptions concerning electricity production by 2030). ICT actors need to react on the access and enterprise segments as they account for most of the energy usage. It is hence urgent to propose innovations in these parts of the network (access and enterprise or in-building).

“6G” is the next generation of mobile communication technology with anticipated commercial deployments from 2030 onward. This is the reason why 6G technologies are already subject to intense research efforts with new usages and emerging candidate techniques. These techniques include sub-terahertz (sub-THz) and Terahertz (THz) spectrum band investigation, Reconfigurable Intelligent Surfaces (RIS) solution, NTN with satellite and High-Altitude Platforms (HAPs), and still its infancy, Optical Wireless Communication (OWC).

5.1.2 Optical Wireless Communication (OWC)

OWC use light to connect across free space without the confinement to a waveguide (Figure 22) [8]. Both LEDs and Lasers can be modulated to provide data communications, for instance, outdoor point-to-point (known as Free-Space-Optics or FSO) with capacity as high as 1.72 Tb/s [9]). Similar systems have also been demonstrated for indoor point-to-multipoint solutions (Light Fidelity or LiFi) with data rate up to several Gb/s or between devices (Optical Camera Communication – OCC) with few kb/s [10] and [11]. A new approach to OWC known as Fiber Wireless (FiWi) offers a direct connection between two optical fibers [12]. Under this concept, light emitted by an optical fiber is collimated and then steered to a receiver. At the receiver, the incoming light is coupled again into an optical fiber. This FiWi operates bidirectionally, and speeds greater than 1Tb/s have been attained (WORTECS project - wireless world record [13]) with a theoretical capacity up to 1.84 Pb/s [14].

OWC has an available spectrum 2600 times greater the radio spectrum (considering the band from 400 to 1900 nm) and can be used to add new capacity to existing radio systems rather than replacing them. Additionally, OWC beam is usually collimated, thereby providing a first physical layer of security and the ability to reuse the same wavelengths in adjacent link, thus radically increasing the total system data throughput capacity.

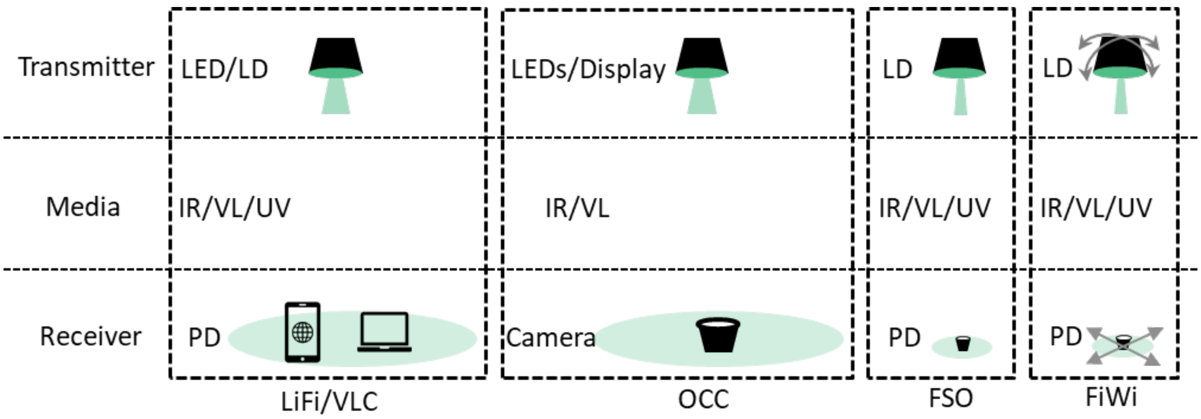


FIGURE 22: OWC WITH PHOTODIODE (PD), LASER DIODE (LD), INFRARED (IR), ULTRAVIOLET (UV) AND VISIBLE LIGHT (VL)

The main OWC applications can be define into five categories with respect to the transmission range:

- Ultra-short range: chip-to-chip communications in cable replacement.
- Short Range: define by Wireless Body Area Network (WBAN) or Wireless Personal Area Network (WPAN) applications and linked to IEEE 802.15.7 standard with for instance OCC or VLC.
- Mid-Range: Indoor multi user application for Wireless LANs (WLAN) define as Light Fidelity (LiFi) or Fiber Wireless (FiWi) and vehicular communications.
- Long range: Outdoor point to point Free Space Optical communications (FSO) and underwater communications.
- Ultra-long range: Optical Satellite Communication (OSC) for Inter-Satellite Links (ISL), Telescope Optical Ground Station (OGS) to satellite communication and Non terrestrial Network (NTN) satellite constellations.

5.1.3 Optical Satellite Communication (OSC)

Due to the wide range coverage and highly accurate communication aspects, satellite communication offers positives aspects. Basically, several types of satellites exist as defined on Figure 23 but mainly there is: (i) LEO, (ii) MEO and (iii) GEO. LEO satellites orbit the Earth between 160 and 2000 km. MEO satellites are between 2000 and 36000 km above the Earth. GEO satellites have a stationary orbit of 22236 km. The latter are mainly used to provide network access medium, for instance: Radio spectrum Ku band – 12 to 18 GHz with data transmission rate around 500 Mbps and 100-6000 km coverage.

Orbit	Altitude	Onboard Angular Range	Visibility Time	Latency
VLEO	<500 km	Beyond ± 60°	<20 min.	<20 ms
LEO	~1000 km	±60°	20 min.	~20 ms
MEO	~10,000 km	±20°	45 min.	~100 ms
GEO	35,786 km	±8.7°	Permanent	~250 ms
HEO	Up to 40,000 km at apogee	±10°	A few hours	~250 ms

FIGURE 23: KEY PARAMETERS OF TYPICAL SATELLITE EARTH ORBITS [15]

Optical Satellite Communication is communication by light which carries information between satellites or between satellites and the ground [16]. The optical system consists of the light source, transmission, and reception subsystems [17].

On average, a data rate of 1 Gbps is achieved (minimum of 0.15 Gbps and maximum currently 10 Gbps). Basically, communication signals are processed in baseband, potentially encrypted, and modulated via the optical antenna and received by one or more optical receiving antennas. The signal is detected and demodulated to obtain the message. The communication is usually full duplex. For instance, Figure 24 indicates OSC satellites in space since 2014.

Vendor/Developer	Terminal	Platform	Data Rate	Mass	Power	Wavelength	Modulation	Launch Date
---	---	---	[Mbps]	[kg]	[W]	[nm]	---	---
NICT	SOTA	SOCRATES	10	5.9	16	976/800/1549	OOK	5.2014
DLR	OSIRISv2	BiROS	1000	1.65	37	1550	OOK	6.2016
DLR	OSIRISv1	Flying Laptop	200	1.3	26	1550	OOK	7.2017
Aerospace Corporation	OCSD-B&C	AeroCube-7	200	<2.3	20	1064	OOK	12.2017
NICT	VSOTA	RISESAT	1	<1	4.33	980/1550	OOK/PPM	1.2019
Sony/JAXA	SOLISS	ISS	100	9.8	36	1550	OOK	7.2019
DLR	OSIRIS4CubeSat	PIXL-1	100	0.4	10	1550	OOK	1.2021
MIT Lincoln Labs	TBIRD	PDT-3	200,000	<3	100	1550	QPSK	5.2022
MIT	CLICK-A	CLICK	10	1.2	15	1550	PPM	7.2022
MIT	CLICK-B/C	CLICK	20	1.5	30	1537/1563	PPM	Est. 2023
AAC Clyde Space	CubeCat	---	1000	<1.33	15	1550	OOK	---

FIGURE 24: OSC SYSTEMS IN SPACE [18].

Optical satellite communication can be divided into several categories: Satellite-to-ground communication and Optical ISL (O-ISL) is classified into Inter-ISL defined as Intraplane (containing GEO-GEO, LEO-LEO) and Inter-Orbit Link (IOL) defined as Interplane (containing GEO-LEO) [19] (Figure 25).The high-orbit GEO satellite has wide coverage, making 3 Earth-covering GEO satellites possible. In that way, it is possible to use GEO optical satellite in high orbit as satellite relay of the LEO optical satellite, mainly builds the connection with the Optical

Ground Stations (OGS), which finally able to propose an all optical space-earth integration communication network [20].

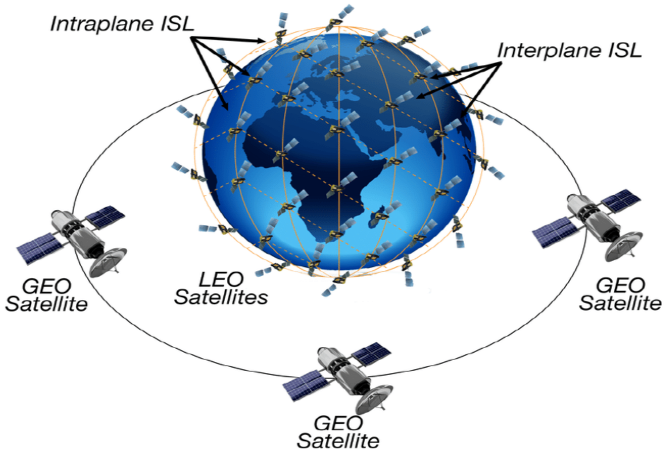


FIGURE 25: GEO & LEO SATELLITES WITH INTRAPLANE AND INTERPLANE ISL [21].

