6G for Connected Sky
"6G-SKY"

Work Package 4

NTN for terrestrial users

Deliverable 4.1

System architecture and network design aspects for NTN-based communication for terrestrial users

6G-SKY Project
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Abstract

The 6G-SKY initiative aims to enable wireless communication for airborne vehicles and ground components, e.g., base stations (BSs). Along with facilitating connectivity for aerial vehicles, 6G-SKY will prioritize ensuring connectivity for terrestrial users residing in rural areas. The main goal of WP4 is to address NTN specific system aspects focusing on communication for terrestrial users. This deliverable provides an overview of system architecture and network design aspects for NTN-based communication for terrestrial users. The deliverable describes a survey of different approaches to achieve coverage for terrestrial services with NTN, considering aspects including functional split, cloud and edge architecture, integration with TN, etc. We then carry out studies and simulations for each topic and provide feasible solutions for the design of the 6G-NTN. The outcome of the deliverable will be an input for evaluation in Task 4.2 and future studies.

The deliverable first highlights an architecture design regarding a possible RAT functional split option between ground and space. In Chapter 3, we address the challenges regarding cloud native architectures in NTN, including latency tolerance, bandwidth limitation, communication disruptions, scalability, etc. Then we elaborate on the eight split options over the protocol stack defined in 3GPP, and discuss advantages and disadvantages regarding each split option in Chapter 4. An Internet of Remote Things (IoRT) scenario is studied in Chapter 5 where UAVs are used as relay between the IoRT devices and LEO satellites. Another scope of the deliverable is to address the possibilities for coexistence and sharing between TN and NTN. The design aspects are discussed in Chapter 6, focusing on interference and an Internet of Remote Things (IoRT) scenario. Chapter 7 presents spectrum sharing techniques from the state-of-the-art and we provide some insights by having separation in space or time for two systems to mitigate the mutual impact. Sustainability and conclusions are drawn at the end of the deliverable.

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6G-SKY, Work Package 4: NTN for terrestrial users

Task 4.1: NTN specific network design and architecture

System architecture and network design aspects for NTN-based communication for terrestrial users

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Executive Summary

This deliverable explores the initial network design and architecture for 6G NTN to support terrestrial users as part of the 6G-SKY initiative. The deliverable addresses crucial aspects related to the network topology, cloud native architecture, integration possibilities of NTN and TN, and spectrum sharing aspects.

Companies involved in the telecommunications industry can benefit significantly from this deliverable by gaining insights into the recommended system level design for supporting terrestrial users in 6G NTN. This can aid in planning and implementing future telecommunications networks that incorporate 6G technology.

The deliverable concludes that careful planning and execution of 6G NTN design and architecture are necessary to meet the increasing demand for higher data rates, lower latency, and greater reliability for terrestrial users. The integration of cloud-native architectures and edge computing can significantly enhance the performance of 6G NTN for terrestrial coverage. Furthermore, effective spectrum sharing techniques are essential to ensure the coexistence of terrestrial and satellite networks without causing harmful interference to each other.

In summary, this deliverable provides valuable insights into the network design and architecture for 6G NTN to support terrestrial users, which can aid in the planning and implementation of future telecommunications networks that incorporate 6G technology.

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Glossary

List of acronyms with alphabetical order.

Acronym	Description
3GPP	3rd Generation Partnership Project
AMF	Access and Mobility management Function
ASN	combined Airspace & NTN
ATN	Air Traffic Management
BER	Bit Error Rate
BS	Base Station
CP	Cyclic Prefix
CU	Central Unit
CU-CP	CU Control Plane component
CU-UP	CU User Plane component
DL	Downlink
DMRS	Demodulation Reference Signal
DSS	Dynamic Spectrum Sharing
DRL	Deep Reinforcement Learning
DU	Distributed Unit
eCPRI	evolved Common Public Radio Interface
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FL	Feeder Link
FRF	Frequency Reuse Factor
FS	Functional Split
FSO	Free Space Optics
GEO	Geostationary Earth Orbit
GFDM	Generalized Frequency Division Multiplexing
GOPS	Giga Operations Per Seconds
gNB	gNodeB
HAPS	High-altitude Platform Station
HIBS	High Altitude Platform Stations as IMT Base Stations

ICT	Information and Communications Technologies
IAB	Integrated Access and Backhaul
IFFT	Inverse FFT
IoRT	Internet of Remote things
IRC	Interference Rejection Combining
ISI	Inter-Symbol Interference
ISL	Inter-Satellite Link
LEO	Low-Earth Orbit
LLS	Lower-Layer Split
LOS	Line-of-Sight
MAC	Medium Access Control
MEC	Mobile Edge Computing
MEO	Medium Earth Orbit
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MRC	Maximum Ratio Combining
MT	Mobile-Terminated
NFV	Network Functions Virtualization
NTN	Non-terrestrial Network
OFDM	Orthogonal Frequency-Division Multiplexing
O-RAN	Open RAN
OOBE	Out-of-Band Emissions
OTFS	Orthogonal Time-Frequency and Space
PAPR	Peak-to-Average Power Ratio
PDCP	Packet Data Convergence Protocol
PHY	Physical Layer
PRACH	Physical Random Access Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RAT	Radio Access Technology
RE	Resource Element

RIC	RAN Intelligent Controller
RF	Radio Frequency
RLC	Radio Link Control
RRC	Radio Resource Control
RRH	Remote Radio Head
RT	Real Time
RU	Radio Unit
SAGIN	Space-Air Ground Integrated Networks
SDG	Sustainable Development Goal
SDN	Software-Defined Networking
SINR	Signal-to-Interference-plus-Noise Ratio
SL	Service Link
SMO	Support Management and Orchestration
TN	Terrestrial Network
UAM	Urban Air Mobility
UAV	Unmanned Aerial Vehicle
UE	User Equipment
UL	Uplink
UNOOSA	United Nations Office for Outer Space Affairs
UPF	User Plane Function
UTM	Unmanned Traffic Management
VLEO	Very-Low Earth Orbit

1 Introduction

The 6G-SKY project provides wireless connectivity for flying vehicles using high altitude platforms, satellites, and ground elements. It also focuses on providing connectivity for rural areas with varying QoS requirements [1].

This work package will focus on specific system aspects of the NTN, with an emphasis on communication for terrestrial users. Building on the system architecture and link design established in WP1 and WP2, respectively, WP4 will address network design and performance considerations. In this deliverable, we discuss several aspects in 6G NTN design, including functional split options between air and ground, edge and cloud deployment in the NTN network, integration of TN and NTN and spectrum sharing possibilities between the two networks. The deliverable provides comprehensive state-of-the-art analysis for each topic and recommendations based on discussion and simulations.

The concept that terrestrial users will benefit from satellite network is gaining an increasing popularity. In 3GPP Rel-19, there is ongoing efforts to extend the study on 'NR to support NTN' which was initially outlined in Release 18. With the ongoing discussion of 6G network design, vendors and operators tend to build a holistic system for both TN and NTN, opting to share knowledge from each other. However, as 3GPP's historical role is to standardize radio communications such as 4G and 5G, there is an increasing need for the insights from satellite community. This collaborative approach is essential to enhance the design of a holistic architecture and functionalities.

1.1 Objective of the document

The inputs for this work are dependent on the deliverables from both WP1 and WP2, where a holistic architecture for 6G-NTN is presented. The objective of the deliverable is to further define research problems in WP1 and WP2 with a focus on terrestrial users.

The deliverable has two main objectives for the project execution:

- Provide an architecture design of NTN architecture for terrestrial users,
- Define scenarios for the simulation work in Task 4.2.
- Provide surveys in each research topic and provide recommendations for the network design.

1.2 Structure of the document

The deliverable is organized as follows. In Chapter 2, we summarize the main findings regarding system architecture design aspects. The results serve as a primary understanding of NTN architecture design. In Chapter 3, we discuss the cloud native and edge computing aspects considering NTN architecture. We present literature review and standardization in 3GPP regarding RAT functional split options in Chapter 4. Strategies for functional split are compared and recommendations are made. Then, an IoRT scenario is described in Chapter 5 where UAVs are used to cope with the degradation in backhaul link. Chapter 6 focuses on an interference study where the state-of-the-art is presented. We also compare two interference mitigation algorithms by utilizing multiple-antenna features on the satellite side for UL interference cancellation. An IoRT scenario is also considered with the aim of data collection with optimized UAV trajectories. In Chapter 7, we highlight the spectrum sharing aspects and discuss the possibilities to have separation in space and time for the two networks. Chapter 8 addresses sustainability and Chapter 9 summarizes the deliverable.

2 System architecture for NTN-based communication for TN users

One main contribution in D4.1 regarding architecture design is to explore the RAT functional split options between ground and space. The study is based on the 5G architecture and assume that 6G may be compatible with existing RAN and core network infrastructures. Options such as transparent architecture, RRH on board, DU on board, DU/CU-UP on board and full gNB on board are compared with several metrics. Regarding the functional split design, among the potential options for 6G architecture, the RRH on board and the gNB on board appear to be the most promising. It is probable that a variation of a lower layer split for the RRH on board and a version of the N2/N3 interfaces for the gNB on board will be incorporated into the 6G architecture concept. These options offer promising solutions for the integration of onboard communication technologies and may provide a solid foundation for the development of efficient and effective 6G networks. Therefore, it is suggested to prioritize these architectures in all future works in this project. A complete summary of all the main pros and cons of each studied function split option can be found in Table 1.

Table 1 Summary of pros and cons of all studied function split options. Colors represent the foreseen effort to solve each issue (green=no effort, yellow=minor effort, red=major effort)

	Dynamic function relationships	Transport aspects	Capacity / performance	HW/SW impact on satellites	Standard impact	Notes
Transparent	Up to satellite operator	Satellite RF techniques (outside 3GPP)	Difficult to scale (outside 3GPP)	Similar to bent-pipe	No impact	Unclear interest to launch this architecture
RRH on board	RRH-DU dynamic association to be implemented in LLS	Extension of LLS routing for multi-hop	Depends on the actual LLS for NTN (influenced by # of served cells plus UE-specific CP/UP traffic), overall difficult to scale	Minimal	No functional split impact	LLS Multi-hop could be a deployment aspect (outside 3GPP)
DU on board	Dynamic association donor-IAB DUs in Rel-18 scope for IAB	BAP mobility enhancements in Rel-18 scope for IAB	User traffic + cell-related control traffic	Moderate (RRH + DU, but not IAB-MT on board)	- Depends on Rel. 18 IAB outcomes - Adaptation to make BAP works with satellite L3/L2 solutions	Requires IAB-enabled DUs and non-legacy UEs acting as IAB MT (currently

						not deployed)
DU/CU-UP on board	- Dynamic association of DU/CU-UP with CU-CP - Handling of dynamic DU/CU-UP configurations	- DU/CU-UP IP addresses visible to the ground system - Multi-hop via satellite L3-L1	Control plane traffic (DU <-> CU-CP, CU-UP <-> CU-CP, RRC, NAS) and function config. + actual N3 user traffic	Same as DU on board + CP-UP UE Context (scale with # of UEs)	Impact to E1/F1-C and their L3 to support dynamic association/cfg	Unclear benefits of having CU-UP closer to the UE if CU-CP is on the ground
gNB on board	- Dynamic gNB association to AMF - Handling of dynamic gNB configurations	- gNB IP address visible to the ground system - Multi-hop via satellite L3-L1	Control plane traffic (NAS, RAN <-> CN) + actual N3 user traffic	Full gNB	Impact to N2 and their L3 to support dynamic association/cfg	May require new standard solutions for handling gNB mobility

3 Cloud native and edge computing

Cloud native architecture refers to the design of software applications that are built specifically to run on cloud platforms which is transforming communication networks for converged network or edge cloud service provisioning platform by leveraging network virtualization and softwarization with a service-oriented architecture [2]. Cloud-native applications are typically composed of small, independent services that work together to provide a larger application. These services are designed to be scalable, resilient, and fault tolerant.

Edge computing refers to the processing and analysis of data at the edge of a network, closer to the source of the data [3], [4]. This approach contrasts with traditional cloud computing, where data is processed in centralized data centers, i.e., it is a decentralized cloud with cloud computing capabilities at the network edge [2].

3.1 Challenges of cloud native architectures in NTN

The cloud native architectures in NTN such as satellite or other space-based networks, usually have unique challenges which are distinct from the traditional terrestrial cloud architectures [4]. One of the most obvious challenges is the latency tolerance. NTN networks often experience higher latencies in communication due to the longer distances. Limited bandwidth is also a challenge in which the NTN should be able to support for. Space-based networks can face communication disruptions due to interference, space weather, frequent handovers (in case of LEO satellite), or satellite positioning issues. Cloud-native applications must be resilient and capable of handling intermittent connectivity.

