RF/Optical High Data Rates Intra/Inter-Orbit Satellites Links in Future NTNs

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***Abstract*—This paper addresses the feasibility, using either RF or optical technology, of high data rates (from 1Gbps to more than 10Gbps) intra-orbit and inter-orbit satellite links in future Non Terrestrial Networks. In the framework of the 3D Non Terrestrial Networks architectures consisting of different aerial nodes, the feasibility of high data rates links among satellites in the same orbits or different orbits enables novel communication architectures able to meet the more and more stringent communication requirements in terms of data rate, latency and service availability. This paper presents some of those architectures and presents a preliminary analysis of the feasibility of RF and/or optical links, highlighting the technological hurdles that must be overcome for each approach.**

***Index Terms*—Inter-satellite links, inter-layer links, multilayer architecture, NTNs, mmwaves/THz, FSO**

I. Introduction

Radio Frequency (RF) Inter Satellite Links (ISLs) have been demonstrated more than 20 years ago. Iridium has been the first constellation for communication purposes designed with ISLs providing a maximum data rate of 25Mbps. At that time, the main reason for using ISLs was the reduction of the ground infrastructure and the higher resilience of the communication system as it is less dependent from the ground infrastructure. Other traditional reasons for using ISLs are: data relay for Earth Observation (EO) satellites, reduction of the latency, formation flying. Traditionally, ISLs have been dominated by RF and microwave technology. Current RF ISL achieve 1–2 Gbps data rates. Optical ISL are starting to be deployed and can offer very high data rates. Examples are the optical ISLs of the European Data Relay Satellite with up to 1.8Gbps over long distances and 5.625Gbps over short distances [1], [2]. However, satellites systems has witnessed an extraordinary evolution in the last 10 years. The role of satellite assets for communication/navigation and sensing is becoming more and more important. 6G will be the standard of the effective integration of terrestrial and not terrestrial networks. 6G foresees a multi-layer communication architecture made of terrestrial nodes and not terrestrial nodes such as Unmanned Aerial Vechicles (UAVs), High Altitude Platforms (HAPs) but also satellites in different orbits (GEO, MEO, LEO and VLEO) [3], [4]. In this framework, both intraorbit and interorbit ISLs could provide many-fold benefits, which enable novel communication architectures. In particular, they provide more degrees of freedom to trade the different communication requirements (coverage, latency etc.) thus contributing to improved communication performance. Moreover, they could enable satellite systems that are more sustainable from the space point of view [5]. However, to bring the above-mentioned benefits, are the currently achievable data rates enough? Is the technology ready? When is it more appropriate to use RF links or optical links?

This paper presents some of the 3D multi-layer architectures Non Terrestrial Networks (NTNs) enabled by the feasibility of high data rates ISLs, also providing some preliminary evaluation of the required data rates. Some link budgets for RF ISLs are shown to verify their feasibility or the need to "fill" some technology gaps. Finally, some considerations on the use of RF and optical links are drawn.

A. Frequency Allocations and Standardization

ISLs can be implemented using either RF or optical technology. Currently, there are no defined standards for ISLs and no regulations for optical technology in space even if some effort is on-going in different space agencies toward RF or optical ISLs. For RF links, the ITU-R regulations specifies the following frequency bands for inter-satellite services as primary services: the K-band, the Ka-band, and the mm-waves bands. Additionally, the footnotes in the ITU-R regulations indicate that other bands allocated to primary services, including the UHF, L-band, S-band, and C-band, can also be used for space-to-space communication. Although Fixed Satellite Service (FSS) connections can include satellite-to-satellite links, this is not explicitly detailed in the allocation tables. One potential solution is to use the bands allocated for industrial, scientific, and medical (ISM) applications. The ISM band corresponding to a fixed-satellite service is 5.725–5.875 GHz.