5.2 OSC AND ISL FOR NTN RECENT TRENDS

Constellation programs were planned and then launched to provide global satellite communications services by non-geostationary orbit (NGSO) satellite systems. However, frequency spectra are potentially depleted, additionally spectrum allocation becomes problematic and costly in Radio Frequency (RF) bands as satellite data throughput increases [22].

So, space communication is compelled to investigate higher RF frequencies up to optical frequency bands. Optical communications are used due to high capacity as well as interference tolerance and lack of regulatory restriction which does not require international frequency coordination [23]. For instance, and Proof of Concept (PoC), NASA's Laser Communication Relay Demonstration Satellite (LCRD) was launched on December 7, 2021. Additionally, several OSC satellites were launched as Proof of Concept, and it is possible to have a global view about the history of space laser communication programs in Figure 26.

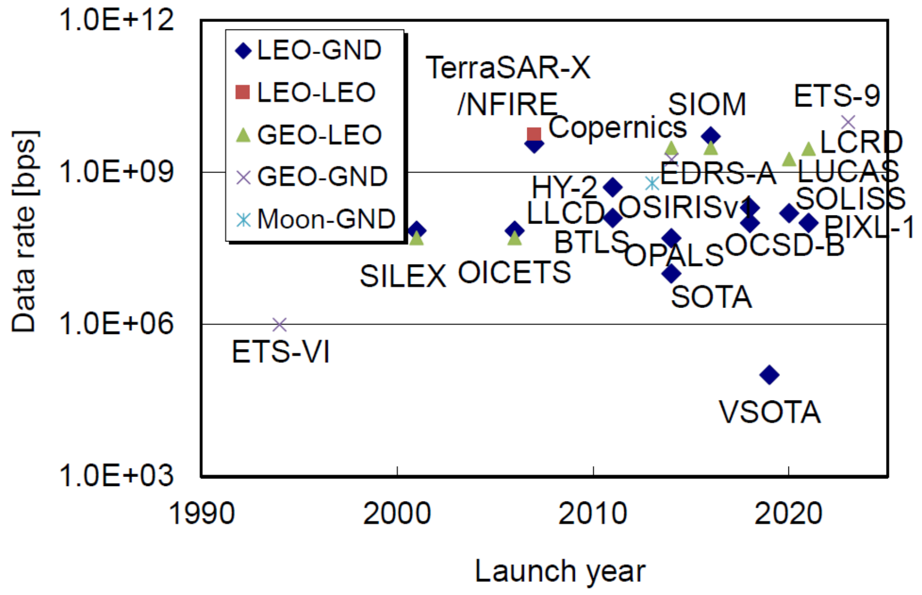


FIGURE 26: SPACE LASER COMMUNICATION: DATA RATE VERSUS YEAR LAUNCH [24].

5.3 KEY SUB SYSTEMS

Optical satellite communication is a multidisciplinary field integrating, at least, optic geometric, atmospheric optic, mechanics, mathematics, and computer science. Figure 27 indicates basic different subsystems constituting an optical transmission satellite.

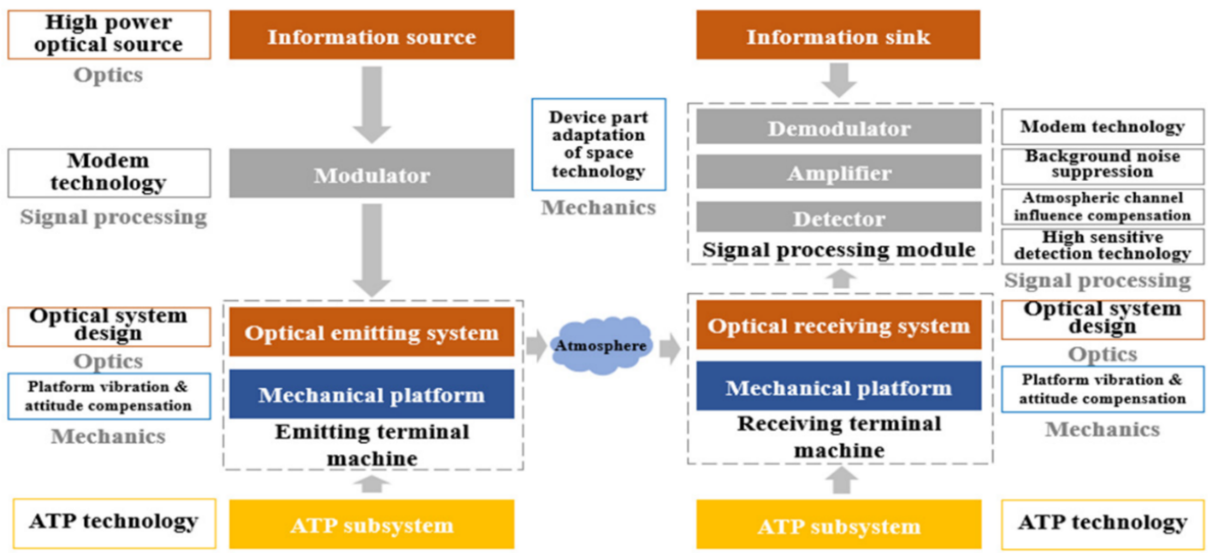


FIGURE 27: SPACE LASER COMMUNICATION: DATA RATE VERSUS YEAR LAUNCH [25].

Like any space device, this one must have specific properties to reduce or cancel the space environment negative effects. It includes, for example, mirror surface performance protection, anti-cold welding of mechanical components, anti-radiation technology of the amplifier, etc.

5.3.1 Optic Layer

5.3.1.1 Optical Emission

The optical sources operate from visible (from 400 nm to 700 nm) to infrared (IR) (up to 10000 nm). In OWC, the two types of sources are LEDs and Laser Diodes.

- Organic LED (OLED) is intended for flat screens. The modulation bandwidth is around hundreds of kHz.
- μ-LEDs (≤ 100 μm) can provide modulation bandwidths of hundreds of MHz, thus offering data rates with many sources to provide sufficient illumination for indoor lighting.
- Phosphor-Converted LEDs (PC-LEDs) are the cheapest with data rate up to few Gbps.
- Red, Yellow, Green and Blue (RYGB) multi-chip LEDs can offer higher aggregate data rates with Wavelength Division Multiplexing (WDM).
- Laser Diodes (LDs) are used in high-speed VLC, infrared OWC, and fiber optic communication. LD output is a coherent light and better collimated than LEDs, improving efficiency and point-to-point data transmission. In addition, its narrow optical emission spectrum enables high aggregate data rates with WDM.

Satellite communication has long distance (up to 40,000 kilometers for instance), so ground and satellite stations must use LD (with sometimes, Optic Amplifier – OA) to achieve high enough transmission power to reach other stations. LDs are also chosen to support high bandwidth modulation and high data rate transfer with special amplifier stage to drive low equivalent impedance. The preferred wavelengths band are around 800nm, 1000nm and 1500nm, corresponding to semiconductor lasers, solid lasers, and fiber lasers applications. In addition, 850nm, 1550nm and 10,000nm are used for ground-satellite links, according to weather conditions, security and atmospheric turbulence.

The signals use to come from Digital to Analog Converter (DAC) stage. For instance, LD with 800 MHz bandwidth of modulated signal can provide up to 8 Gbps throughput with optimal OFDM treatment.

5.3.1.2 Optical Receiver

About the receiver side, photodetectors (PDs) convert light into electricity. Various types of PD are used in OWC, silicon (Si), germanium (Ge), gallium arsenide (GaAs), gallium aluminum arsenide (GaAlAs) and indium and gallium (InGaAs). Each of these detectors has a specific spectral sensitivity, quantum efficiency and strongly depends on the wavelength used.

For instance, silicon PDs have the highest sensitivity in the NIR region (800 nm and 1000 nm) and are cheaper than other PDs. For higher wavelength ranges, other technologies, such as InGaAs and Ge PD are used for Avalanche Photo Diode (APD) for instance.

To achieve a high Signal to Noise Ratio (SNR) and guaranty a long-range link quality, APD photodiode are used with generally two amplifier stage for circuitry conception. Additionally, to avoid interference and improve the SNR, a narrow band optical filter is used in front of APD. Amplification and filtering ensure an optimal signal transfer for Analog to Digital Converter (ADC) stage.

5.3.2 Signal Processing and Modulations

Signal processing technology has two main approaches: modem technology and background noise suppression management. Modem technology includes modulation and demodulation. Modulation uses a baseband signal to control the change of one or more parameters of the carrier signal (amplitude, frequency, phase) and form a modulated signal transmission. Demodulation is the reverse process of modulation, as the original baseband signal will be recovered from the change in parameters of the modulated signal.

Optical satellite communication potentially uses various modulation formats but the simplest and most effective seems to be On-Off Key modulation (OOK) with Intensity Modulation/Direct Detection (IM/DD) to obtain the best efficiency against turbulent atmospheric conditions [26]. The information is encoded with light intensity variation. OOK modulation is simple and robust against the nonlinearity but with spectrum efficiency limitation. Alternatively, Pulse Position Modulation (PPM) and Minimum Shift Keying (MSK) Subcarrier Intensity Modulation (PPM-MSK-SIM) offers advantages of strong anti-interference and high-power ratio. To increase the spectrum efficiency, OFDM modulation is proposed to increase the robustness to multipath propagation (or Interference Inter Symbol - ISI). In addition, the main noise comes from solar radiation and the intensity of the radiation decreases as the wavelength increases. To decrease the background noise, spatial filtering and signal modulation technology is applied. Like radio system, Multi-Input Multi-Output (MIMO) technique is also provided for better bandwidth and throughput. Finally, optical coding division multiple access (OCDMA) technique offer channel allocation flexibility, asynchronously operative ability, privacy enhancement, and network capacity increment but with complexity and cost.