Scalability is yet another crucial challenge in NTN where adding or replacing satellites can be a complex and expensive process. Security is a significant concern especially when the data is transmitted through space for longer distances. Satellites may have limited power resources, which impact the performance of cloud-native applications. Optimization of power to increase its efficiency is crucial. Keeping cloud-native software up to date and maintaining it remotely in space can be logistically challenging. Automated software updates and maintenance processes need to be robust.

3.2 Edge computing in NTN-based communication

By bringing computational resources closer to the edge of the network, mobile edge computing (MEC) can reduce latency, improve user experience and save energy, etc. This is particularly useful for computationally demanding services or in scenarios where local devices have limited or no computing capabilities. LEO satellites are capable of reaching places where cables cannot, ensuring ubiquitous and continuous service in NTN. However, due to the large propagation loss and limited energy capacity of ground devices, directly connecting them to the LEO satellites is often impractical. With its high mobility and larger transmit power, unmanned aerial vehicles (UAVs) can build much better connections with both the ground devices (by approaching each of them in proper order) and LEO satellites (by transmitting with larger power). Therefore, the integration of MEC and Space-Air-Ground Integrated Networks (SAGIN) provides a promising complement to terrestrial users, especially in remote and depopulated areas. Note that, unlike MEC in terrestrial networks where edge nodes are typically situated at base stations or local data centers, in NTN, edge nodes are located on satellites orbiting in space. As a result, MEC in NTN faces higher latency due to the extended signal travel distance to and from satellites in orbit. Additionally, the channel between ground devices and space-based edge nodes exhibits distinct characteristics compared to terrestrial networks. Therefore, there is a need for a proper channel model that is specifically designed for space-based edge computing. This modeling takes into account the peculiarities of signal propagation, signal strength, and dynamics in the space environment, which are significantly different from the characteristics of terrestrial channels.

Deep Reinforcement Learning (DRL) has demonstrated its efficacy in solving complex problems that are not easily tackled using conventional optimization techniques. The dynamic nature of SAGIN caused by the movement of the UAV and satellites poses additional challenges in finding an optimized solution. DRL can continuously learn and update based on new experiences, allowing them to adapt to changing environments and improve performance over time. This advantage of DRL make it an excellent solution for tackling the challenges in SAGIN.

3.3 Conclusions

In conclusion, the convergence of cloud-native architecture and edge computing is revolutionizing communication networks, especially in non-terrestrial networks (NTN) such as satellite-based systems. However, implementing these innovations in NTN comes with a unique set of challenges. The need to address latency tolerance, limited bandwidth, communication disruptions, scalability, security, power constraints, and maintenance in the space environment poses significant technical and logistical hurdles. These challenges require innovative solutions and a multidisciplinary approach.

4 RAT functional split between ground and space

The disaggregation of the RAN introduces novel architectural possibilities that can be integrated into the terrestrial spatial ecosystem. Furthermore, the telecom operators want to open these interfaces between the logical nodes of the RAN to achieve multi-vendor interoperability. Due to this open RAN (O-RAN), there is an additional fronthaul/midhaul transport technology involved other than backhaul transport technology. A functional split (FS) divides the baseband processing functions between the entities. 3GPP and Small Cell Forum (SCF) have standardized several split options numbered from 1 to 8 as shown in Figure 1(a). Each FS decision has a different capability of service that they can provide. The FS decision will be affected based on the different requirements of the users, constraints due to the network architecture, and limitations of resources at each node [4] [5].

4.1 State of the art/literature review

The RAN architecture evolves with different generations of mobile communication technologies and forms an indispensable component of the mobile network architecture. The main component of the RAN infrastructure is the base station, which includes a Radio Frequency unit and a baseband unit. Functional splitting is one of the key enablers for 5G networks. It supports different setups such as Centralized RAN (C-RAN), virtualized RAN (vRAN), and the recent O-RAN.

The advancement towards cloud-native networks has led to centralizing the baseband processing of radio signals. There is a trade-off between the advantages of RAN centralization (energy efficiency, power cost reduction, and the cost of the fronthaul) and the complexity of carrying traffic between the data processing unit and distributed antennas [6]. The vRAN is split into a distributed unit (DU) and a centralized unit (CU), based on where the split is considered. The DU node will include a certain sub-set of gNB functionalities that are usually close to the end user, which may be placed on the satellite. The Radio unit (RU) completes the whole RAN protocol stack performing radio frequency (RF) related functions as shown in Figure 1(b). To indicate that the interfaces of the RAN are open, “O” is prepended to each terminology. The higher layer (Layer 3) functions like RRC and PDCP are hosted in O-CU. Middle layer (Layer 2) and low layer (Layer 1) functions like RLC, MAC, and some PHY (based on the FS) are hosted in O-DU. Some PHY layer (based on the FS) functions and RF functions are hosted in O-RU.

Since it is expected that satellite payloads will become regenerative in the coming years, 3GPP Release 19 is expected to support regenerative architectures. A satellite with a regenerative payload is expected to have the required computational capabilities that will enable the satellite to host the radio signal processing unit on board. In Release 19, the functionalities of a regenerative payload are being discussed, whether it will be a full gNB or only the DU part of the split gNB on board.

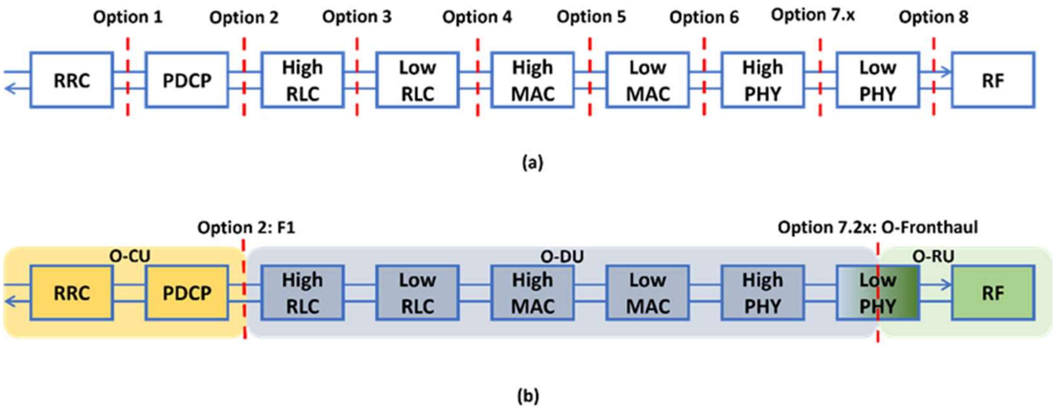

Figure 1(a) 3GPP FS options; (b) O-RAN FSs and interfaces

Several different functional splits are currently being investigated to be used for NR. From the 8 split options defined by 3GPP only split option 2 has been considered and standardized. The F1 interface, between PDCP and RLC layers, is standardized over this split option 2. On the other hand, O-RAN has specified a new split option on the physical layer 7.2x as shown in Figure 1(b), which is different from options 7.1, 7.2, and 7.3 defined by 3GPP as shown in Figure 1(a) and Figure 2.

The idea of splitting functions across the NTN is as follows:

Split Option 8: This split option is defined between the RF and the PHY layer, where only the RU functions like RF sampler and upconverter are placed on the NTN entity (i.e., satellite) resulting in a very simple unit, which supports different Radio Access Technologies (RATs) [6].

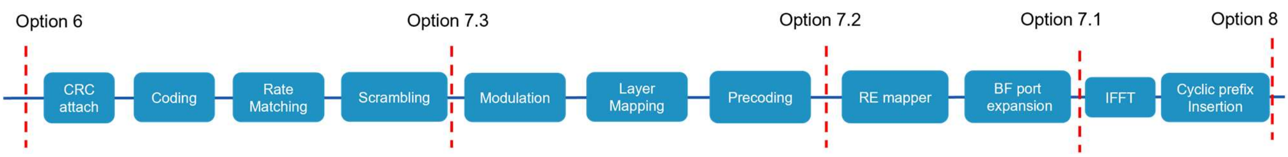

Figure 2 Physical Layer functions

Split Option 7.1: This split option is defined between the digital beamforming/ Resource Element (RE) mapping and the inverse fast Fourier transform (IFFT) operation in the DL as shown in Figure 2, where the IFFT, the cyclic prefix (CP), and the analog beamforming are performed with RU onboard satellite along with above mentioned PHY layer functionalities and the rest of the upper layer functions are placed on the ground. In the UL, this interface is defined between the fast Fourier transform (FFT) and the RE de-mapping. Additionally, PRACH filtering is performed on satellite as well.

Split Option 7.2x: This split option is defined by the O-RAN alliance, and contrary to 3GPP definition of low-PHY and high-PHY split options (options 7.1, 7.2, and 7.3), it is defined between the RU and the DU as shown in Figure 1(b), where depending on the category of the RU, the pre-coding is or is not included on the RU (onboard the satellite) and DU is on ground. This split option is defined between the resource element (RE) mapping (on DU as per O-RAN definition) and the pre-coding/beamforming functions. When compared to split option 7.1, this option has the beamforming performed on the RU side, which is equivalent to DU in 3GPP definitions.

Split Option 7.2: This split option is defined by 3GPP, and it is defined between the precoding and the RE mapping as shown in Figure 2. Both the beamforming and the RE mapping functionalities are co-located with the DU on the ground. There are ongoing discussions on whether to include the precoding on the DU. Including both the precoding and the RE mapping in the DU has many advantages when it comes to the fronthaul bit rate requirements and multi-connectivity support. This split option keeps the FEC inside the CU-pool which is a benefit for the close cooperation between the forward error correction (FEC) and the MAC [6].

Split Option 7.3: This split option is defined between the coding stage and the modulation as shown in Figure 2. Compared to split option 7.2, it includes the precoding, layer mapping and modulation on the ground DU along with CU. It is worth mentioning that precoding could be included in the DU in split option 7.2 as already mentioned.

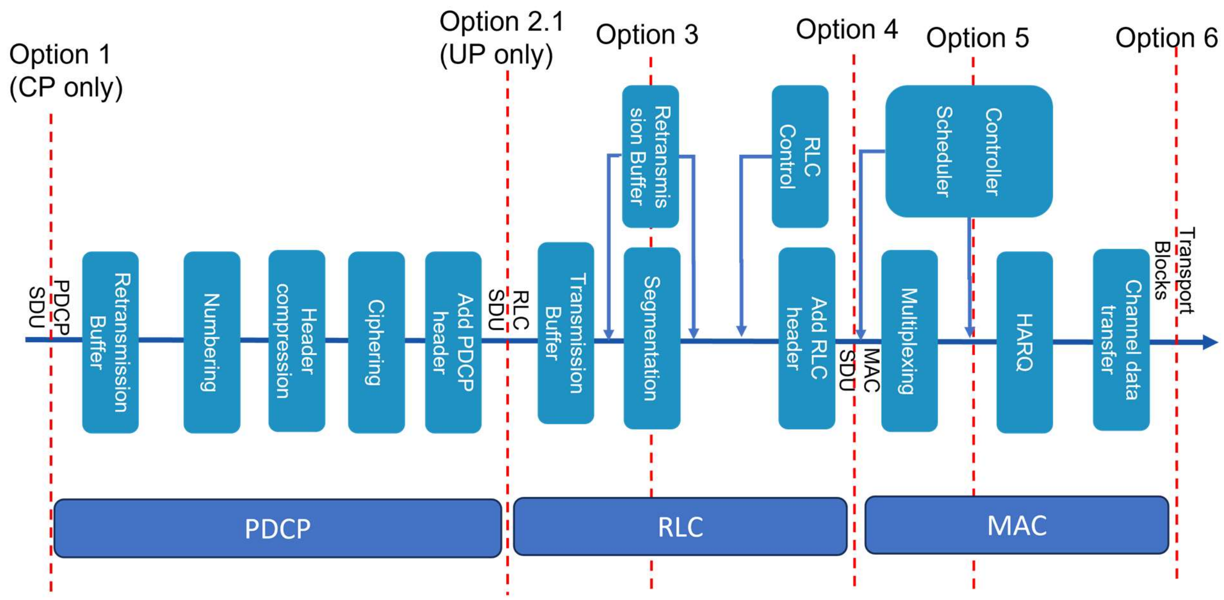

Figure 3 Higher Layer functions

Split Option 6: This split option is defined between the MAC and PHY, where all PHY functionalities are performed by a part of DU onboard the satellite.