B. Optical Intra/Inter-orbit links

Intra/Inter-orbits links are a subset of the more general Inter/Intra-X Links (IXLs) part of the NTNs links, which are so far thought to implement the backhaul links, such as the links between the intra and inter-layer of aerial and space network nodes, like Inter-Satellite, inter-HAPS, inter-UAVs, HAPSs-to-satellites, and UAVs-to-satellites. Those links are

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the ISLs and ILLs of the xEO (x Earth Orbit) satellites in the space network, that is GEO-GEO, GEO-MEO, MEO-MEO, MEO-LEO, LEO-LEO, LEO-HAPS (besides the LEO-HAPS links) and the HAPS-HAPS links in the NTN aerial network. When a capacity of at least 10Gbps is needed, optical technology should be used. When these links are realized via Free Space Optics (FSO) technology, they are called Optical Inter/Intra-X Links (OIXLs). FSO technology carries out wireless data transmission using laser lines in the 760–1600 nm part of the Near InfraRed (NIR) spectrum, especially in the C-Band (1530–1565 nm) corresponding to (192–196 THz): indeed, this Terahertz (THz) band is license free and it makes use of Commercial Off-the-Shelf (COTS) components, which are available for Optic Fiber Communications (OFC) for decades. Since these wavelengths are very short, narrow angular beams with high directivity are radiated at the transmitter (TX), so that high SNRs can be detected at the receiver (RX). So, the main advantages of FSO use are: the highest possible relative bandwidths (BWs) and so the highest possible data rates, possibility of extremely high distance ranges, the greatest achievable mobility management, absence of Electromagnetic Interference (EMI), absence of Adjacent Satellite Interference (ASI) and of Adjacent Channel Interference (ACI) phenomena, very low eavesdropping possibilities, that means the most superior data security in the physical layer. On the other hand, the main drawbacks of FSO use are: the physical feasibility of the RX (telescope and Photo-Diode (PD)) and of the TX (Telescope), especially when they are orbiting in the atmosphere and/or in the space, also in relation with Size Weight And Power (SWaP) issues, required to get an adequate Signal to Noise Ratio (SNR) and so an adequate Bit Error Ratio (BER) to set up the link; then pointing, alignment and tracking issues between TX and RX.

II. Novel Architectures enabled by High Data Rates ISLs

A. *Fractioned Satellite for Feeder links in VHTS scenarios*

In Very High Throughput Satellite (VHTS) scenarios, the aggregated capacity on the user link can be very high (close or above 1 Terabit/s). In this context, the feeder link can become the bottleneck. An idea, currently being patented, is using the concept of Fractionation, replacing a traditional satellite that includes both a User Link component and a Feeder link component with a distributed system of N satellites, where one of the satellite deals with the links to the users, while the Feeder Link is handled by several smaller relay Feeder satellites interconnected with the User satellite using high data rate ISLs. These Feeder satellites are orbiting in inclined orbits around the user satellite and are connected to an equivalent number of Ground Gateways.

Fig. 1 shows the considered use case. Under the following assumptions:

- User links (aggregated capacity): 1 Gbps
- Feeder links (aggregated capacity): 100 Gbps
- Number of secondary satellites: 10

the data rate required by the single ISL is 10 Gbps, corresponding to the single feeder link capacity. Assuming a limit

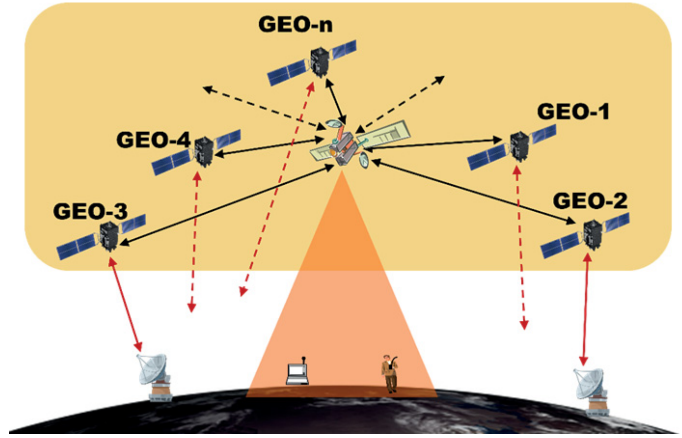

Fig. 1. Fractioned Satellite for Feeder links in VHTS scenarios.