5.3.3 Pointing Acquisition and Tracking (PAT)

Pointing, Acquisition and Tracking (PAT) is the foundation for long-range spatial optical communication and it is the most difficult step since the optical beams are inevitably smaller than the reception estimation area [27]. To precisely point its beam, each satellite terminal must be able to know the distant satellite exact position or of Optical Ground Station (OGS) terrestrial zone. A first searched area estimation will come from the satellite orbit information. The first terminal points to the supposed position of the remote device using the complete displacement of said satellite or else thanks to a particular pointing unit integrated into the satellite and carrying out a search on two axes. In parallel, a beacon is activated by one or both terminals to inform the remote system of the coarse direction towards which to point the optical beam before starting the communication process. Figure 28 presents different solution for PAT mechanism.

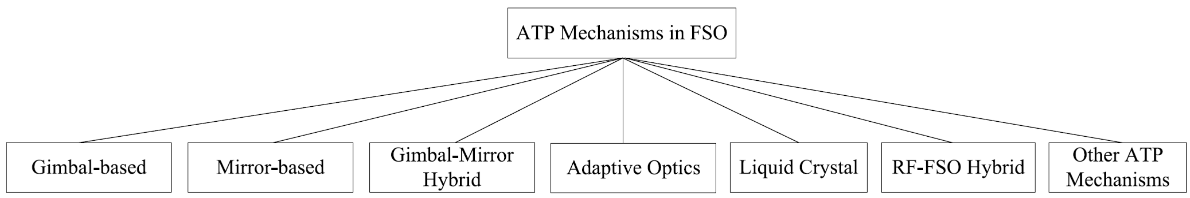


FIGURE 28: CLASSIFICATION OF ACQUISITION, TRACKING, AND POINTING MECHANISMS IN FSO COMMUNICATIONS ACCORDING TO THEIR WORKING PRINCIPLE [28].

For instance, a gimbal-based solution is capable of rotating in most directions to provide a wide pointing range of the incident light beam to the receiving terminal and several alternative technological solutions are provided in ground-to-satellite and satellite-to-satellite communications [27]. Figure 29 shows for instance the gimbal-based solution block diagram of a PAT system.

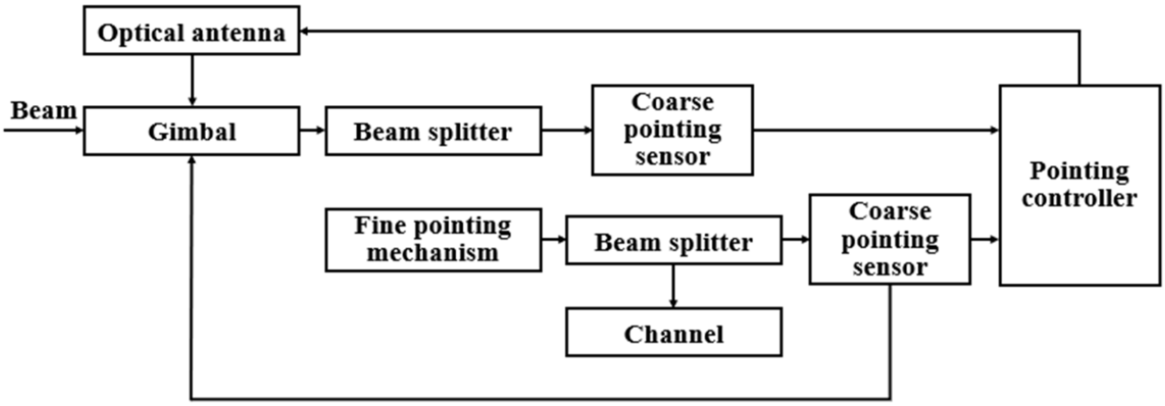


FIGURE 29: PAT BLOCK DIAGRAM [21].

Alternatively, tracking the beacon or the optical communication beam can be done with mirror-based solution as a fast orientation mirror to follow the exact position of the other terminal during their mutual movements.

The main difficulty is an emitted optical beam diameter (beacon) at the receiving terminal much smaller than the reception estimation zone, mainly due to atmospheric disturbances, azimuth or elevation errors, bad mechanical resonances orientation control servo motors, poorly controlled inertial movements, etc. Figure 30 shows an example of an acquisition protocol for a LEO-GEO link.

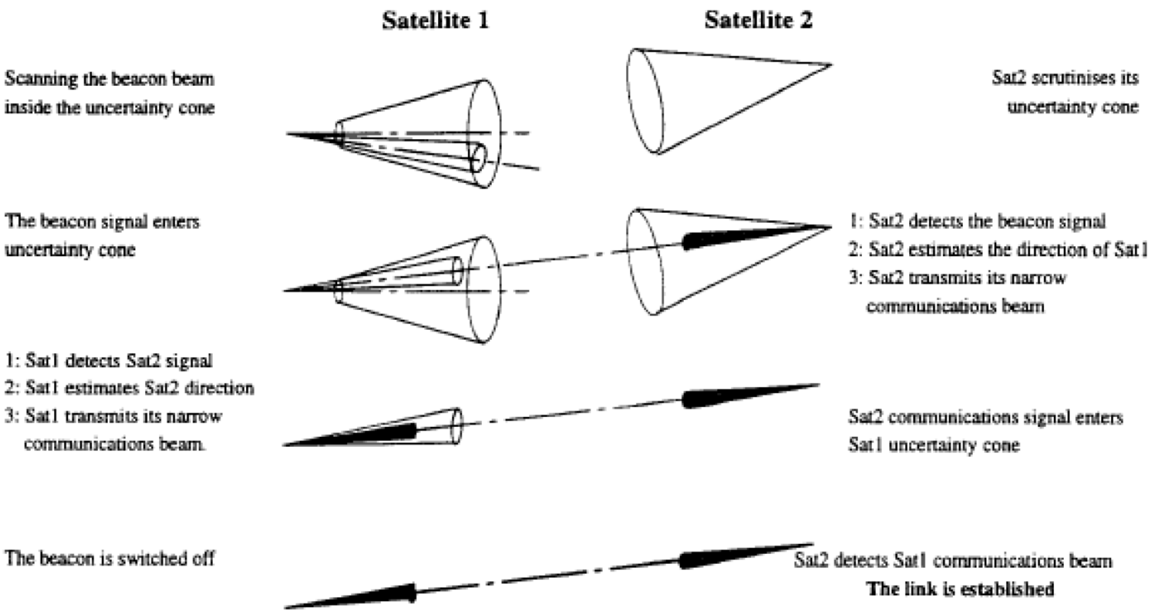


FIGURE 30: EXAMPLE OF THE ACQUISITION PROCEDURE [23].

In this example, a laser emits a beacon to the remote terminal assumed to be in the reception estimation area. It must have a large angular divergence (to minimize the acquisition time) and a high power (from 1 to 20 Watt with Optical Amplifier for instance) to reach large distances. At the same time, the remote terminal uses in reception a detector with a wide Field of View (FoV) whose angle is, in principle, greater than the angle of the estimation zone. This detector can be a CCD camera, for example with a generally low sampling frequency or FPS (Frame Per Second) and high sensitivity to the emitted wavelength spectral band. Generally, this first process for an Optical Inter-Satellite Link (OISL) must be less than 60 seconds including the three phases: Acquisition, Pointing and Tracking (PAT).

For instance, during inter-satellite or inter-orbit optical communication, one scenario considered is that each satellite continuously sends a communication beam to the distant satellite to improve pointing accuracy. This coarse pointing can be performed using a control loop (Frequency around 10 Hz for instance). It is possible to use one or more lasers to generate the signaling beacon, either operating at the communication wavelength, or with different wavelengths. When this acquisition sequence (Acquisition) is finalized, the transmitter switches from coarse pointing mode to fine pointing mode (Pointing). In the case of the fine pointing control loop, the bandwidth should have a higher frequency, order of 1 kHz. This function measures the angular error between the direction of the incoming and outgoing beams and this difference is used as feedback for pointing. There are two types of angle error sensors: CCDs arrays and quadrant photodiodes (QPDs). Depending on the scenario considered, the relative speed of the two terminals which can have very high values, the target is the maximum angular speed that the pointing device is able to reach. When the link is established, the satellites still potentially experience vibrations or misalignments. This leads to a degradation of optical link budget following the elevation and/or azimuth pointing error which is corrected mechanically and/or by software (Tracking). Due to the important role of the PAT system, much work is still undertaken to optimize latency, size, weight, energy consumption and cost.

5.4 STANDARDS

5.4.1 Communication Protocol

First standardized and commercial OWC products was provide thanks to Infrared data association (IrDA) in the 1990s. Then, start in 1997, IEEE 802.11 defined data transmission over infrared spectrum with 2 Mbps data rate but with few commercial products.