Split Option 5: This split option is defined between the lower MAC and the higher MAC as shown in Figure 3, where the MAC time-critical functionalities such as HARQ are performed by part of DU onboard the satellite. In this split, an overall scheduler is centralized in the CU, and a MAC sublayer is local in each DU to handle time critical processing. From this split and below, the time critical procedures in the HARQ are performed locally in the DU, and also the functions where performance is proportional to latency [6].

Split Option 4: This split option is defined between the MAC and the radio link layer (RLC) as shown in Figure 3, where the PHY and the MAC functionalities are performed by the part of DU onboard the satellite.

Split Option 3: This split option is defined between the low RLC and the high RLC as shown in Figure 3, where the low RLC functionalities such as segmentation are performed by the part of the DU onboard the satellite. The UP processing of PDCP and asynchronous RLC processing takes place at the CU on ground. All other UP functions remain in the DU including synchronous RLC network functions [6].

Split Option 2: This split option is defined between the RLC and the PDCP as shown in Figure 3. This is the only option that is considered in 3GPP up to now where the complete DU is onboard the satellite along with RU and CU is centralized on the ground.

Split Option 1: This split option is defined between the PDCP and the RRC for the control plane and between the PDCP and the SDAP for the user plane.

It is important to highlight that the RRC layer is in fact distributed across the protocol stack as each functionality is configured and controlled by this layer. Therefore, each split option will also result in a split of the RRC layer. Specifically with split option 2 decisions regarding MAC and PHY, typically related to the cell configuration, are taken in the DU, while decisions on higher layer configurations are taken in the CU. As a result, some of these decisions are taken sub-optimally because neither the CU nor the DU has all the information available by design (i.e., each unit does not share information with the other because of the separation of concerns implied by the functional split and in fact F1 interface does not support the sharing of such information).

4.2 Recommended functional split options

We consider a system model where there is a LEO satellite serving the ground users and a baseband FS decision is taken for each user. Accordingly, the FS happens between satellite and ground station as shown in Figure 4. The objective of the problem is to minimize the total power consumption of the network which includes satellites and a ground station. The FS decision impacts the power consumption in terms of computational/processing power which in turn affects the total power consumption. Usually, the computational/processing power consumption trend decreases as we increase the FS due to more centralization of the functions. To solve this problem, firstly we need to study what are feasible FS options that can be used.

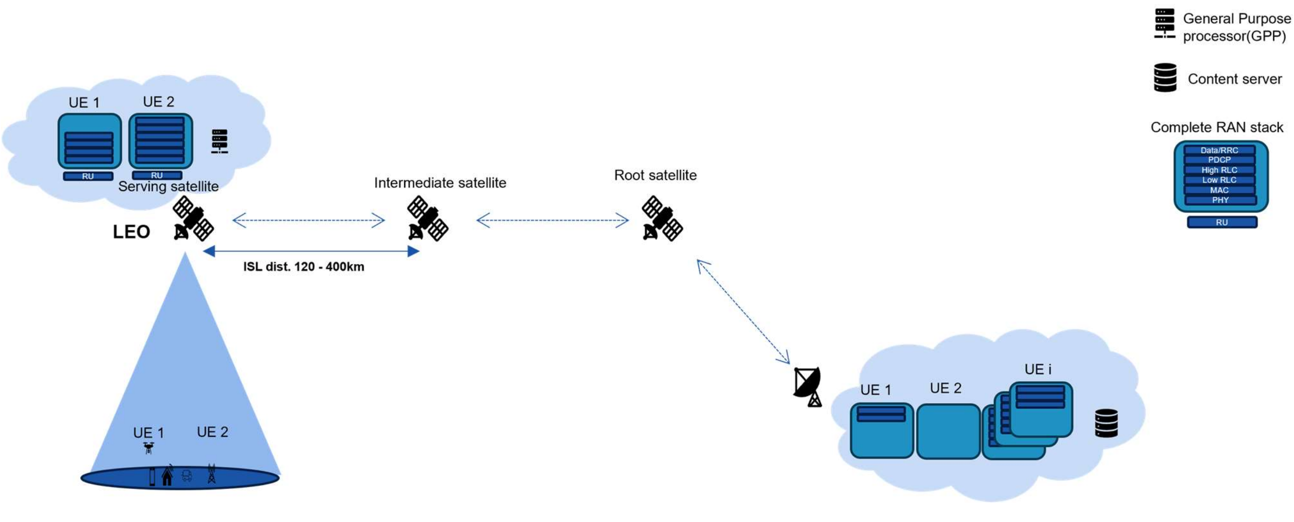

Figure 4 System Model

The distance between the satellite and the ground station restricts some of the FS to be infeasible because they fail to satisfy the stringent fronthaul latency requirement specified by some standardizations like 3GPP [7] and SCF [8]. The fronthaul latency specifications in both standards are meant for LTE terrestrial networks and might not be used for NTN. However, we did the study assuming that it can be scaled to NTN and thereby analyze the feasibility of different FS options by calculating the maximum fronthaul distance. We did an initial study where we can see the feasible split options for a serving LEO satellite, corresponding maximum fronthaul distance and required computational resources, i.e., Giga Operations Per Seconds (GOPS) [9], at both the satellite and the ground station as shown in Table 2. We can see that latency constraints are much more relaxed in SCF specifications than in 3GPP. As the FS increases, the latency becomes stringent in both standards.

Table 2 Fronthaul latency constraints and corresponding maximum fronthaul separation distance. Colors represent the feasibility of the FS between the satellite and the ground station (green=Feasible, orange=Feasible when the latency is not stringent, red=Not feasible).

FS option	One way latency specifications		Max. Fronthaul distance in free space		Processing requirements [9]	
	3GPP [7]	Small cell forum² [8]	3GPP [7]	Small cell forum [8]	Towards CU (Ground)	Towards RU (Satellite)
1 – { RRC-PDCP }	10ms	Non-ideal-30ms	3000km	9000km	< 8GOPS	>36.5GOPS
2 – { PDCP - RLC }	1.5~10ms	Non-ideal-30ms	450-3000km	9000km	< 8GOPS	>36.5GOPS
3 – { hRLC - lRLC }	1.5~10ms	Non-ideal-30ms	450-3000km	9000km	< 8GOPS	>36.5GOPS
4 – { RLC - MAC }	~0.1-1ms	Sub ideal-6ms	30-300km	1800km	< 8GOPS	>36.5GOPS
5 – { hMAC - lMAC }	~0.1-1ms	Sub ideal-6ms	30-300km	1800km	< 8GOPS	>36.5GOPS
6 – { MAC - PHY }	0.25 ms	Near ideal-2ms	75km	600km	8GOPS	36.5GOPS
7.3 – { hPHY - lPHY }	0.25 ms	Near ideal- 2ms Ideal-0.25ms	75km	600km 75km	15.9GOPS	28.6GOPS
7.2 – { hPHY - lPHY }	0.25 ms	Near ideal- 2ms Ideal-0.25ms	75km	600km 75km	18.5GOPS	26GOPS

7.1 – { hPHY - lPHY }	0.25 ms	Near ideal- 2ms Ideal- 0.25ms	75km	600km 75km	19.8GOPS	24.7GOPS
8 – { PHY - RF }	0.25 ms	Ideal- 0.25ms	75km	75km	23.8GOPS (18GOPS)	20.7GOPS

From Table 2, we can infer that the higher layer splits seem to be feasible due to the relaxed latency requirements. For a LEO satellite orbiting at an altitude of 600 km, as per 3GPP specifications, FSs 1-3 are feasible because the maximum fronthaul distance is much more than the separation distance between the satellite and the ground station. Whereas FSs 4-8 are infeasible because the fronthaul distance is less than the separation distance. However, FS 4 and FS 5 may be feasible for a VLEO satellite orbiting at an altitude of 300 km which then satisfies the fronthaul distance and separation distance constraints. The color coding of the table conveys a similar message where green represents full feasibility for a given standard FS specification, whereas orange represents the feasibility in the upper range of the standard FS requirement. Red indicates that the specific FS is infeasible.

The separation distance is calculated assuming that fronthaul latency as the maximum propagation delay between the satellite and the ground station. A large fronthaul distance indicates a relaxed latency requirement which may translates to, a single hop with maximum separation of said fronthaul distance or may include multiple hops as long as the total separation distance is less than the fronthaul distance (actually for every hop there will be some processing delay which reduces the fronthaul distance). The computational resources required for each split at both the ground and satellite are calculated from [9], where we accumulated the GOPS required for each end (satellite and ground station) based on the corresponding RAN functions. It is observed that the computational resource requirement at the satellite decreases if the FS shifts towards the lower layers (i.e., less functions onboard the satellite). Similarly, the computation resource requirement at the ground station increases if the FS shifts towards the higher layers (i.e., more functions onboard the satellite).

These fronthaul latency specifications are based on LTE terrestrial networks, but there are several dimensions where the latency can be relaxed for NTN. For NR, these fronthaul latency requirements maybe relaxed by asynchronous HARQ instead of the synchronous HARQ. Furthermore, in NTN Rel-17, disabling the HARQ feedback completely is allowed.

Furthermore, one of the major bottlenecks in the fronthaul latency specifications from 3GPP and SCF is CSI reporting or reciprocity-based measurements which require a very short delay. In this study, it is assumed that all LTE features are supported (as we adopted the latency requirements from Rel-15). It is unlikely that these kinds of features will be used in NTN as they only boost data rate in good terrestrial coverage or in TDD deployments. If disabled, they do not prevent basic functionalities so that we can come to a consensus that these kinds of features are not necessary in NTN.

The fronthaul latency requirements can be relaxed for NTN as discussed above, however, another major bottleneck in defining FS feasibility, especially LLS, seems to be the fronthaul bandwidth requirements which will be studied in our future work.

4.3 Conclusions

In conclusion, the disaggregation of the RAN and the introduction of the FS between the ground and space components present exciting architectural possibilities within the telecommunications industry. This development aligns with the broader trend of O-RAN, where telecom operators aim to foster multi-vendor interoperability by opening interfaces between logical RAN nodes.

However, the choice of FS is not arbitrary, as the distance between the satellite and the ground station introduces constraints. Some FS options may become infeasible due to stringent fronthaul latency requirements, as stipulated by standards like 3GPP and the SCF. The solutions are discussed to relax the fronthaul latency to complement the larger propagation delay incurred in NTN. Furthermore, a minimization problem is formulated whose objective function is the total power consumption of the network and the decision variable is the FS decision taken for each user served by the satellite.

5 Network flexibility and redundancy

We have studied the data collection of Internet of Remote Things (IoRT) where there are no terrestrial base stations. The fast development and widespread deployment of Low Earth Orbit (LEO) satellites in recent years (e.g., Starlink, Kuiper, and OneWeb, etc.) present a solution to overcome the above challenge. These satellites offer a means to provide service to IoRT devices in remote areas without the need for extensive ground infrastructure. Building ground infrastructure along the entire route would be inefficient when the goal is to connect devices at the end of the link. Additionally, irrespective of the high costs, constructing ground facilities may be infeasible for hazardous or hard-to-reach areas. LEO satellites are capable of reaching places where cables cannot, ensuring ubiquitous and continuous service. However, due to the large propagation loss and limited energy capacity of IoRT devices, directly offloading data of IoRT devices to the LEO satellites is often impractical, especially for large data volumes such as videos or high-definition pictures collection.

Leveraging its high mobility and larger transmit power, an Unmanned Aerial Vehicle (UAV) can build much better connections with both the ground IoRT devices (by approaching each of them in proper order) and LEO satellites (by transmitting with larger power). Therefore, we propose to utilize the UAV as a relay between the ground IoRT devices and the LEO satellites to expedite the data collection process. To mitigate the influence of link capacity fluctuations, we further propose equipping the UAV with a cache node. This enables the temporary storage of collected data from IoRT devices in the UAV during low data rate periods of the satellite link. Subsequently, data can be offloaded to the satellites once the link capacity improves.

We have proposed a novel Space Air Ground Integrated Network (SAGIN) that incorporates a cache node on the UAV to cope with the data rate fluctuation in the backhaul link (UAV to satellite), allowing temporary storage of collected data during low data rate periods. The proposed SAGIN architecture consists of LEO satellites in the space, cache-enabled UAV in the air, and IoRT devices on the ground, as shown in Figure 5. It is worth mentioning that colored arrows in the figure stand for the moving directions of satellites on different orbits.