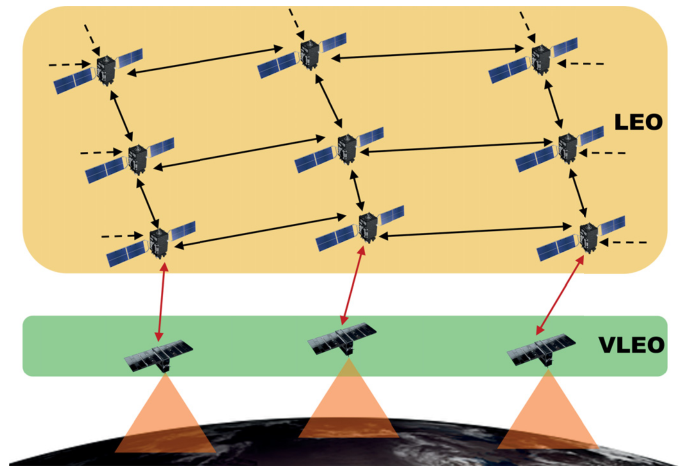

Fig. 2. VLEO-LEO double layered architecture

of 10 Gbps of the ISL in each direction (from User satellite to Feeder satellite and viceversa), the aggregated capacity of the feeder link can be increased by using a higher numbers of Feeder satellites. This architecture is characterized by a much smaller number of gateways compared to a traditional system. Moreover, it has the ability to grow and upgrade the system gradually to meet growing demand.

B. *Multilayer NTN architectures*

Figures 2 and 3 show two double-layered architectures, each one optimizing different constellation and communication design parameters. In both architectures, we assume the typical set of ISLs for the LEO layer that is 4 ISLs, two intra-orbit ISLs (with the previous and the next satellite in the same orbital plane), and two inter-orbit ISLs (with the nearest satellites on two adjacent orbital planes).

Architecture 1 – The architecture shown in Fig. 2 consists of:

- A lower layer made of VLEO satellites (orbit height of around 300 km), whose main role is to provide broadband access to handhelds and to VSAT-like UEs. These satellites will connect via ISLs to the upper layer but will have neither feeder links nor ISLs among them.
- An upper LEO layer made of less satellites implementing the transport network and providing additional processing

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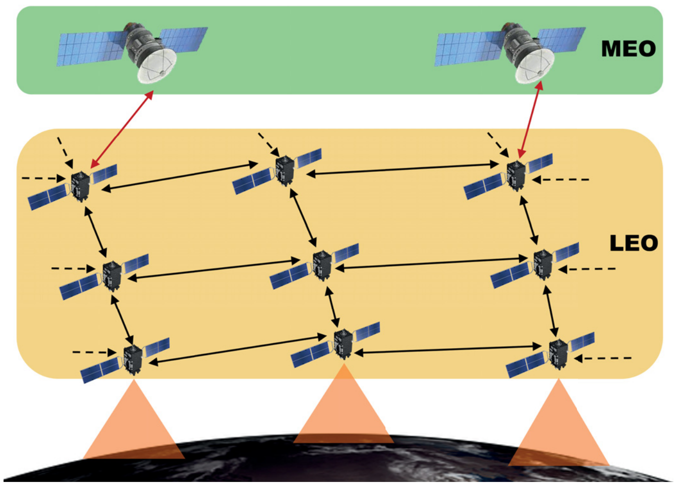

Fig. 3. LEO-MEO double layered architecture

capabilities in space. These satellites will have no direct user links with ground terminals but will be connected to the lower VLEO layer with ISLs. Moreover, they will have feeder links with ground gateway stations.