In 1999, LEDs interest for communication led to standards in Visible Light Communication (VLC) with IEEE 802.15.7, IEEE 802.15.13, and ITU-T G.9991 (also known as G.vlc). On the other hand, the Japan electronics and information technology industries association (JEITA) published two VLC standards, namely the JEITA CP-1221 and JEITA CP-1222 in 2007. IEEE 802.15.7 2011 revision was proposed by including infrared and near ultraviolet wavelengths (in addition to visible light), and Optical Camera Communications (OCC) specifications for positioning and broadcasting by using led and camera on smartphone.

The IEEE 802.15.7 is an available standard since 2016 with a physical layer (PHY) and medium access control (MAC) sublayer for short-range optical wireless communications (OWC) in optically transparent media using light wavelengths from 190 nanometer (nm) to 10000 nm. The standard can deliver data rates sufficient to support audio and video multimedia services. It also accommodates optical communications for cameras (OCC) where transmitting devices incorporate light-emitting sources and receivers are digital cameras with a lens and image sensor like smartphone device.

The IEEE 802.15.13 Multi-Gigabit/s Optical Wireless Communications Task Group defines a PHY and MAC layer using same wavelengths spectrum band. The standard can deliver data rates up to 10 Gbit/s at distances in the range of 200 meters unrestricted line of sight. It is designed for point-to-point and point-to-multipoint communications. Work on LiFi was continued in 802.15.13 since March 2017. The standard is finalized since 2021, with HHI, pureLifi and ETRI as main actors.

To introduce LiFi to the market, IEEE 802.11 (WiFi) created, in 2017, a new study group, IEEE 802.11bb (TGbb) proposed by HHI, pureLiFi, Oledcomm, Mediopol University and Bims Laboratories. The general scope for this TG is defined by:

- Uplink and downlink operations in 800 nm to 10000 nm band,
- All modes of operation achieve minimum single-link throughput of 10 Mb/s as measured at the MAC data service access point (SAP),
- Interoperability among solid state light sources with different modulation bandwidths.
- Hybrid coordination function (HCF) channel access,
- Overlapping basic service set (OBSS) detection and coexistance,
- Existing power management modes of operation (excluding new modes),
- The project also addresses the security of the transition between the new LC PHY and the existing 802.11 PHYs as well as the security implications in supporting Fast Session Transfer.

In parallel, new products have been proposed based on ITU-T G.vlc standard. This is an high speed indoor communication transceiver with physical layer and data link layer specification. This standard is approved since 2019 and proposed by Huawei, Max linear, Lucibel, Nokia, HHI, CAICT and Signify, mainly for networking wireless indoor communication.

In addition, 6G is currently at the level of discussions by many standardization bodies. Thus, the specification of use cases, technical challenges and potential solutions is not yet finalized. The 3rd Generation Partnership Project (3GPP) has initiated working groups (eg, SA1, SA2, RAN1, RAN2, RAN3) for the integration of satellite access network and Optical Inter satellites Link (O-ISL) into next generation communication technologies. Similarly, the European Telecommunications Standards Institute (ETSI) has launched a working group named SCN TC-SES which works on the integration of drones and satellites. ITU-R is designing key elements for satellite and NTN integration with 5G.

But currently, there is no specific protocol or standard defined for OSC. Given the early stages of development for optical communication systems, both policy and regulatory approaches are still evolving. In the policy realm, there is an initial draft CCSDS Pink Book in process (CCSDS 141.0-P-1.1) with a goal to facilitate interoperability and cross-support between different communication systems. There is also an optical communication Working Group (WG) with NASA and ESA participation.

5.4.2 Regulatory

Up to now, optical frequencies are unregulated, unlike RF systems which require a licensing process to be able to communicate with a spacecraft. Lasercom interference is not currently coordinated by a regulatory body (like the ITU or NTIA in RF) for two major reasons:

- Laser communications is highly directional, which makes interference unlikely, due to the narrow divergence of the transmitting beam and corresponding small beam footprint at the receiver.
- Up to now, the small number of laser communications systems currently deployed doesn't warrant a complex coordination body like ITU.

5.5 PROPAGATION

The main advantages of OSC links face to microwave/radio links are low gain (telescope) antennas, lightweight terminals, highest data rates with low signal strength, no interference with other transmission systems. Another benefit is a wider bandwidth and narrower beamwidth; with positive and negative aspects: if interference and background noise are reduced, unfortunately the pointing acquisition and tracking (APT) system becomes more complex.

Possible applications of free space optical links are ISL in satellite networks, links for deep space missions, links between UAVs, for HAPs and data links from GEO, MEO, LEO satellites to earth ground stations (OGS).

Space applications are divided into free-space optical links in the troposphere (e.g., uplink and downlink between Earth and satellite) and FSO links above the troposphere (e.g., inter-satellite optical links). Links through the troposphere are primarily influenced by weather conditions similar but not equal to terrestrial FSO links. Inter-satellite optical links are not influenced by weather conditions, as the orbits of the satellites are above the atmosphere.

Compared to the propagation of microwave and RF waves, the transmission of an optical wave through the atmosphere suffers from various negative effects. As shown in Figure 31, atmospheric effects can be divided into two main groups: attenuation effects and refractive index effects.

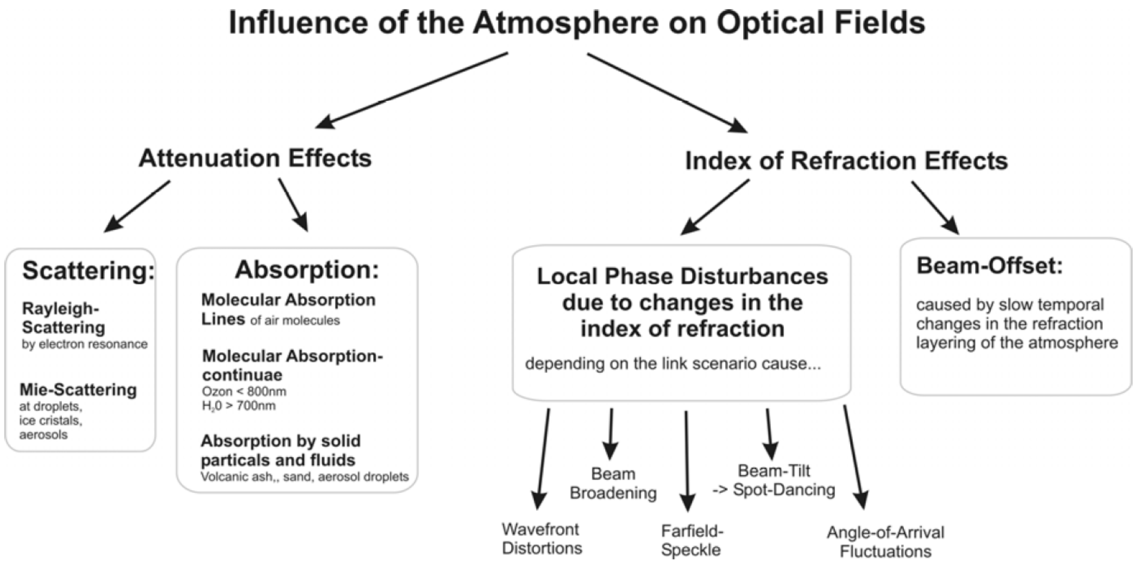


FIGURE 31: OVERVIEW OF ATMOSPHERIC EFFECTS [29].

The level of attenuation effects for a given scenario can be predicted relatively well while variations in refractive index due to turbulence are random and difficult to evaluate. In particular, the different effects of turbulence on the laser beam are:

- Wavefront distortion: successive phase distortions along the path make the beam less and less coherent. Large tilts of the wavefront are called fluctuations in the angle of arrival.
- Beam Broadening: As a result of the deflected light, beam broadening increases the radius of the beam and thus reduces the average intensity.
- Redistribution of the intensity within the beam: the propagation of the deformed wave front leads to destructive and constructive interferences which break the intensity profile of the beam.
- Beam Centroid Wandering: This is caused by turbulent cells larger than the beam radius. The beam is then redirected and drifts on a "medium" optical axis.

Note that for the tropospheric uplink beam, the diameter becomes noticeably wider due to the rapid variation of refractive index with height, causing the optical beam to bend away from the normal. A similar but milder effect is experienced by the tropospheric downlink beam.

Another atmospheric effect related to the refractive index is the beam shift caused by the stratification of the atmosphere. This is especially important for uplinks and downlinks at large zenith angles.

To predict attenuation through the atmosphere, the molecular composition of the atmosphere must be studied and modelled. A strong height dependence of the attenuation can be observed. Regarding the effects of turbulence, several theories have been developed to characterize the distorted beam wave. On the other hand, not all communication systems are equally sensitive to wave distortions. For IM/DD systems, the signal is carried only by optical power and therefore phase distortions are less significant. For coherent systems, however, phase distortions significantly reduce system performance.

Like RF system, the first step is to define a link budget, which determines the quality of the link under certain given weather conditions. For outdoor communication, weather conditions such as fog, clouds, scintillation, snow are more less considering. Due to the distance, atmospheric and molecular attenuations (water, carbon dioxide, ozone molecules) are also having to be taking account with a better deterministic approach. So, the link margin could be mainly expressed by emitted power (Pe), received sensitivity (Sr), power losses in an optical system (Sl: lens, filter…), geometrical/alignment losses (Al), atmospheric loss, etc.