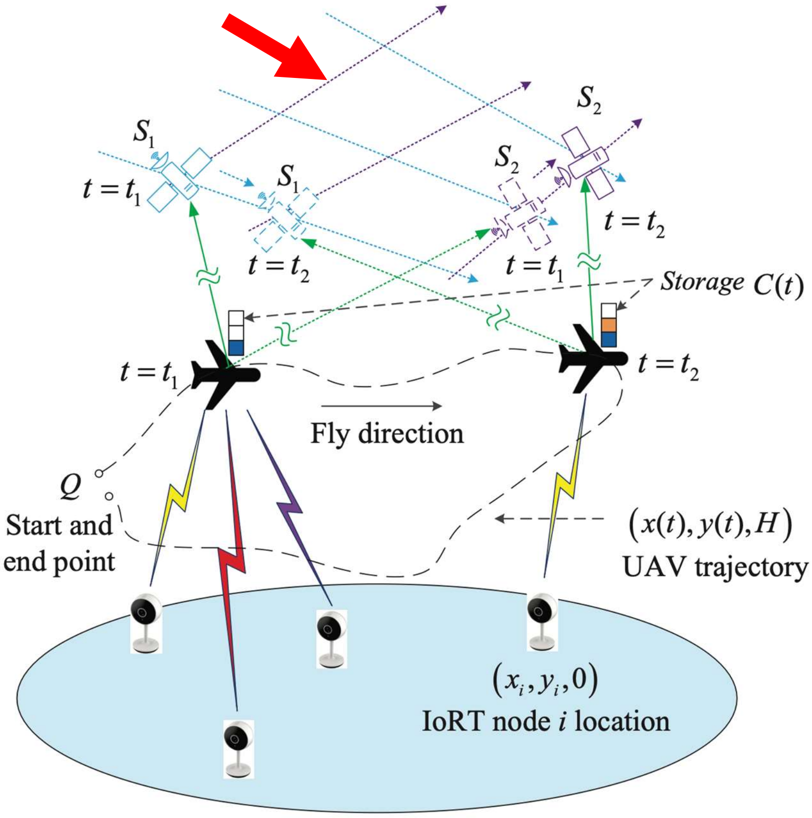

Figure 5 IoRT data collection with LEO satellite-assisted and cache-enabled UAV

To overcome the constraint of limited onboard energy in IoRT devices and investigate the impact of heterogeneity in IoRT devices, a modified SAGIN has been proposed, as shown in Figure 6. This modified SAGIN is designed to simultaneously collect the generated data from heterogeneous IoRT devices and provide wireless charging for them. IoRT devices typically face challenges with maintaining a continuous power supply, as they are commonly deployed in remote areas with limited or no access to electricity infrastructure. The limited battery capacities of IoRT devices further impede their ability to operate for extended durations as needed. Meanwhile, these remote areas often lack the necessary wireless coverage required for collecting the data generated by IoRT devices. To address these challenges, this modified SAGIN is designed to collect generated data and wirelessly charge IoRT devices by leveraging the ubiquitous coverage of LEO satellites, mobility and larger onboard energy of UAV. In this SAGIN, ground-based IoRT devices perform various tasks, such as monitoring temperature, measuring carbon dioxide levels, or capturing area photos. A UAV in the air collects data from IoRT devices and wirelessly charges them. Additionally, LEO satellites in space provide connectivity. Note that ground IoRT devices can connect directly to LEO satellites, depending on favorable channel conditions, without the necessity of connecting to the UAV. The fluctuating of the LEO satellite link is caused by the rapid movement and frequent handovers of the satellites.

The objective is to maximize the amount of collected data while minimizing the number of underserved devices to ensure fairness. Underserved devices are defined as those with collected data falling below a predefined threshold, which is a percentage of the total amount of data. In this study, we use 80% for running simulations. We aim to jointly determine the UAV's trajectory, the IoRT devices' association policy, and bandwidth allocation, considering the constraints of the UAV's limited on-board energy and ensuring that IoRT devices' harvested energy is no less than consumed. To address this challenging problem in a dynamic environment, we propose a learning-based algorithm to discover a near-optimal solution.

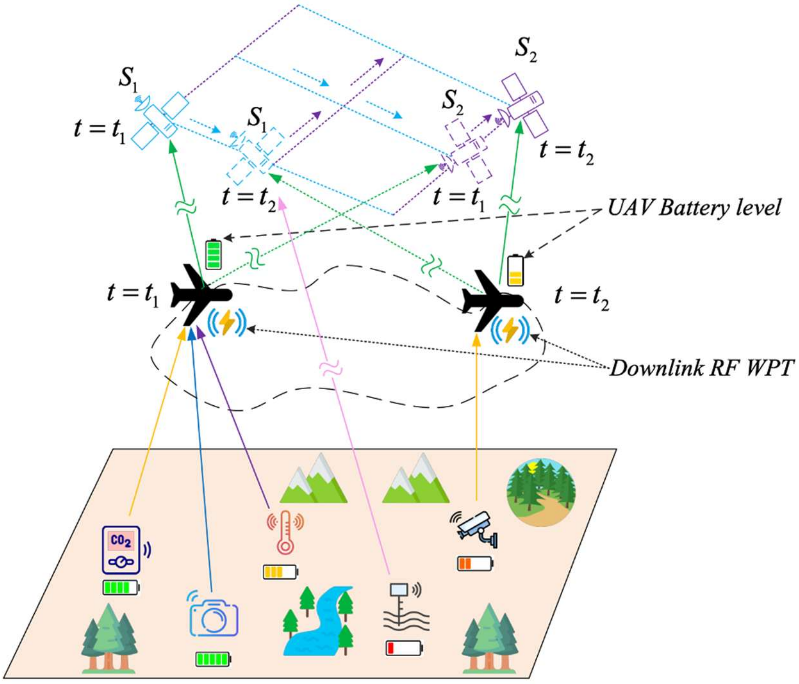

Figure 6 Simultaneous data collection and wireless charging

6 Seamless integration of NTN and TN

TN and NTN technologies followed separate development paths. Starting with 5G, there was a growing emphasis on standardization efforts that aimed to create a more holistic architecture, considering both TN and NTN networks. This was a recognition of the evolving connectivity landscape, which required a unified and seamless network experience. With 6G development, the integration of NTN with terrestrial networks gained further prominence. The goal was to develop these technologies together, allowing for a more comprehensive and versatile network architecture. This approach brings a new set of opportunities and challenges to the fore.

In this chapter, we provide an overview of the integration challenges and possible solutions from the state of the art. Then we discuss the interference mitigation techniques and scheduling and resource allocation of NTN IoRT nodes.

6.1 Integration challenges and solutions

The integration of terrestrial (TN) and non-terrestrial networks (NTN) can lead to global connectivity, transforming how we access and use data around the world. With the seamless integration of these two types of networks, the coverage, bandwidth, and reliability of connectivity can be vastly improved, bringing about new opportunities and solutions for various industries and communities. For instance, this integration can enable global access to telemedicine services, improving healthcare in remote or under-served regions. It can also facilitate international collaboration in research, education, and innovation, leading to advancements in science and technology. Furthermore, this integration can enhance transportation, logistics, and supply chain management, resulting in more efficient and sustainable global trade.

Several organizations, including government agencies, non-profit organizations, and private companies, are actively working on this integration of TN and NTN. For example, the United Nations Office for Outer Space Affairs (UNOOSA) launched the Access to Space 4 All initiative, which aims to promote the integration of non-terrestrial networks to improve global connectivity and address the digital divide [10]. Private companies such as SpaceX [11] and OneWeb [12] are developing satellite constellations that can provide high-speed internet access around the world, including in remote and rural areas. Despite the potential benefits, the integration of terrestrial and non-terrestrial networks to achieve global connectivity is not without challenges. Technical and regulatory issues such as interference and spectrum management must be addressed. Nevertheless, the potential of this integration to provide global connectivity and transform industries and communities makes it a promising field of research and development. As innovation and collaboration continue, we can expect to see new possibilities and solutions emerge that leverage the seamless integration of terrestrial and non-terrestrial networks to improve connectivity and address global challenges.

In this section, we will provide a more comprehensive study of the topic, highlighting the latest advancements, and follow with our simulation results and conclusion.

6.1.1 State of the art

The authors in [13] studied the interference in NTN UL using reverse pairing, where NTN UL is the vulnerable link and TN BSs are aggressor links. The findings reveal that spectrum sharing generally enhances spectral efficiency, but when TN base stations experience severe interference, dedicated resources are more optimal, highlighting the importance of context-specific spectrum allocation strategies.

In [14], the authors consider a multi-LEO constellation system with two-way transmission framework without explicitly utilizing channel information. A multi-agent multi-armed bandit resource allocation scheme is proposed for LEO constellation by learning allocation of available power, beams and channel resources.

Paper [15] studies a scenario where non-terrestrial networks (NTN) share bandwidth with terrestrial network (TN) operators to extend coverage to rural areas. The study demonstrates that in low-traffic scenarios, the primary TN users do not experience negative effects, enabling NTN to serve rural areas effectively. In high-demand traffic situations, although the peak performance of the TN network may suffer, both TN cell edge and NTN user performance improve, showcasing the benefits of dynamic spectrum sharing in these conditions.

In [16], the authors focus on the scenario where TN has a priority over the satellite network. The paper presents that by utilizing the dynamic spectrum access techniques, improvements can be observed regarding several KPIs, including interference level, capacity, coverage and spectrum utilization efficiency. The authors also highlight that the result is highly dependent on the direction and form of the satellite beams.

A deep reinforcement learning framework is established for a multi-beam uplink channel allocation strategy that minimizes interference with incumbent stations under the given quality of service (QoS) constraints [17]. The author compares the DRL-based channel allocation model with existing graph coloring algorithms and demonstrates that it not only outperforms them but also approaches optimal performance levels in the simulation results. However, the scenario in the paper only considers single satellite case and the constellation of satellites is not considered in the study.

A white paper [18] released by MediaTek [19] details many aspects for 6G NTN regarding key drivers and enablers, e.g., waveform design, mobility enhancements, and interference mitigation. The paper illustrates the spectrum sharing's impact on average SINR, showing variations across different links ranging from -20 dB to 11 dB.

The authors in [20] present interference study for a scenario where NTN is used for complementing TNs. The results show that Moving from FRF = 3 to FRF = 1 entails full reuse and thus inter-beam interference, degrading the median downlink SINR by approximately 8 dB and 14 dB for elevation angles of 90° and 87°, respectively. The SINR experiences a prominent degradation when the LEO satellite moves from 90° to 87°, owing to a larger propagation distance and a lower antenna gain, with the median loss in excess of 8 dB for FRF = 1.

Table 3 Summary on the state-of-the-art

Paper Title	Focus	Key Findings
Rate region and Interference impact analysis for spectrum sharing in 6G NTN-TN networks	NTN UL interference in spectrum sharing	Spectrum sharing enhances spectral efficiency; dedicated resources are optimal in severe interference situations.

Paper Title	Focus	Key Findings
Hierarchical Multi-Agent Multi-Armed Bandit for Resource Allocation in Multi-LEO Satellite Constellation Networks	Multi-LEO constellation system resource allocation	Proposed multi-agent multi-armed bandit scheme for LEO constellation without explicit channel information utilization.
Coordinated Dynamic Spectrum Sharing Between Terrestrial and Non-Terrestrial Networks in 5G and Beyond	Spectrum sharing between NTN and TN in rural areas	Dynamic spectrum sharing benefits low-traffic scenarios; in high-demand situations, TN cell edge and NTN user performance improve.
Coverage and interference in co-channel spectrum sharing between terrestrial and satellite networks	TN priority over satellite network	Dynamic spectrum access improves interference, capacity, coverage, and spectrum utilization efficiency, dependent on satellite beam characteristics.
Multi-Agent Deep Reinforcement Learning for Interference-Aware Channel Allocation in Non-Terrestrial Networks	Deep reinforcement learning for channel allocation	Outperforms graph coloring algorithms in interference-aware channel allocation for single satellite scenarios.
MediaTek 6G Technology White Paper	MediaTek's 6G technology overview	Details on 6G NTN key drivers and enablers, spectrum sharing impact on SINR variations across links.
Integrating Terrestrial and Non-terrestrial Networks: 3D Opportunities and Challenges	Interference study for NTN complementing TNs	Full reuse (FRF = 1) leads to inter-beam interference and SINR degradation, particularly when LEO satellite moves from 90◦ to 87◦.