Therefore, this architecture includes intra-orbit links (between LEO satellites in the same orbit) and inter-orbit links (among VLEO and LEO). Such a two-layer architecture eases the direct satellite connectivity also with small terminals (eventually, directly with smartphones). **Architecture 2** – The architecture shown in Fig.3 consists of:

- A layer made of LEO satellites that provides broadband access to handhelds, to VSAT-like UEs and to 6G ground base stations. These satellites will have both feeder links and ISLs among them. Moreover, they have ISLs toward the upper MEO layer, which is used when the user link (uplink/downlink) and the feeder link (uplink/downlink) are covered by LEO satellite that are connected through many hops. In this case, forwarding the data to the upper MEO layer allows to decrease the additional congestion of LEO ISLs which should be used effectively only when data packets may be delivered through a small number of hops.
- An upper layer made of less satellites in MEO orbit providing data forwarding.

This architecture would help in reducing the number of satellites to provide a given coverage with respect to architecture 1.

C. Cluster constellation-based NTN

Cluster constellation-based NTN (CCB-NTN) is the efficient and effective deployment option regarding spatial diversity (the lack of a direct contact with the ground), scalability on demand (connectivity between one cluster and the next for wide coverage), and ease of maintenance in the event of a node failure. In CCB-NTN, whenever more than one node is required to cover a specific geographic area, a cluster will be formed. Examples include UAVs cluster in the troposphere, HAPSs cluster in the stratosphere, and the satellite cluster in space. A schematic of this architecture is presented in Fig. 4. The master node of a cluster communicates with the nearest cluster master in the intra-layer and in the inter-layer (ground aerial and space network) to minimize the number of ground stations, and point-to-point links. The NTN gateway plays the role of data relay between the NTN and the terrestrial Core Network (CN) to facilitate an unified network coverage.

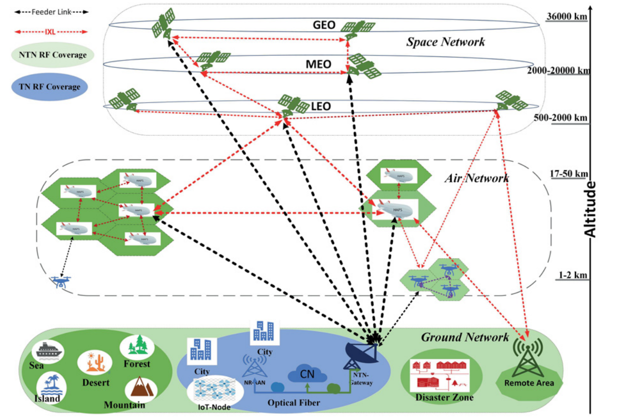

Fig. 4. Cluster Constellation Based-Non Terrestrial Network (CCB-NTN) architecture.

D. ISLs for a more sustainable space

It is becoming more and more clear the need to design future satellite systems having in mind the need to make them sustainable in the long term. Space is extremely crowded and soon it will become a not safe place to operate. Enabling the reuse of already deployed space resources/infrastructure and the effective use of the multilayered NTN architecture can help in designing more space sustainable systems. However, both reusing the space infrastructure and using effectively the multilayer NTN require an extremely high level of flexibility, both at payload level and network level. The flexibility at network level require the implementation of concepts well investigated for terrestrial networks such as Software Defined Networking (SDN) and Network Function Virtualization (NFV). Such a highly softwarized space infrastructure, with many decentralized functions and high level of autonomy will generate higher volumes of signalling and control data will have to be exchanged by network nodes, besides the user data. In this framework, stable and high-throughput ISL and inter-layer links are needed as well as to enabling the reuse of the space resources through the federation of satellites [5].

III. Preliminary Link Budgets for RF V-band ISLs

A link budget analysis has been conducted to identify the average data rate of V-band ISL links for two different ISL scenarios: ISL with a distance of about 5000 km, ISL with a distance of about 2000 km. The first distance could be representative of the fractioned VHTS scenario. Such scenario is characterized by longer connection time between satellites and moderate requirements in terms of steering capabilities and simultaneous connections between constellations elements.