Figure 32 shows an example of 10 Gbps LEO link budget.

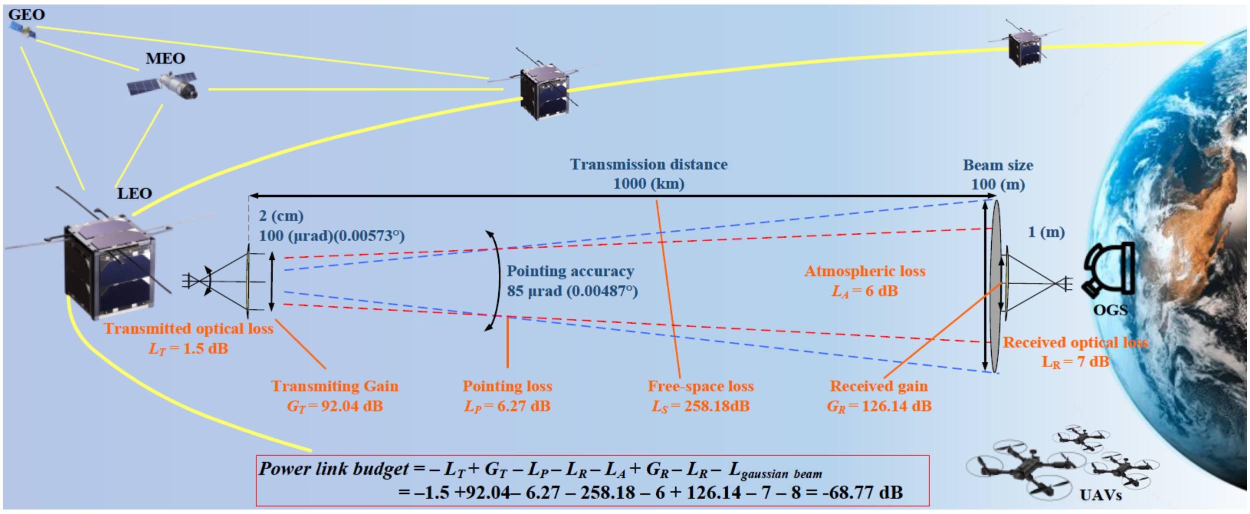


FIGURE 32: LEO LASER OPTICAL COMMUNICATION POWER LINK BUDGET [30].

5.6 QUANTUM COMMUNICATION

Advances in quantum computing offer opportunities far beyond current information and communication technologies, as quantum algorithms could break the security of public-key cryptographic standards currently in use. The operating principle of Quantum Key Distribution (QKD) protocols requires dedicated optical and photonic systems (transmitters and receivers able of generating and measuring quantum states, especially for DV-QKD, Discrete Variable QKD which are very specific). Their technological maturity has steadily increased and continues to increase, and several commercial solutions are available today, at a significant cost. Worldwide efforts are trying to miniaturize this technology to drastically reduce the cost.

Currently, quantum communication can be carried out over optical fibers over a distance that, usually, does not exceed a few hundred kilometers because quantum signals cannot be amplified, and their intensity decreases exponentially and is then disturbed by noise. Use of different concepts of quantum repeaters can improve the range.

A conceptual diagram (Figure 33) of quantum technology platform including future quantum networks is proposed by NICT (Japan), Quantum ICT Collaboration Center.

In comparison to fiber links, free-space links are much more interesting for the loss value versus possible range ratio (Figure 34), so the great interest of space quantum communication segments.

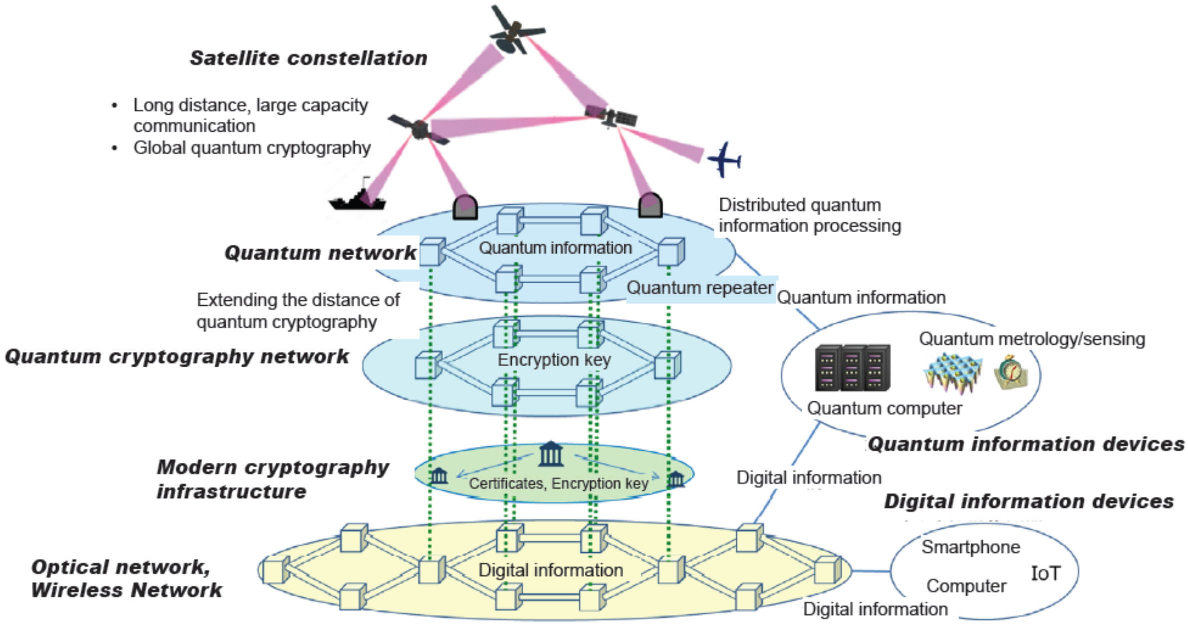


FIGURE 33: GENERAL VIEW OF FUTURE QUANTUM NETWORKS [31].

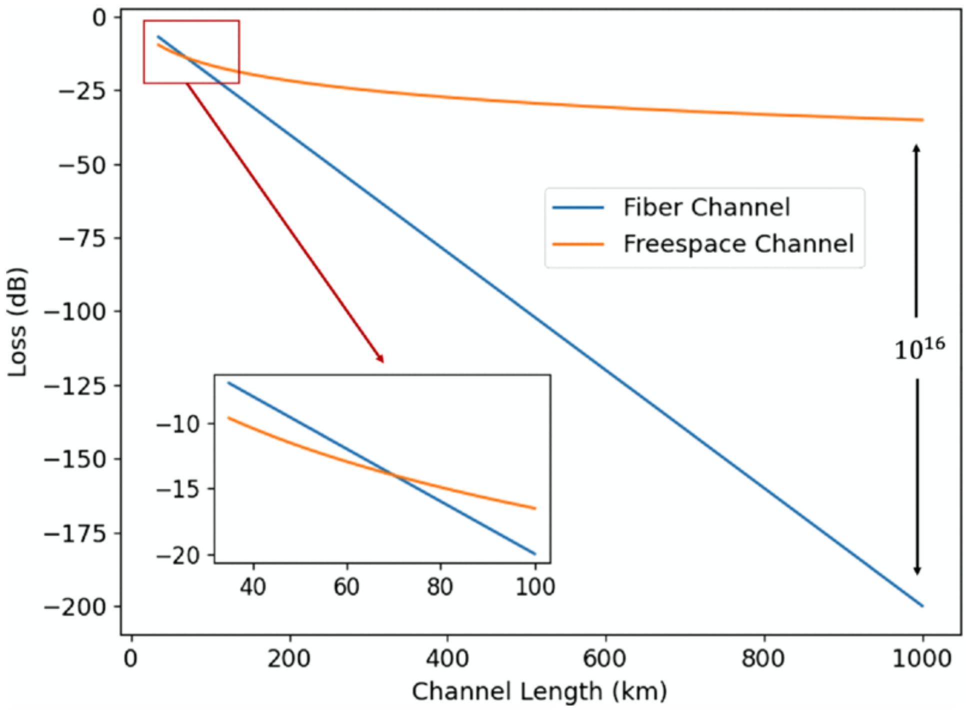


FIGURE 34: TYPICAL LOSSES IN FIBER AND FREE-SPACE CHANNELS [32].

In the field of quantum optical communication by satellite (Sat-QKD), several studies and experiments have been carried out:

- The Matera Laser Ranging Observatory demonstrates sensitivity at the single photon level by exploiting corner retroreflectors mounted on a satellite [33].
- From a mobile platform, the first experiments were carried out with a quantum transmitter installed in an airplane and the receiver installed in the optical ground station Oberpfaffenhofen of the DLR [34].
- Another space-to-ground communication was carried out with SOCRATES satellite (Space Optical Communications Research Advanced Technology Satellite) of NICT (Japan). LEO-to-ground polarization measurements aiming for later space QKD was performed [35].
- The Chinese Academy of Sciences has achieved, with Micius satellite, a QKD downlink with different ground stations allowing the exchange of cryptographic keys between Asia and Europe with entanglement based QKD over 1200 km [36].
- The European Space Agency (ESA) piloted the launch of the SAGA project to prepare the design of the EAGLE-1 QKD satellite.
- And several national aerospace agencies are also undertaking the construction of Sat-QKD demonstrators, for example QUBE (Germany), QEYSSat (Canada), QT Hub (United Kingdom) and SpeQtral (Singapore) [37].