Interferences to consider:

- Inter-beam interference (IBI): This type of interference occurs when the aggressor belongs to another beam of the same NTN gNB that uses the same frequency band [21].
- Inter-cell interference (ICI): This type of interference occurs when the neighboring gNBs uses the same frequency band. The neighboring gNBs can be either terrestrial or non-terrestrial type [22].
- Adjacent channel interference (ACI): This type of interference occurs when an unwanted signal transmission occurs on the adjacent carriers of the desired signal [22].

These different interference types affect the victim's user throughput, which is a function of the CNIR (Carrier-to-Noise-Interference-Ratio). The overall CNIR is:
$\mathrm{CNIR} = -10\log_{10}(10^{-0.1\mathrm{CNR}} + 10^{-0.1\mathrm{CIR}} + 10^{-0.1AC})$ [22],
where $CNR = \mathrm{C} - N$, is the carrier-to-noise ratio, $CIR = C - I$, is the carrier-to-interference ratio where the interfering signals could be from neighboring beams or cells and ACI is the adjacent channel-to-interference ratio. The CNR and CIR model depends on the system parameters and the scenario deployment geometry. The intended signal power received is:
$C = EIRP + G_{RX}(\alpha) - PL$.
Equivalent Isotropically Radiated Power (EIRP) from the transmitter is:
$EIRP = EIRP_{Density} + 10\log_{10}(B/FRF) + G_{TX}(\theta)$ [21] [23],

with $EIRP_{Density}$ being the maximum power density that can be used, B is the available bandwidth for use, FRF is frequency re-use factor, $G_{TX}(\theta)$ is the transmitter antenna gain as a function of θ and θ is the angle between transmitter antenna's boresight and the direction of the receiver. $G_{TX}(\theta)$ is maximal at boresight, i.e. $\theta = 0$. Similarly, $G_{RX}(\alpha)$ is the receiver antenna gain as a function of α and α is the angle between receiver antenna's boresight and the direction of the transmitter. $G_{RX}(\alpha)$ is maximal at boresight, i.e. $\alpha = 0$. PL refers to overall path loss that is a result of free space, clutter, shadowing, atmospheric conditions and tropospheric scintillation effects. The noise power on the receiver is defined as
$N = N_f + 10\log_{10}(T_0 + (T_a - T_0)10^{-0.1N_f}) + k + 10\log_{10}(B/FRF)$ [21] [23],
N_f is the receiver noise figure, T_0 is the ambient temperature, T_a is the antenna temperature and k is the Boltzman constant. Finally, the overall interference on the victim from other aggressors is evaluated as:
$I = 10\log_{10}(\sum_{j=1}^{N_{usesrs}} 10^{0.1C})$.
The ACI ratio is defined as: $\frac{1}{\frac{1}{ACLR}+\frac{1}{ACS}}$, ACLR is the Adjacent Channel Leakage power Ratio of the interfering systems transmitter (specified as the ratio of the mean power centered on the assigned channel frequency to the mean power centered on an adjacent channel frequency) and ACS is the corresponding receiver requirement on Adjacent Channel Selectivity of the victim system receiver [24]. As per [24] and [25] for downlink a common ACIR for all frequency resource blocks to calculate inter-system shall be used and for uplink the table 2.5-1 in [22] can be used for initial co-existence scenarios.

There can be various combination of aggressor and victim based on Uplink/Downlink direction and gNB type (NTN/TN) [22] [24]. To generalize a set-up for evaluating a co-existence scenario, consider one TN cell and NTN cell, where an NTN cell can comprise of one or several spot beams. Position the TN base station at any random position within the NTN cell. N users connect with the TN and N other users connect with NTN such that each user connects to a base station with the highest RSSI when initialized. The traffic type assumed for the network is a periodic model in both uplink and downlink. A round-robin scheduler is assumed on the gNB side, which is responsible for assigning resource blocks to their corresponding users [22]. Following parameters can be considered for dimensioning and controlling the network congestion:

1. No. of deployed users
2. Transmission data rate, by adjusting the packet size and the activation rate
3. Channel related properties that impact the LOS/NLOS link quality such as building heights or rain probability etc.

6.1.2 Interference mitigation

In this part, we introduce two methods that can be used for dealing with interference by leveraging the MIMO features on the receiver side. We show how different methods can improve the system performance by comparing BER results under a certain range of SINR. Then additional computational complexity of the two algorithms is discussed and trade-off between the system performance and complexity is presented.

In 5G NR, Maximum Ratio Combining (MRC) is employed to optimize the signals on the receiver side. This method utilized the features provided by multiple antennas. With MRC, the received signals are combined by assigning different weights to each receiver antenna. MRC assigns higher weights to signals with superior signal-to-noise ratios (SNR) and thus enhances the overall SNR. It boosts the quality of received signals, making it helpful in 5G NR networks for countering fading effects and interference. This technique plays a vital role in ensuring reliable and high-capacity wireless communication, contributing significantly to the network's ability to achieve remarkable data rates and improved spectral efficiency. In this part, we will use the same concept as introduced in NR and try to adopt the algorithm for combining the received signal on the satellite side, i.e., satellite UL, for improving the signal quality.

Interference Rejection Combining (IRC), similar to MRC, also refers to the technique of combining multiple received signals. However, the IRC algorithm intends to cancel the interference from other users, hence improve the overall SINR. To implement IRC algorithm, the system needs to analyze the received signals and identify interfering users. The channel information of the interferers is then used for the weights calculation of the receiving antennas. By applying the MMSE method, these interference components are then suppressed or eliminated from the combined signal. As presented in the sate-of-art in this chapter, interference is seen as a big issue for NTN communication, considering the large footprint size and limited link budget. Thanks to the advanced antenna technologies, we see a great potential for IRC with massive antennas on the satellite.

In the following, we derive the equations that are used to calculate the weights for implementing MMSE-IRC and MRC.

Consider a scenario where there is NTN uplink, and assume N antennas on the satellite, the received signal at the satellite side can be expressed as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{H}_\mathbf{I}\mathbf{x}_\mathbf{I} + \mathbf{n} = \mathbf{H}\mathbf{x} + \mathbf{z}$$

where $\mathbf{y}$ is the received signal vector. $\mathbf{H}$ is the desired uplink channel, $\mathbf{H}_\mathbf{I}$ is the interference channel, $\mathbf{n}$ is the noise component, $\mathbf{x}$ and $\mathbf{x}_\mathbf{I}$ are the transmitted signals from the desired user and interference, respectively. The vector $\mathbf{z} = \mathbf{H}_\mathbf{I}\mathbf{x}_\mathbf{I} + \mathbf{n}$ denotes the combined interference and noise on the receiver side.

The estimation error can be written as $\mathbf{e} = \mathbf{x} - \hat{\mathbf{x}} = \mathbf{x} - \mathbf{W}\mathbf{y}$. The goal of the estimator is to minimize the $\mathbf{e}$, and according to [26], MMSE estimator can be written as:

$$\hat{\mathbf{x}}_{\mathrm{MMSE}} = \arg\min_{\hat{\mathbf{x}}} \mathrm{E}[||\mathbf{e}||_2^2]$$

The weight for IRC is expressed as

$$\mathbf{W}_{\mathrm{MMSE-IRC}} = \hat{\mathbf{H}}^{\mathrm{H}}(\hat{\mathbf{H}}\hat{\mathbf{H}}^{\mathrm{H}} + \hat{\mathbf{R}})^{-1},$$

where $\mathbf{R} = \mathbf{H}_\mathbf{I}{\mathbf{H}_\mathbf{I}}^{\mathrm{H}} + \sigma^2\mathbf{I}_N$ is the combined interference and noise covariance matrix, $\hat{\mathbf{R}}$ is the estimate of $\mathbf{R}$.

For the MRC method, the weight is calculated as [26]

$$\mathbf{W}_{\mathrm{MRC}} = \hat{\mathbf{H}}^{\mathrm{H}}.$$

Computational complexity

From the equations above, we understand that both MRC and IRC methods leverage the knowledge of the channel information to calculate the weights of the antennas. For MRC algorithm, it focuses on maximizing the signal strength which only requires channel information of the desired channel. On the other hand, the IRC methods need not only the channel information of the desired channel, but also information of the interference channel. This brings additional complexity for the IRC methods, especially when there are multiple interferers in the channel. In the following, we will discuss channel estimation methods used in NR.

Channel estimation
In order to perform MRC or IRC algorithm, it is necessary to acquire channel information from the received signal. In 5G NR, there are several ways for achieving this by using the pilot symbols transmitted together with the message. The DMRS-based channel estimation method is such a pilot-based approach that estimates the channel coefficients by exploiting the known properties of the DMRS signals. To further simplify the problem, in this study, we first assume perfect channel knowledge on the receiver side. Then we introduce different level of channel estimation impairments and possible channel estimation schemes to acquire channel knowledge.

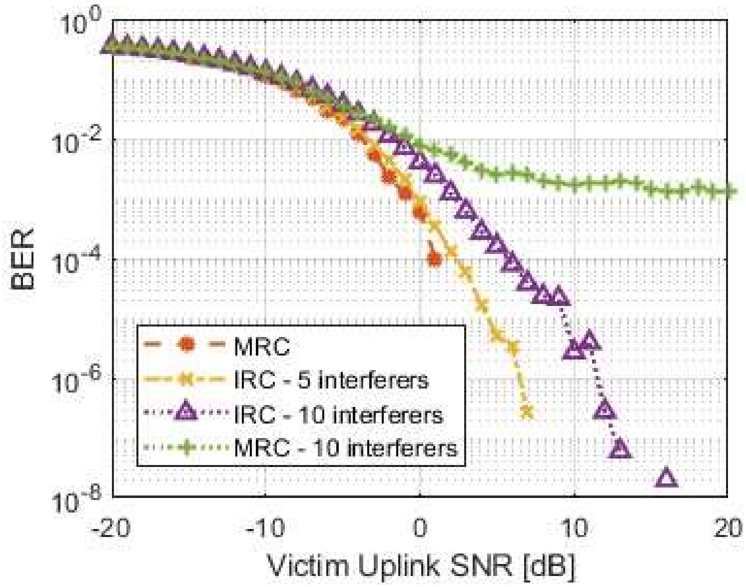

Figure 7 System performance for MRC and IRC algorithms at different uplink SNR values

Figure 7 depicts the system performance (BER) for MRC and IRC algorithms applied to the system where victim uplink is considered. From the figure, we observe that the MRC case without interferer outperforms the other cases where different numbers of interferers are introduced to the system. For MRC method with 10 interferers, the curve starts to converge at around 10 dB, indicating that it fails to mitigate the interference even higher SNR is achieved. For two IRC cases with 5 and 10 interferers, the scenario with 5 interferers shows better performance than the scenario with 10 interferers, which is reasonable. We can also observe from the figure that performance gain is achieved when SNR is higher than -8 dB and increases with SNR increases. This means that at higher SNRs, IRC method is the better option over MRC, and MRC can be used when the SNR is low since it only requires the channel knowledge of the desired link, which in return is less complexed.

Trade-off
While IRC performs better in mitigating interference and delivering better performance, it comes at the cost of increased complexity. IRC requires additional processing and computational resources to effectively reject interference, i.e., it needs to estimate the channel matrix for the interference channel, which can make it less practical in scenarios where

computational overhead or hardware constraints are a concern. On the other hand, MRC, being less complex, is suitable for situations where simplicity and reduced computational burden are desired, even though it may not perform as well as IRC in highly interfered environments.

Except for the trade-off when choose from IRC or MRC. The estimation of the channel matrix can also improve the overall performance by providing more accurate calculation of the weights assigned to the antennas. In 5G NR, enhanced channel estimation can be achieved by having more DMRS symbols. In this way, the receiver has access to additional reliable reference points, allowing for more accurate estimation of the channel characteristics. The extra symbols also occupy valuable bandwidth and resources, which can lead to reduced data throughput. Therefore, there is a trade-off to consider between the benefits of improved channel estimation and the increased overhead.
Selecting between IRC and MRC involves finding a balanced compromise between improved performance and increased system complexity. This decision must align precisely with the specific requirements and limitations of the wireless communication system in use.

6.1.3 Conclusions

In this chapter, we first analyzed the challenges and some solutions in the literature regarding the integration of TN and NTN. We first presented the state of art regarding the insights into the challenges and benefits of an integrated TN and NTN. The integrated network holds promises for extending coverage and improving overall network performance, but effective management of interference remains a key focus for industry and academia.