The same scenario could be representative for a LEO-LEO intra-orbit ISLs when the altitude of satellites is 2000km. Table V shows the involved ISL distances for the different LEO satellite altitudes. Then we have considered a second scenario that is characterized by shorter distances, short connection times between satellites and high requirements in terms of links reconfiguration due to fast relative movements of satellite nodes. This scenario could be representative of the VLEO-LEO connection in the architecture 1. Table VI shows the involved distances for different LEO satellite altitudes. The distances has been estimated assuming the satellites in the same orbit and equally spaced. In the link budget, for this second scenario, a distance of 2000km is considered. In this framework, for the first scenario an antenna with a diameter of 0.4 m and an efficiency of 0.65 has been considered, while for the second one a 32x32 patch array antenna is used, with a dimension of about 20x20 cm and a gain of 41 dBi. The latter antenna provides the possibility to create simultaneous beams with high steering capabilities which are needed in a scenario where nodes have fast relative movements. For both scenarios a 60 GHz central frequency has been considered as well as a 15W SSPA. This power level can be achieved using state-of-the-art combined GaN MMIC technology. A receiver noise figure of 4 dB has been used, moreover a pointing error of 0.5 dB has been included in the calculation. Link budget analysis for the two scenarios are reported in Tables I and II.

Link budget		Data
Antenna gain	dBi	46.13
Pointing error	dB	0.5
EIRP	dBW	57.9
Free space loss	dB	201.9
Rx G/T	dB/K	17.5
Carrier to noise power ratio	dBHz	101.62

TABLE I
LINK BUDGET FOR 5000 KM DISTANCE SCENARIO AT 60GHZ.

Link budget		Data
Antenna gain	dBi	41.0
Pointing error	dB	0.5
EIRP	dBW	52.83
Free space loss	dB	194.0
Rx G/T	dB/K	12.4
Carrier to noise power ratio	dBHz	99.31

TABLE II
LINK BUDGET FOR 2000 KM DISTANCE SCENARIO AT 60GHZ.

For what concerns the radio interface, DVB-S2 standard has been considered. An overall available bandwidth of 4,5 GHz has been considered for both scenarios. Tables III and IV reports the useful data rate obtained for the different scenarios. For the first scenario a data rate slightly lower than 5 Gbps can be achieved with a margin higher than 2 dB, while a data rate of about 4 Gbps con be guaranteed for the second scenario with a margin of 1 dB.

For a rough estimate of the involved data rate, let us consider as use case the provision of broadband communications to maritime users (for work and leisure). Improving the quality of life on board when sailing for long distances, but also the provision of commercial services on cruises, requires more advanced communication systems beyond those offered by current satellites or maritime radio. Direct connectivity of handheld to satellites connected to 5G network could be provided, or access through 5G relay nodes. In case of direct connectivity of handheld to satellites, architecture 1 is considered, for indirect connectivity through 5G relay nodes, architecture 2. Table VII shows a rough estimate of the data rates requirements of the considered links for both direct and indirect connectivity.

LB Digital section		Data
Useful rate	Mbps	4850
DVB-S2 ModCod		QPSK 3/5
Spectral efficiency	bits/symb	1.1883
Roll-off		0.1
Occupied bandwidth	MHz	4489
Implementation loss	dB	1
Required Es/N0	dB	2.23
Actual Es/N0	dB	4.41

TABLE III
DATA RATE FOR 5000 KM DISTANCE SCENARIO AT 60GHZ.

LB Digital section		Data
Useful rate	Mbps	4040
DVB-S2 ModCod		QPSK 1/2
Spectral efficiency	bits/symb	0.9889
Roll-off		0.1
Occupied bandwidth	MHz	4493
Implementation loss	dB	1
Required Es/N0	dB	1.0
Actual Es/N0	dB	2.19

TABLE IV
DATA RATE FOR 2000 KM DISTANCE SCENARIO AT 60GHZ.