Several protocols exist, such as entanglement based or measurement-device-independent, but the oldest and most widely studied protocol is the BB84 (Prepare-and-Measure - PM) protocol.

However, Sat-QKD terminals must meet the Size, Weight, and Power (SWaP) requirements of satellite platforms. A promising solution for reducing SWaP is the use of integrated photonic chips, which can integrate a complex array of passive and active optical elements (including lasers, phase and amplitude modulators, filters, etc.). A fundamental element is the optic terminal which contains the antenna and the beam steering systems with a modification to accommodate to QKD modules. With respect to the optical budget, the significant transmission loss is related to the divergence of the optical beam (geometric attenuation), then atmospheric scattering and absorption. Coupling, pointing inaccuracy, and internal systems can add losses up to -40dB.

The Sat-QKD operating wavelength should exploit atmospheric transparency windows either in the near infrared band (NIR, around 850 nm), it has slightly higher atmospheric absorption, but with less diffraction losses; or in the C band (around 1550 nm) which makes it possible to use commercial solutions available from conventional fiber optic communication.

Different scenarios are possible for photonic transmission in space constellation configuration (Figure 35).

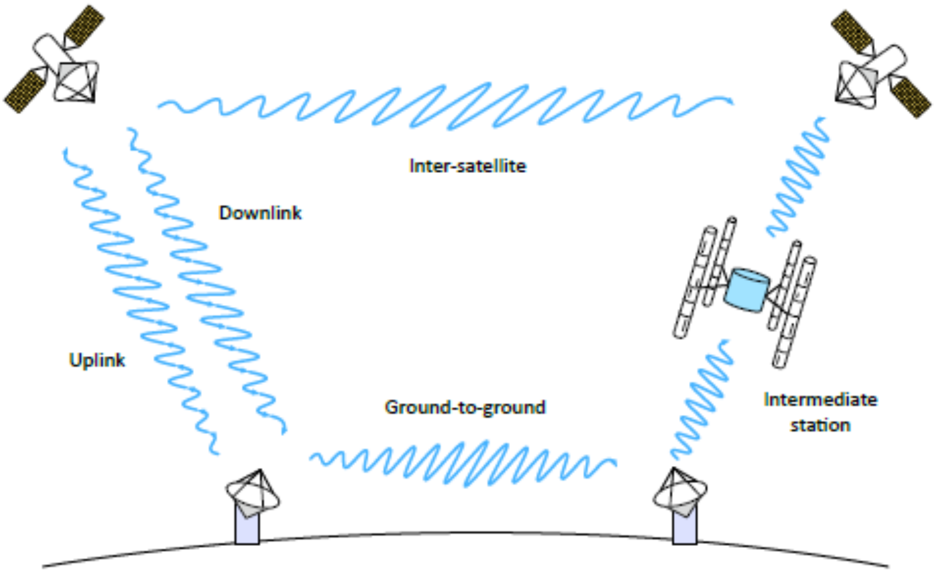


FIGURE 35: OPTICAL QUANTUM COMMUNICATION SCENARIOS [38]

For example, Micius was in downlink scenario and in night-time condition. It is due to lower impact of atmospheric turbulence on the induced broadening and deflection of the light emitted by the satellite at the final part of its path towards receiver. Night operation is preferable to lower background solar light, but is possible only around 30% of the orbit time (around 90 min) for Micius altitude (500 km). Precisely, one-downlink setup was used for QKD and two-downlink setup for entanglement distribution. Moreover, one-uplink setup was tested for quantum teleportation experiment. China also tested QKD from its Tiangong-2 space station [39].

Note that for entangled links between non-line-of-sight ground stations from LEO satellites, a quantum memory will be required, with SwaP requirements especially if cooling is required. Indeed, different quantum memory technologies are already being explored. Terrestrial proof-of-concept tests will be achieved prior to embedded space-qualified modules.

It will be possible to cover different ground stations with inter-linked MEO satellites as depicted in Figure 35.

For use in 5G and beyond NTN situations, the European IRIS^2 project is promising. It will include the EuroQCI initiative space segment with QKD links from specific satellites [40].

5.7 SAFETY

IEC 60825-1 is the main reference applicable for laser safety products (wavelength from 180 nm to 1 mm). In NIR (700 nm − 1400 nm), the predominant consideration is to avoid retinal damage. For wavelengths longer than 1400 nm, the main consideration is to avoid damaging the cornea and the skin, as radiation at those wavelengths is absorbed by water, and the vitreous humor of the eye protects the retina from damage [41]. Several decades of testing and experimentation have made it possible to define several laser classes (from 1 to 4) depending on the uses and applications. The telecommunication products for satellite use cases have no specific restrictions except information class on product.

However, in the US there are three regulatory entities that are concerned with aspects of outdoor laser operations: The FAA, DoD Laser Clearing House (for DoD missions) and the NASA Laser Safety Review Board (for NASA missions).

- FAA coordination is required if potentially harmful laser irradiance is transmitted through navigable airspace. This includes prevention of injury as well as potential distraction of pilots by visible lasers. The FAA will most likely only be concerned about transmitters at ground stations because transmitters on spacecraft are hundreds of miles above the highest-flying aircraft and beam dispersion is large enough that there are usually no safety implications. Missions should coordinate with their local FAA service center to get approval, documented with a “letter of non-objection.”
- The DoD Laser Clearinghouse (LCH) works to ensure that DoD and DoD-sponsored outdoor laser use does not impact orbiting spacecraft or their sensors. That includes both US DoD and foreign assets. LCH and mission operators might enter close cooperation where LCH permits specific laser engagements. The process of coordinating with LCH to get to that point can take many months and should be started as early as possible. However, currently LCH will only engage DoD and DOD-sponsored missions.
- NASA’s Laser Safety Review Board (LSRB) is focused on personnel safety for all outdoor laser operations. NASA missions prepare safety documentation and submit to LSRB for review before launch. LSRB will also verify FAA concurrence. Further information on regulations can be found in ANSI Z136.6 “American National Standard for Safe Use of Lasers Outdoors”.

5.8 OPTIC VERSUS RADIO (RF)

Optical communication by satellite is of increasing interest to researchers and industrials, probably due to several following advantages. Figure 36 seems to indicate the distinctive elements of optical communication compared to RF, i.e., smaller antennas, lighter mass, and lower power.

Link senario	Data rate	Frequency band		
		Optical	Ka-band	Millimeter-band
GEO-LEO				
Antenna dia.	2.5 Gbps	10.2 cm (1.0)	2.2 m (21.6)	1.9 m (18.6)
Mass		65.3 kg (1.0)	152.8 kg (2.3)	131.9 kg (2.0)
Power		93.8 W (1.0)	213.9 W (2.3)	184.7 W (2.0)
GEO-GEO				
Antenna dia.	2.5 Gbps	13.5 cm (1.0)	2.1 m (15.6)	1.8 m (13.3)
Mass		86.4 kg (1.0)	145.8 kg (1.7)	125.0 kg (1.4)
Power		124.2 W (1.0)	204.2 W (1.6)	175.0 W (1.4)
LEO-LEO				
Antenna dia.	2.5 Gbps	3.6 cm (1.0)	0.8 m (22.2)	0.7 m (19.4)
Mass		23.0 kg (1.0)	55.6 kg (2.4)	48.6 kg (2.1)
Power		33.1 W (1.0)	77.8 W (2.3)	68.1 W (2.1)
Moon-satellite				
Antenna dia.	155 Mbps	15.7 cm (1.0)	3.5 m (22.3)	3.2 m (20.4)
Mass		100.5 kg (1.0)	243.1 kg (2.4)	222.2 kg (2.2)
Power		144.4 W (1.0)	340.3 W (2.4)	311.1 W (2.2)

FIGURE 36: OSC AND RF COMMUNICATION SYSTEMS WITH TRANSMIT POWER OF 10, 50, AND 20 W FOR OPTICAL, KA AND MILLIMETER BAND SYSTEMS, RESPECTIVELY (VALUES IN PARENTHESES ARE NORMALIZED TO OPTICAL PARAMETERS) [42].

5.9 OSC USE CASE

5.9.1 Use Case Example

There are many constellations project and programs mainly in Medium Earth Orbit (MEO) and Low Earth Orbit (LEO) which have the advantage of low latency and lower power possibility due to the shorter distance compares to orbiting satellites geostationary terrestrial (GEO). Space-X has launched more than 1,892 LEO satellites since May 2019 to establish a global network of broadband satellites under the Starlink program [43]. Amazon has announced its intention to launch more than 3236 LEO satellites, called Kuiper Systems [44]. Laser Light Communications plans to create a 12-MEO constellation satellite network to reach a total capacity of 7.2 Tbps [45]. Analytical Space uses hybrid RF and optical downlinks to provide high-speed, low-latency data transmissions via the LEO data relay network of nanosatellites [46]. BridgeCom intends to create laser communication services based on a worldwide network of optical earth stations [47]. Kaskilo will create a LEO constellation of 288 satellites and will mainly provide Internet of Things (IoT) service for Industry 4.0 [48]. Huawei plans to build a LEO constellation of 10,000 satellites called Massive VLEO for 6G [49]. Many other missions are planned for CubeSats and micro-satellites like Transcelestial Technologies [50] or Golbriak Space [51].