6.2 Scheduling

6.2.1 State of the art

We have considered the completion time minimization of IoRT data collection in SAGIN by optimizing the UAV trajectory, IoRT device association scheme, and data caching policy (whether to store data temporarily or not in the UAV). Since the formulated problem is challenging to solve by using traditional optimization methods due to the unknown number of decision variables and the changing environment, we propose a Deep Reinforcement Learning (DRL)-based algorithm to efficiently solve it.
Deep Reinforcement Learning (DRL) has demonstrated its efficacy in solving complex problems that are not easily tackled using conventional optimization techniques. Different from traditional optimization methods which assume static relationships between inputs and outputs, the learning- based methods can adapt and learn through interactions with the dynamic environments. The agent takes actions in the environment, receives feedback in the form of rewards or penalties, and learns to improve its decision-making over time [20]. Moreover, DRL can effectively approximate the optimal solution without exhaustively exploring every possible state. Instead, it generalizes from what it has learned to unseen or unvisited states to acquire a near-optimal solution, which guarantees the sample efficiency and convergence of the algorithm. By tuning the parameters of individual neurons in the neural network, the neural network can be used as function approximators to approximate the value function or policy function. This property enables neural networks to capture the underlying dynamics of the environment, which are often complex and non-linear. Additionally, neural networks can continuously learn and update their parameters based on new experiences, allowing them to adapt to changing environments and improve performance over time. The advantages of DRL make it an excellent solution for tackling the challenges posed by our proposed SAGIN.

Therefore, we reformulate the problem as a Markov Decision Process (MDP) and propose a DRL-based algorithm to learn the near optimal solution of the UAV trajectory, the IoRT devices' association scheme and the caching strategy of collected data.

6.2.2 Simulation results

In this study, we assume all the IoRT nodes can be associated with UAVs during the whole mission. The learning by the agent decides at which time slot and which location the UAV is connected to a certain node. Simulation results demonstrate that using our proposed algorithm requires less time to complete data collection compared to both the circular trajectory scheme and the no-cache node scheme under different setups. Moreover, our proposed algorithm can adapt to uneven data distribution by approaching closer to the IoRT nodes with large data sizes, and it can also mitigate the influence of backhaul link fluctuations with the aid of the cache node.

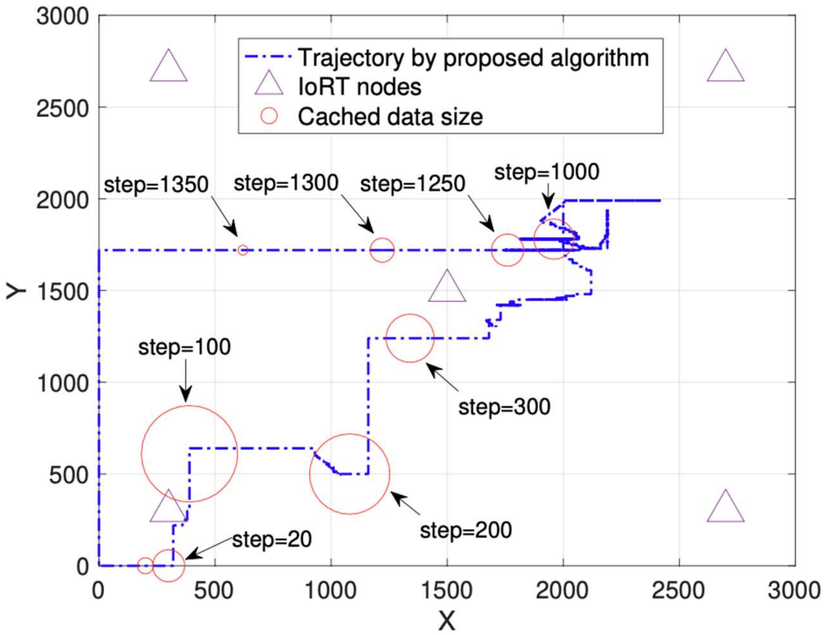

Figure 8 Snapshot of UAV's trajectory obtained by the proposed algorithm.

Figure 8 illustrates a snapshot of the UAV's trajectory obtained using the proposed algorithm and depicts the variation in the cached data size within the UAV. Note that the UAV starts by approaching the nearest IoRT device. In the meantime, the amount of cached data in the UAV continuously increases during this phase because the backhaul link capacity is not large enough to accommodate all the data collected in the access link and the excess data has to be stored in the UAV temporarily. However, as the backhaul link capacity surpasses that of the access link, the cached data size gradually decreases, as observed from steps 100 to 300 and steps 1000 to 1350.

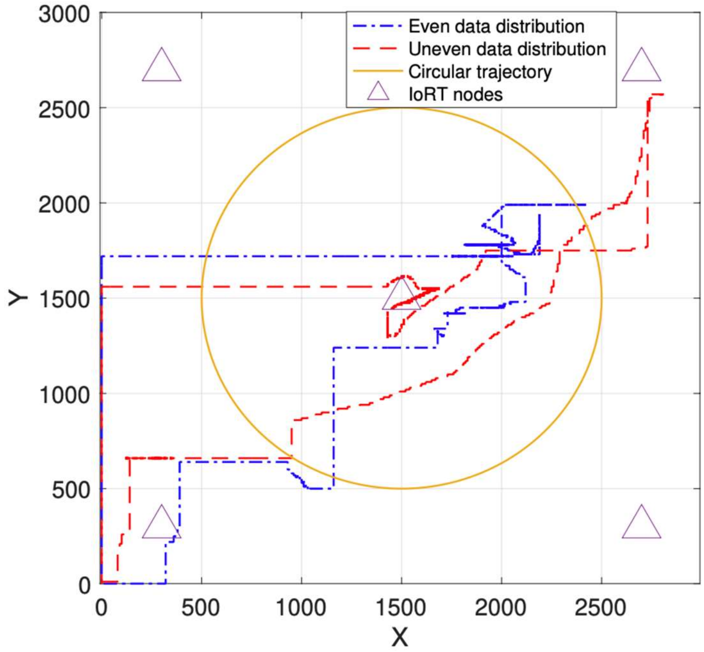

Figure 9 UAV's trajectory with even and uneven IoRT data size.

Figure 9 illustrates the trajectory of the UAV obtained by the proposed algorithm in two scenarios: even data distribution and uneven data distribution. In the even distribution scenario, all IoRT device have the same data size of 2 GB. However, in the uneven distribution scenario, the data size of the IoRT device located at the upper right (2700, 2700) is increased to 4 GB. It can be observed that the UAV approaches the IoRT device with the larger data size more closely in the uneven distribution scenario because the time saved in data collection by approaching the IoRT device with a larger data size outweighs the additional distance traveled by the UAV. This result demonstrates the adaptability of our proposed algorithm and its intelligent adjustment to minimize the completion time in different scenarios.

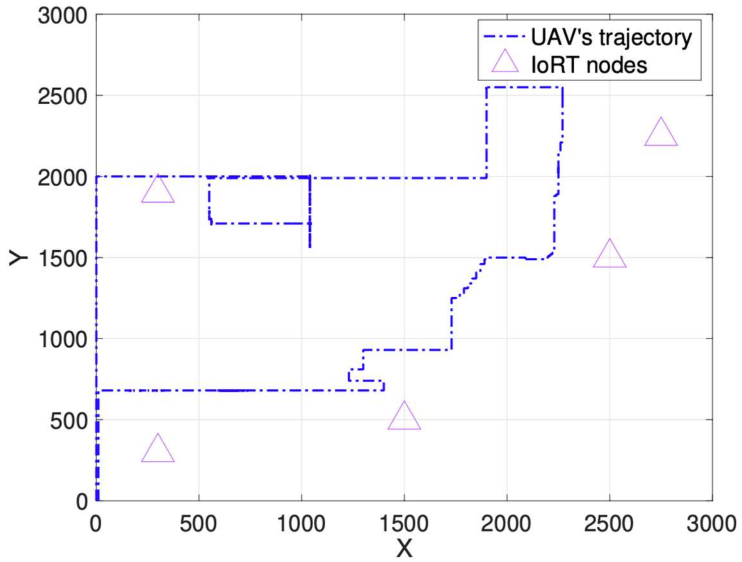

Figure 10 UAV's trajectory with non-uniformly distributed IoRT devices.

Figure 10 illustrates the UAV's trajectory in a scenario with non-uniformly distributed IoRT devices. In this case, the five IoRT devices are located at (300, 300), (1500, 500), (2500, 1500), (2750, 2250) and (300, 900), respectively. All other parameters remain consistent with the scenario where IoRT devices are uniformly distributed. The figure demonstrates that, using the proposed algorithm, the UAV can adaptively adjust its trajectory and approach the IoRT devices properly to potentially reduce the completion time. Furthermore, Figure 11 confirms that the performance of the proposed algorithm remains superior to the other two benchmark algorithms, just as it does when IoRT devices are uniformly distributed.

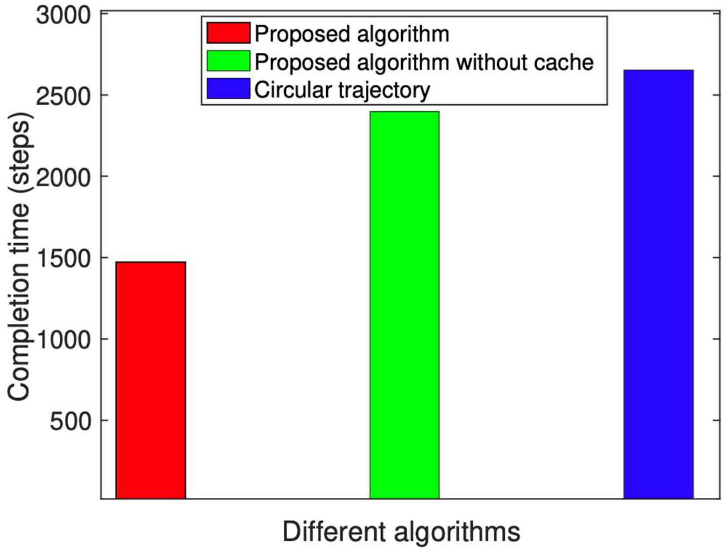

Figure 11 Completion time with non-uniformly distributed IoRT devices.

6.3 Network operator setups

Another important aspect related to seamless integration of NTN and TN is the question who owns and operates the infrastructure. Historically, satellite network operators (SNO) and terrestrial mobile network operators (MNO) have been rather detached and partially even in competition to one another. In a future seamlessly integrated network, these roles are not clearly defined yet and there are multiple options conceivable.

One option would be a single operator for both the TN and the NTN part operating on the same core network. In this case said operator would need to possess necessary spectrum licenses for both the terrestrial and the non-terrestrial parts obeying to the respective regulatory rules. This setup seems to be the easiest solution for a seamless service offering towards the end user as the operator could offer a single subscription to the user offering seamless connectivity services through both terrestrial and non-terrestrial infrastructure. Furthermore, the operator could offer carrier aggregation and dual-connectivity options as the infrastructure is fully controlled.

Another option is to consider distinct operators for the terrestrial and non-terrestrial infrastructures, each with their own core network and having a roaming agreement to support seamless connectivity services. Carrier aggregation or dual connectivity, if possible at all, at least seem to be more challenging to manage in such a setup.

A third option could be to separate out the infrastructure operation from the network operation. In this case, e.g. a satellite constellation, a fleet of high-altitude platforms or a combination thereof is run by an infrastructure operator that owns and maintains the respective platforms and a number of network operators can incorporate parts of the capabilities offered into their networks.

7 Spectrum sharing between TN and NTN

In Chapter 6, we discussed the possibility of a seamless integration of NTN and TN scenario, and the interference and scheduling challenges. For an integrated NTN and TN system, spectrum sharing is crucial due to the increasing demand for efficient utilization of limited spectrum resources, especially in lower bands, e.g., C band.

7.1 Spectrum regulations

7.1.1 TN Spectrum

Radio spectrum for Terrestrial Networks is regulated by national regulatory bodies, generally following recommendations and policies that are issued by regional bodies such as CEPT and European Commission's Radio Spectrum Policy Group (RSPG) for Europe.

Further coordination among countries and on global level is done through International Telecommunication Union (ITU).

TN networks operate on bands that are standardized, licensed and/or unlicensed (ISM, E-band, etc). For licensed bands, regulators allocate dedicated portions to spectrum licensees (such as Mobile Network Operators (MNOs)).