LEO Altitude (km)	ISL range (km)
600	1567
800	2065
1000	2600
2000	5200

TABLE V
LEO-LEO ISLS DISTANCES

LEO Altitude (km)	ISL range (km)
800	1200
1000	1500
2000	3300

TABLE VI
VLEO-LEO ISLS DISTANCES

Application	User Link	Inter-orbit	Intra-orbit
direct connectivity	1-10 Mbps	VLEO-LEO 1 Gbps	10Gbps
indirect connectivity	100 Mbps	LEO-MEO 1 Gbps	10Gbps

TABLE VII
DATA RATE REQUIREMENTS MARITIME BROADBAND

In both cases, a data rate of the order of 10Gbps would be

required on the involved intra-orbit ISLs while 1Gbps for the inter-layer links.
From the preliminary link budgets we can conclude that the fractioned VHTS scenario is rather challenging for RF links at V-band unless it is possible to foresee a higher number of smaller satellites (to reduce the requirement on the data rate from 10Gpbs to 4.5Gbps). This is also true for intra-orbit links when LEO satellites are at high altitude. On the other hand, the higher flexibility and data rates of RF V-band links are more suitable for the VLEO-LEO links of architecture 1. These are just preliminary considerations strictly related to the state-of-the-art for the antenna and front-end technology.

IV. RF VS OPTICAL FOR DIFFERENT ARCHITECTURES

In case of ISLs, the main concerns related to the use of FSO links, which provides extremely high data rates are related to the pinpoint errors due to the misalignment of the TX and of the RX, which can occur as a result of vibrations, and of imperfect acquisition and tracking due to different relative speeds of two NTN nodes. Therefore, FSO is definitely suitable for high data rate intra-orbit links, or inter-layer links where one of the satellite is a GEO satellite, as the relative position of NTN nodes is rather stable. For inter-orbit satellite links, when LEO or VLEO satellites are involved, given the high velocity of the nodes and the change of the relative positions, the use of RF ISLs rather than optical links could be more suitable, even if lower capacity are attainable. For instance, RF ISLs in V-band based on antenna arrays are extremely suitable for adaptive pointing. In fact, adaptive beamforming techniques may be applied to a planar array of small V-band antennas to follow the movement of the destination or source satellite for both intra-orbit ISLs (LEO-LEO) and inter-orbit ISLs (LEO-MEO or LEO-VLEO). In the context of LEO satellite systems electronic beamforming is a very efficient solution in terms of mass and dimensions w.r.t. mechanical steering (required by FSO links). Moreover, mechanical steering on small satellites has to be balanced by attitude control systems. Furthermore, beamforming techniques may be used to focus the antenna pattern simultaneously in more than one direction, enabling the simultaneously inter-orbit and intra-orbit ISLs. Also for other use cases, to say LEO-UAV in the (NTN) space network and HAPS-UAV, UAV-UAV in the (NTN) aerial network, it is convenient to adopt RF/mmWave technologies. The link budgets of Section III shows that for the fractioned VHTS scenarios, where GEO satellites are involved and data rates higher than 10Gbps are preferable, FSO would be an effective solution. For LEO-LEO intra-orbits links, as they are rather ”stable” links, FSO technology could be suitable. However, when lower altitudes are considered and hence, lower distances are involved, also high data rate RF links are feasible.

V. CONCLUSION

This paper presents a preliminary analysis of high data rates intra-orbit inter-orbit ISLs, which will play an important role in the integrated terrestrial NTNs 3D architecture. ISLs are not only fundamental in data relay scenarios for EO or to reduce the need of ground infrastructure. Novel architectures might be enabled by the feasibility of high data rates ISLs. Some of those architectures are characterized by a lower number of satellites to guarantee the same communication requirements (more space sustainable), or they provide more degrees of freedom to meet the trade-off involved in the design of future communications systems. They might be implemented at high frequency bands (V-W-band or sub-THz) or in FSO. Preliminary links budgets in V-band have been used to make considerations on the use of RF ISLs of the intra/inter-orbit ISLs of the shown architectures. It is worth outlining that the link budgets are based on specific choices on the antennas and front-end technology for the RF links. Further studies are needed considering both the technology evolution in antennas and front-ends for the RF links and the evolution of the systems for the FSO links.

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