Applications of space laser communications can be classified into five categories:

1. data download for Earth Orbital missions based on ground-to-satellite links,
2. GEO data relay,
3. wideband satcom using 10 thousand class satellites,
4. all-optical high-speed communications
5. cybersecurity guaranteed by Quantum Key Distribution (QKD) technologies.

Figure 37 shows a summary of OSC link applications.

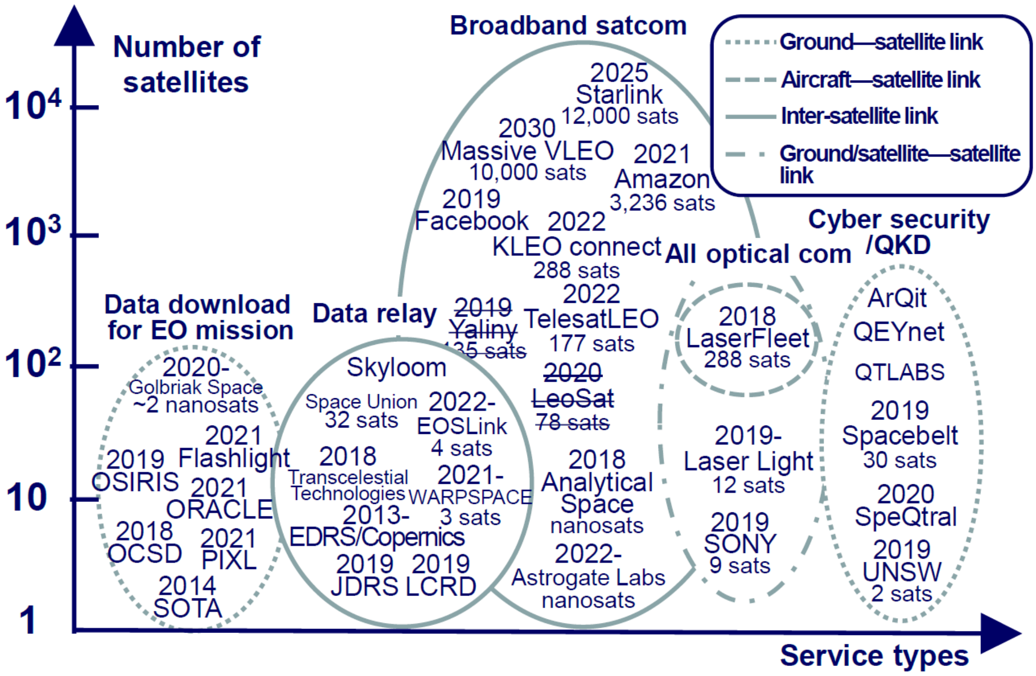


FIGURE 37: APPLICATIONS FOR OSC [17].

5.9.2 Optical Satellite Network

GEO satellites appear stationary to observers on the ground because the satellite rotates synchronously with the Earth. This property makes GEO satellites particularly suitable for communications, streaming or weather monitoring. GEO satellites are attractive because of their coverage as only three satellites can provide global coverage. Optical communications in GEO were primarily developed for data relay from LEO (prime example with ESA EDRS system). New communications satellites may require data rates up to Tbit/s and more for the uplink. Optical links offer this potential throughput with global coverage.

Optical satellite communication has mainly been developed for point-to-point transmission, by LEO links or GEO relays. Radiofrequency satellite networks have been studied for a long time with different constellations in GEO, MEO and LEO [52]. Routing process manages constellation traffic, notifying gateways of traffic congestion or inter-satellite link failures. The design of the switching and monitoring approach between the layers to guarantee a desired QoS (Quality of Service) depends on the number of layers (constellations and satellites per orbit), the number of inter-satellite links and the available throughput. It is now possible to envisage a combination of radiofrequency and optical links to deal with all possible applications.

Optical LEO satellite constellations are available due to short lead times, optimized power budgets and closer distances to MEO and GEO. But the satellite-to-ground pointing accuracy is limited due to the larger pointing angles. Typically, 5 to 10 times greater beam divergence is expected for LEO communications than for GEO. The main disadvantage is therefore a decrease in received power, leading to similar transmitted power requirements for LEO and GEO, with current technologies. This constraint is less during inter-satellite optical communication, but the APT device must be more precise and faster. GEO satellites are more expensive to develop and deploy, due to the greater launch distance and higher radiation requirements. On the other hand, the advantage is wide coverage but less availability due to the properties of the atmosphere.

An optical global network would be a combination of the three orbits (as shown in Figure 38), optimizing QoS and combining several applications.

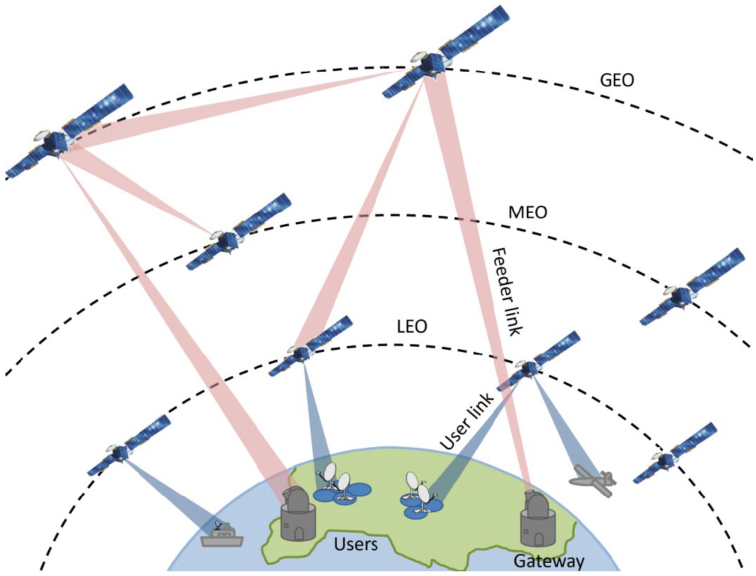


FIGURE 38: OPTICAL SATELLITE-COMMUNICATIONS NETWORK [53].

A system combining variety of applications may need to combine a mesh configuration with constellations of satellites. Figure 39 shows a satellite network concept. The development of ad hoc satellite platforms, for backhauling and switching between the ground and the GEO for example, would make it possible to increase the data rate of the feeder links. In this case, the GEO platform could integrate signal regeneration (error correction algorithms protecting the data through atmospheric turbulence.) and optical switching to other application-oriented satellites (MEO or LEO).

Satellites at shorter distances can be easily connected to optical links with limited power requirements and carrying high data volumes. Other dedicated platforms can connect other GEO nodes over large distances, for instance between Europe and Asia or to LEO constellations. Optical frequencies could be best candidates for such networks because they are more mass and power efficient, also more resistant to interference and this give alternative solution face to RF spectrum bottleneck. However, a combination of optical and RF technologies is required to meet the requirements of such a variety of applications.

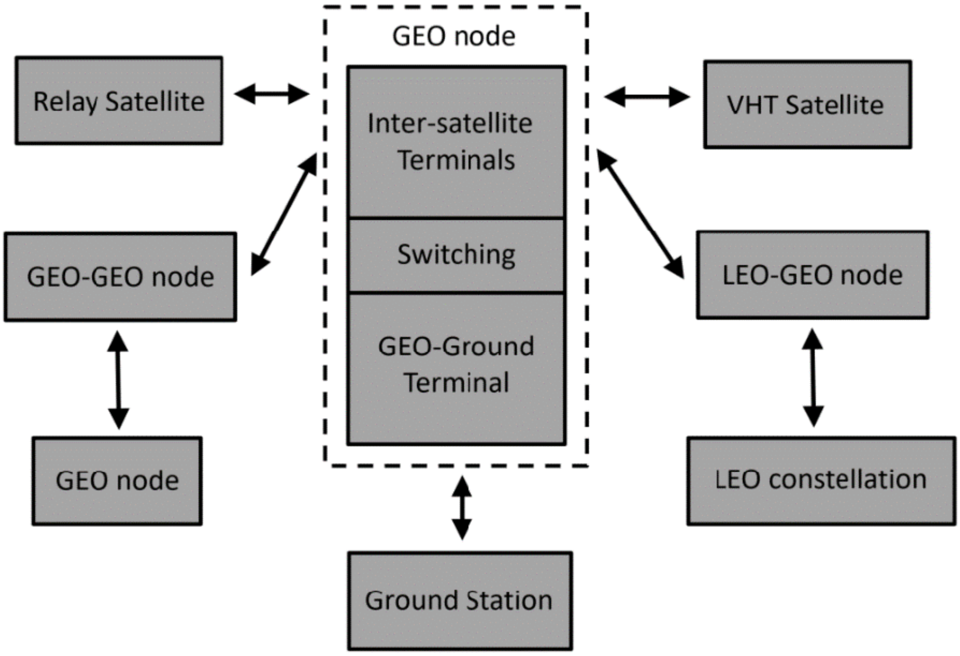


FIGURE 39: CONCEPTUAL BLOCK DIAGRAM FOR AN OPTICAL SATELLITE NETWORK [54].