The need for Cross-border Coordination

As each country manages the spectrum allocations on their own geographical territory, measures must be in place to avoid harmful interference towards neighboring countries. In general, this is controlled by defining maximum power limits for at certain distances of national borders. Further technical cross-border coordination tools and recommendations are defined by ITU and ECC [27].

Use of Terrestrial Spectrum Aerial Applications

Most of current mobile networks operate on spectrum classified for "Land Mobile Services". This by definition excludes aerial use on basis of interference protection. There are of exclusions allowing certain bands to provide mobile communications services on aircraft (MCA services), however, these exclusions allow use only inside the aircraft (small onboard BTS), rather than allowing general use in aerial platforms [28] [29].

Use of Terrestrial Spectrum for NTN applications

Regulation-wise, terrestrial spectrum allocations do not generally allow aerial use, nor space-based communications. However, there are number of initiatives aiming to provide "Direct to Handset" services that utilize terrestrial spectrum served from LEO satellites at orbit altitude of typically 550 km. Regulators are expected to react on this; currently such services are run in experimental mode [30] [31].

In the U.S., FCC has recently proposed a new regulative framework for Supplemental Coverage from Space (SCS) [32] that allows use of spectrum allocated to Terrestrial services also on satellite.

Coming closer to earth, High Altitude Platforms (HAPS), operating in stratosphere at altitudes of approx. 20 km, can offer IMT-services complementary to terrestrial networks on local or regional areas.

There are two categories of HAPS authorised to operate according to the ITU's Radio Regulations, depending on the type of service they provide. HAPS can operate either fixed services or mobile services.

While HAPS fixed services connect houses in remote locations or provide backhaul links to base stations, HAPS mobile services would connect directly to the user equipment, operating as a base station in the sky.

Under ITU regulations, the only terrestrial spectrum band where HAPS can currently act as a cellular base station is 2.1 GHz (B1). WRC-23 plenary has newly approved HAPS operations on additional spectrum ranges of 698-960 MHz, 1710-2170 MHz and 2500-2690 MHz. For fixed services, the following allocations exist for ITU globally: 31-31.3 GHz, 38-39.5 GHz, 47.2-47.5 GHz and 47.9-48.2 GHz.

As can be seen, the overall total bandwidth is rather modest, and is not seen as sufficient for future 6G demands. Here, the expectation is that additional allocations are needed, for example in E-band and sub-THz. Other emerging technologies, such as Free Space Optics (FSO) are also expected to play a significant role, particularly for inter-HAPs and HAPs to Satellite communications, as is being used in satellite industry (e.g. Starlink) [33].

Towards 6G, a new frequency range of FR3 (7-24 GHz) is being studied. Such frequencies are not particularly attractive for terrestrial mobile networks in rural areas, where terrain morphology must be accounted for. However, for aerial or generally NTN applications, where the link is predominantly Line of Sight (LOS) the higher frequencies could be effectively utilized.

While adjacent channel coexistence in S-band is studied in 3GPP. Co-channel coexistence of terrestrial and NTN-networks may face more challenges with current standards and regional spectrum allocations, therefore physical separation between the systems tends to be a promising solution.

In large scale, such as between adjacent countries, frequency allocations for certain operator are not usually homogenous even if the same operator has operations in many countries. To avoid cross-border interference, buffer zones are needed. The extent of the required buffer zone depends on the minimum beam size and sidelobe suppression characteristics of the satellite system, and it differs between satellite systems. Figure 12 shows examples of LEO satellite service footprint over Germany and Austria with different assumed buffer zone extents.

We can observe that a large percentage of geographic area must be excluded to avoid cross-border interference. Also, the smaller the country, the bigger the impact as generally the expected minimum exclusion zone is in the range of tens of kilometers.

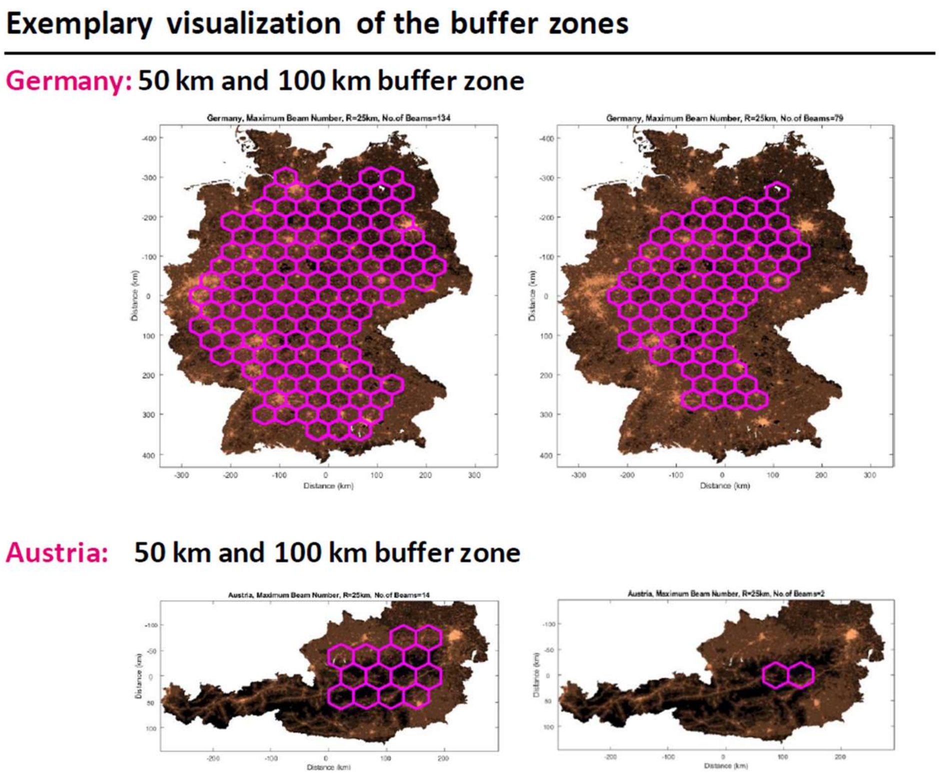

Figure 12 Exemplary visualization of the buffer zones

For high altitude platforms, the same principles apply but on a different scale. Due to the comparably low distance to earth, the ground illuminated beam size of HAPS is much smaller than of a satellite – in range of hundreds of meters to kilometers. The fact that a beam illuminates ground from above, rather than at low slant angle as is the case of Terrestrial network, the signal emissions can in principle be controlled more precisely than on TN network as illustrated in Figure 13. This could be exploited to enhance service quality close to cross-border situations – be it international border or region within operator's own network.

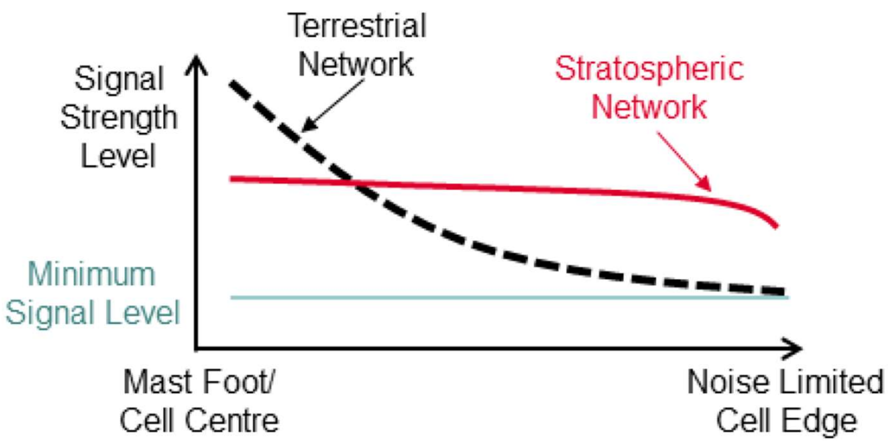

Figure 13 Signal strength for high altitude platforms

For functioning coexistence, it is necessary to manage the spectrum resources among the different network layers in an orchestrated manner. Therefore, a 3D orchestration is seen as mandatory. If operations involve only a single operator and their dedicated spectrum, such orchestration could be managed by the operator itself, with tools developed for the purpose. However, when more operators and/or a shared spectrum resource is used, some standardized approach needs to be followed.
In Europe, a study has been carried out on utilizing license assisted spectrum access (LSA) mechanism as means for allowing spectrum use both for terrestrial and NTN applications in a coordinated manner [34].

7.1.2 NTN Spectrum

Non-Terrestrial spectrum is regulated by International Telecommunication Union (ITU) and further by national regulatory bodies.

Satellite
Satellite services spectrum can be categorized as Fixed Satellite Services (FSS) or Mobile Satellite Services (MSS). The frequency bands are generally shared among Satellite Operators. Therefore, operators need to prove (by ITU provided interference assessment tools [35]) that they do not exceed maximum allowed geographic power flux densities, or cause interference to other satellite operators. Further, different countries may apply additional limitations such as bandwidth allocation and geographic exclusion zones.

Most prominently used bands for high throughput services are Ku (12-18 GHz) mainly for service link application and Ka (26.5-40 GHz) for both service and feeder link applications. These bands are further divided to segments based on the geographic area and usage type (TV broadcast, data services, Ground to Space, Space to Ground etc.) This provides generally 500-2000 MHz signal bandwidth.

Generally, the allocations are for fixed satellite services (FSS), not allowing for mobile use of the service. However, with the advent of high throughput satellite services and relatively low cost Electronically Steered Antennas (ESA) user terminals, there is growing demand for mobile use (Earth stations in motion (ESIM)). This is being addressed by ITU in WRC19 and WRC23 [36].

Low bands of L (1-2 GHz) and S (2-4 GHz) have allocations for Mobile Satellite Services (MSS) but with lower amount of spectrum so they are not suited for high throughput services. L-band is used notably for Conventional Satellite Telephony, satellite navigation and radio astronomy. On S-band, in Europe, Inmarsat holds 2x15 MHz allocation that is used by the European Aviation Network (EAN).

7.2 Spectrum sharing techniques

In [13], the authors studied the spectral efficiency in a scenario where sharing between NTN UL and TN DL is considered. The results show that the spectrum sharing between TN and NTN can improve the NTN UL throughput with the BS sharing ration from 0 to 0.99. However, the system performance will drop significantly due to the severe interference.

The paper [15] presented a spectrum sharing scheme which the system gives priority to TN and taking the peculiarities of the NTN frequency re-use scheme into account. In this way, the scheme enables the NTN deployment on a shared spectrum while causing minimal disturbance to primary TN.

The authors in [37] use a novel reverse spectrum pairing mechanism to mitigate the co-channel interference to the NTN service link. Simulation results indicate that the use of reverse spectrum pairing allows achieving SINR levels similar to those observed in terrestrial cellular networks in the case of high elevation angle. Besides, there is another advantage of reverse pairing which is the convenience of applying the interference mitigation mechanism. The network can quickly identify and manage aggressor BSs to avoid harmful interference on the NTN service link due to the already known BSs information.

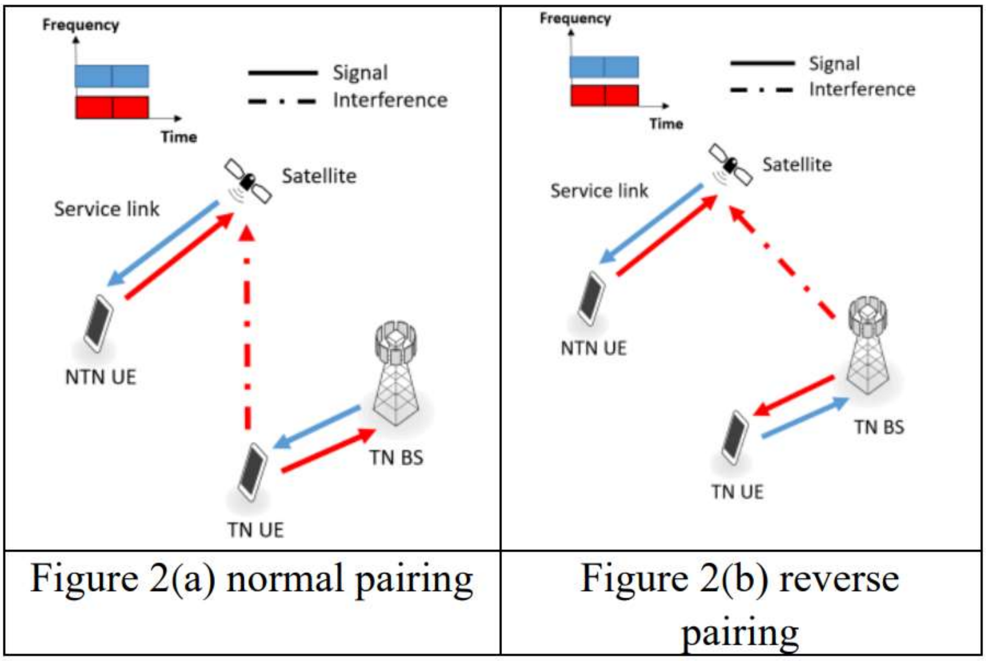

Figure 14 NTN-TN spectrum sharing system in paper [37]

In [38], a scenario where sharing satellite spectrum to terrestrial-mobile in-building small cells is studied. The paper explores the external wall penetration loss of a building as well as a configuration and a handover procedure for the satellite UEs. Numerical and simulation results show that while spectral efficiency improves linearly with the number of buildings, the relationship with energy efficiency is complex.