5.9.3 Space Air Ground Integration Network (SAGIN)

SAGIN concept integrated satellite links, aviation system and ground communication network. SAGIN's vision requires a multi-level approach and includes space, air and ground network elements: a) ground center design, (b) air center design, (c) satellite center design, (d) and SAGIN communication global control center. As shown in Figure 40 this network (or network of networks) is consisting of GEO, MEO, LEO, aerial (airships, UAVs, HAVs) and ground devices (WLAN, LoRan, WiMAX, 4G, 5G…), which makes the integration of whole communication networks possible. Future communication networks target is to build an integrated network framework (SAGIN) and realize the interconnection, complementarity and efficient coordination between Space, Aerial, and ground Network.

- Satellites: It is very likely that several satellites (GEO, MEO and LEO) will use optical beam. Multi-layer satellite (intraplane and interplane) communication must improve service availability and therefore resilience. For this, Acquisition, Pointing, Tracking (APT) functions still need research and study work.
- Aerial: High Altitude Platforms (HAPs) can have an intermediate role and operate seamlessly in continuous collaboration with Low Altitude Platforms (LAPs) such as drones to provide improved latency.
- Ground: Ground communication system is mainly defined by LoRaWan, Wi-Fi and 2G, 3G, 4G, 5G technologies and 6G technology before 2030. Device-to-device connectivity, IoT and peer-to-peer networking are the basis of these solutions.

This integrated network includes the integration of system, terminal, and application, and it help the network layer protocol realize the interconnection (or Interplane and Intraplane switching – for instance by using protocol IEEE 1905 [55] or Ethernet) of the whole network and achieve compatibility between systems. An efficient routing process is essential to achieve effective and low latency communication and work has been done to integrate FSO and optical communication [56] and [57].

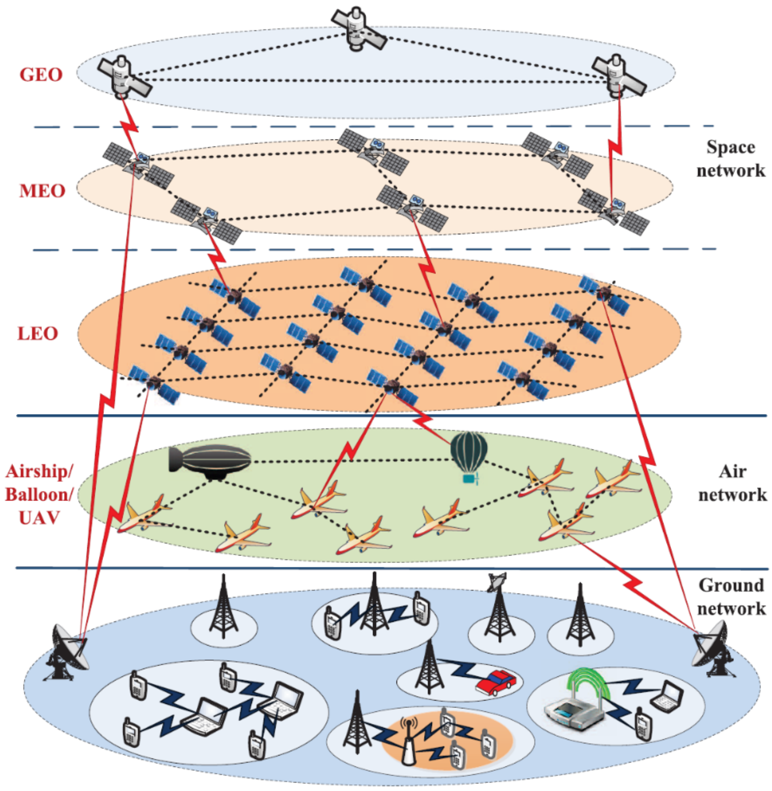


FIGURE 40: SAGIN EXAMPLE [51].

5.10 OSC AND FUTURE TREND

OSC technology development is now on operational phase and due to the laser beam small divergence angle, the current satellite optical communication links are point-to point transmission. Space optical communication, with its advantages of high speed, small size, lightweight and low power consumption, has become an effective approach to high-speed communication between satellites, especially in the application of small satellites. Face to limited onboard resources (payload) for satellite communication systems, optical solutions offer an attractive approach as shown in Figure 41 these potentialities are a low onboard resource need, including energy consumption, in relation to the potential throughput.

Additionally new research area is explored. Such as Quantum key Distribution, QKD is a protocol that shares a secret cryptographic key through entangled photons. Sources and optical front ends have been development for transmitting these keys from small satellite spaceborne platforms [59] and [60].

Deployable Optical Receiver Aperture (DORA) project is developing a OSC 1 Gbps full duplex [61] large apertures in space. The inter-spacecraft optical communicator (ISOC), which includes arrays of fast photodetectors and transmit telescopes to provide full-sky coverage, gigabit data rates and multiple simultaneous links, was initially developed at NASA's Jet Propulsion Laboratory with funding from NASA’s Small Spacecraft Technology (SST) program from 2018 to 2020.

There are also currently several (Inter satellites Optical Communications (ISOC) for short-, mid-, and long-range applications that use appropriate levels of power and aperture size, respectively, to achieve Gb/s data rate [62]. A new O-ISC version is currently developed by

Chascii Inc. for cislunar applications. Major programs, such as European Data Relay System use small satellites in low-Earth orbit is to form an intersatellite link to geosynchronous orbit. NICT (Japan) is looking to establish this type of link with a CubeSat through the CubeSOTA program [63].

In addition to CubeSat terminals, larger terminals for larger SmallSats are under development by Tesat, Mynaric [64], SpaceMicro [65], and SA Photonics.

DARPA has funded the Space-BACN program that seeks to develop a reconfigurable and multi-protocol inter-satellite OSC that can be supported on small satellites.

The use of WDM and coherent detection paves the way for an explosion of capabilities. Thus, to further expand the satellite network with optic solution, it is judicious to look after point-to multipoint or multi point to point solutions with one global protocol and more advanced technologies.

Operator needs will be sensitive to transparent services as envisaged in a SAGIN solution. Services centered around Extremely Enhanced Mobile Broadband (eeMBB), Extremely Reliable Low Latency Communications (eRLLC), and Ultra-Massive Machine Type Communications (umMTC) need to be improved. Augmented Reality (AR) and Virtual Reality (VR) sensitive broadcasts must contend with proactive content caching or high throughput techniques. OSC solution has a card to play.

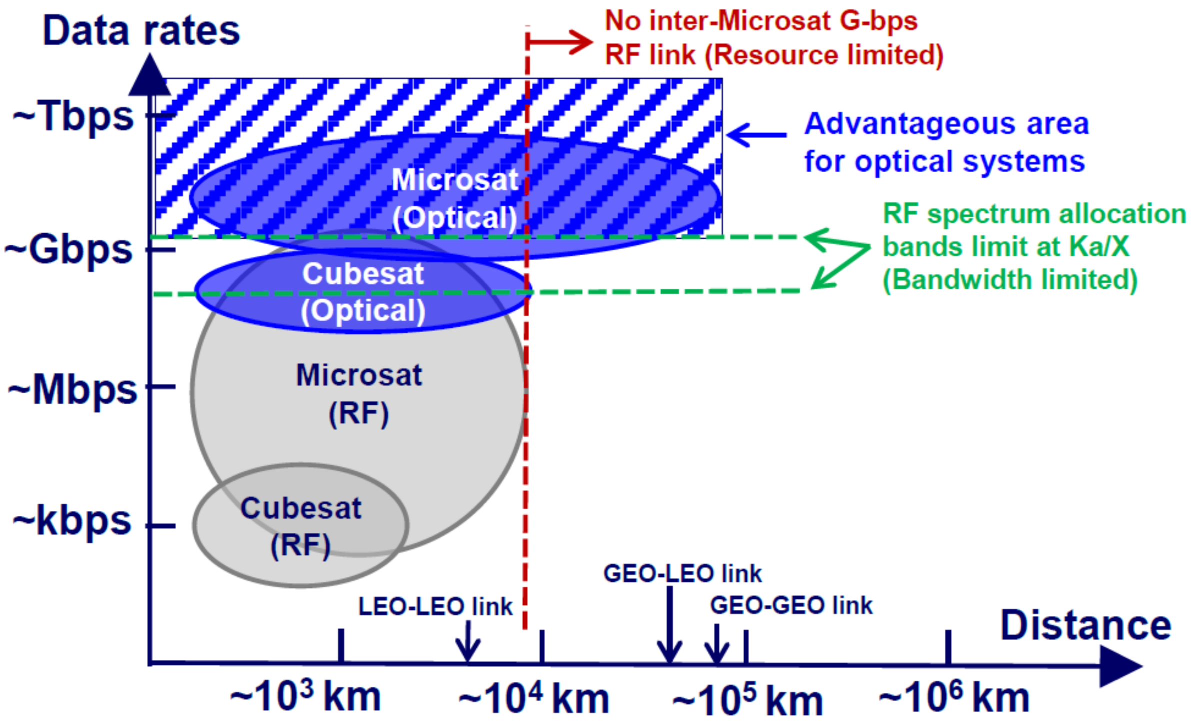


FIGURE 41: OSC POTENTIAL DATA RATE AREA (FOR MICRO-SATELLITES) [17].