7.3 Waveform compatibility with TN

In 5G, OFDM is used as the primary waveform for both uplink and downlink transmissions. The downlink transmission waveform is conventional OFDM using a Cyclic Prefix (CP). The uplink transmission waveform is conventional OFDM using a CP with a transform precoding function performing DFT spreading that can be disabled or enabled. The 5G OFDM waveform uses a larger number of subcarriers than previous generations of wireless communication systems, allowing for higher data rates and improved spectral efficiency. In addition, the 5G waveform uses advanced modulation schemes such as Quadrature Phase Shift Keying (QPSK), 16 Quadrature Amplitude Modulation (QAM), 64QAM, 256QAM and 1024 QAM, which allow for higher data rates and improved spectral efficiency.

OFDM is expected to remain a key technology in 6G, but with further advancements and improvements. One area of research for 6G OFDM is the use of wider bandwidths and higher frequencies, which would allow for even higher data rates and improved spectral efficiency. Additionally, a new technique such as polar constellations is being explored for 6G OFDM in Hexa-X-II, which would allow for more efficient use of the available spectrum by improving performance against Phase Noise (PN) and doppler shift.

To design NTN waveform with a sharing purpose, it is important to evaluate the NTN waveform compatibility with terrestrial waveform which will most likely be OFDM or OFDM-based waveform. Having a uniformed waveform will simplify the handover and roaming process between the TN and NTN. As a mobile users move across different coverage areas of the two networks, it's essential to maintain a consistent waveform to ensure a seamless transition without any interruptions or degradation in connectivity. This approach not only enhances the user experience but also simplifies device compatibility, minimizing the necessity for additional hardware or software adjustments. The advantages become even more pronounced when both TN and NTN employ the same waveform. This commonality allows existing devices initially designed for TN to seamlessly function in the NTN environment. Consequently, this eliminates the need for costly upgrades or replacements, making the transition smoother and more cost-effective. Moreover, when there are technological similarities between 6G NTN and 6G TN (or even 5G TN), it promotes a seamless integration process. This common ground facilitates the utilization of existing 6G/5G infrastructure, maximizing the benefits of both generations. In essence, establishing such technological commonalities not only ensures optimal performance but also paves the way for a fluid transition to the next level of network technology.

7.4 Proposed sharing solutions

In this part, we propose two promising solutions for the sharing between TN and NTN. We present the possible ways of tackling the sharing challenges and then discuss the limitation that may occur.

7.4.1 Separation in space

Considering separation in space, one approach is to place communication systems in different cities or countries, which is a classical method used for sharing purpose. However, there is a significant challenge due to the considerable separation distances required, especially when dealing with high-gain antennas and sensitive receivers. Deploying 6G in the same city as the incumbent system proves to be impractical unless regional differences allow for specific deployments.

Another method to have separation in space is to use shields in specific locations or equipping base stations with shields to control emissions. This can effectively reduce the interference and thus provide better sharing possibilities. However, this method is restricted by regulatory challenges and difficulties in obtaining permits. Using advanced antennas technology to direct energy away from interference victims is another possibility, but the aggressor's needs to have the location information of the victims, which adds additional complexity to the system. Besides, there could be some other limitations, such as incomplete or non-shareable position information.

Beamforming antennas, while promising, present challenges in controlling energy direction, especially regarding nulls and sidelobes. Beam steering is reasonably controllable on the channel, but uncertainties arise in adjacent channels with unwanted emissions, as demonstrated in satellite sharing scenarios.

When incumbents use beam steering to counter interference, challenges related to costs and benefits emerge. The 6G network benefits, but incumbents incur costs for receiver updates. Lastly, if suppression is implementable, questions revolve around its effectiveness in decibels and whether it enables spectrum sharing for a viable 6G business case. The exploration of spatial separation involves addressing technical, regulatory, and practical challenges.

7.4.2 Separation in time

The other main class of isolation is separation in time. Conceptually it is straight forward: One system uses the spectrum for a certain time and when done another system can use the spectrum.

The various ideas for this kind of solutions can be classified considering two properties: The granularity of the time sharing the solution allows and how decisions are made about who can use the spectrum.

Although not commonly considered as a time-sharing solution, the current licensing process can be seen as one way of time sharing. A license is issued for a certain number of years and system A can then use the spectrum. After the license has expired system B may obtain a license and use the spectrum for a while. Then a new license is issued for system C and so on. The problem with this is the long timescale that does not allow adaptation to need that changes quickly. Also, the process relies a lot on manual work which makes it slow and costly. For Ericsson the problem is also that it is regulators that decide, and they may not think that new 6G spectrum benefits society the most.

For shorter timescale sharing, e.g., for a day or a few hours there have been ideas where the licensing process is automated. This reduces the amount of manual work making the process quicker. Since processing is easier it makes licenses for smaller areas practical as well. The CBRS implementation in US is one example where a central database is responsible for the licensing decisions. Another suggested solution has been automated short term spectrum leasing where a spectrum holder can “sublet” their spectrum to someone else. There have also been suggestions on how to automate the contract writing in this case using blockchains. All these suggestions fall into the category of automated spectrum licensing.

The main problem with these solutions is the inherent uncertainty in whether there is spectrum available when needed that has prevented wide adoption of this kind of solutions, and maybe also a bit of inertia for the regulators.

The limit on the timescale of the automated licensing is the processing time of each license. Since entities may be distributed the process takes some time and realistically minutes and shorter timescales is probably not practical. For sharing on millisecond level there is a need to directly coordinate the spectrum use with some kind of signaling between systems. On a conceptual level this is not difficult to do. After all, inside a normal 5G system there is a lot of signaling going to coordinate spectrum, which in the 5G system context is known as radio resources. Today this kind of signaling between a 6G network and an incumbent is not there. It needs to be developed and possibly standardized and while this requires effort it can be done.

The difficult problems with the direct signaling are not technology, it is more a matter of the uncertainty if spectrum is available when needed which makes this kind of solution not so interesting. In addition, the tight signaling between users may reveal too much information to a competitor.
It is also possible to combine the separation in space and in time. One example of this could be to avoid transmitting at certain times when the victim antenna is pointing toward the transmitter. Examples that come to mind is to use the times when a radar is pointing away or when a satellite receiver is receiving from the other direction.

The problem here is to know when and where the victim antennas are pointing. For example, in a LEO satellite constellation there are several satellites that an incumbent could steer the antenna to. If it is necessary to consider all the possible directions to be on the safe side the exclusion zones around the victim become impractically large.

One more thing to discuss is if there actually will be spectrum to share. The assumption underlying all time-based sharing is that when system A is not using the spectrum it can be used by system B. Whether this is a valid assumption is not well understood. Qualitatively one can make the argument that many of these systems may see high demands for spectrum at the same time. For example, at a concert there may be a high need for access spectrum for the people at the venue, but there is also a high demand for fixed link spectrum to move data out of the venue. On the other hand, one could argue that a lot of spectrum sits unused large portions of the day and there must be some opportunities for sharing. This kind of correlated demand studies have not been done and given the other problems associated with time-based spectrum sharing it is not likely to be a prioritized issue.

8 Sustainability

The information and communications technologies (ICTs) industry plays a vital role for combating the world's climate change and sustainability challenges. The United Nation's introduction of its sustainable development goals (SDGs), which include a framework of the 17 areas that need to be addressed and that works as a guideline for reaching a sustainable world [39]. The ICTs are the backbone of today's digital economy and have enormous potential to accelerate the progress for reaching the SDGs and improve people's lives by enabling and providing worldwide mobile connectivity and global coverage [40]. ICT is crucial for achieving all the 17 SDG goals and should be considered as a catalyst for accelerating the three pillars of sustainable development: economic growth, social inclusion, and environmental sustainability.

Figure 15 The United Nation's 17 Sustainable Development Goals.

With more than half of the world's population already living in urban environments, and with the estimation that about 70% of the world's population will be living in urban areas, by 2050, ICTs will be essential in offering innovative ways to managing cities more effectively. Nevertheless satellite-based communication systems do not only provide data for monitoring of weather, climate data etc. but can ultimately also complement the terrestrial communication networks by providing additional connectivity for rural and sparsely populated areas. The 2030 Agenda for Sustainable Development highlights that the continuous development and the spread of information and communication technology has a great potential to bridge the digital divide.

The architecture discussed in this document aims to provide coverage in such remote areas where it might be economically inconvenient, or even impossible, to deploy ground stations. More specifically, as a reference, in the Hexa-X project the target chosen to represent global coverage is that at least 99% of population is reached with at least 1 Mbps data rate [41]. Due to the geometrical constraints of a LEO constellation, it would be impossible for a satellite flying over these areas to have a direct connection with the closest ground station. In Figure 16, it is shown how far away from a ground station a user can be reached without using inter-satellite links for several altitudes and minimum elevation angles. If we assume that ground stations will be deployed in fairly densely populated areas, we can conclude that certain areas such as the oceans or the Amazon forest might be difficult to reach. Moreover, to provide the required capacity, it is possible that multiple satellites should cover the same area, making this requirement even tighter. For this reason, one of the architectural requirements that should be included is the possibility to have multi-hop connections through inter-satellite links.

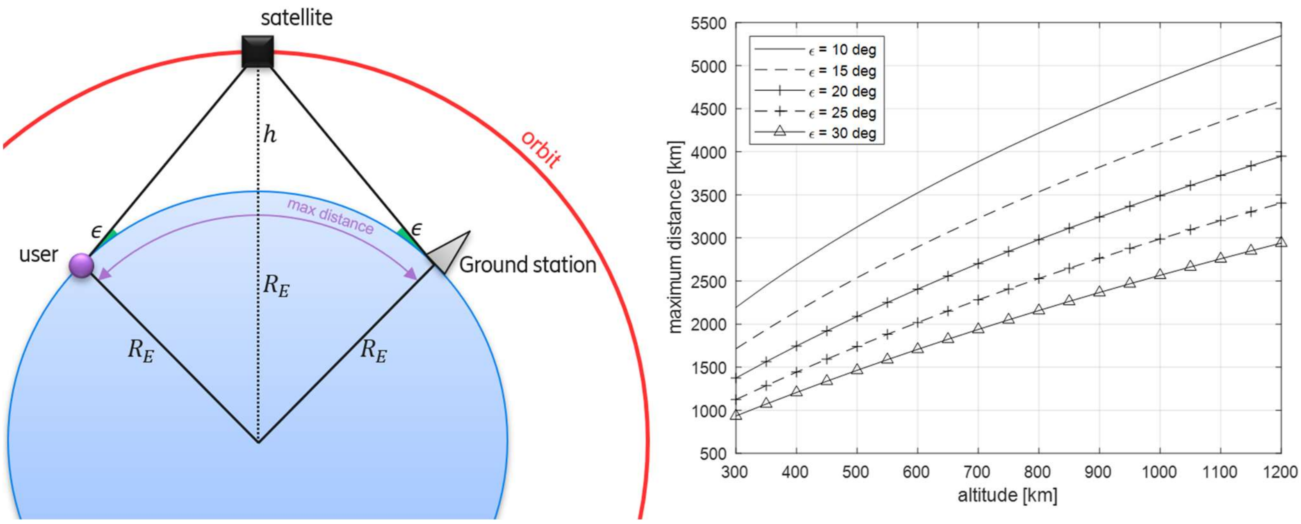

Figure 16 Maximum distance from a ground station without inter-satellite links for various altitudes and minimum elevation angles

In terms of sustainability for operating a satellite constellation, de-orbiting is an important aspect to take into account. This means that after end of life of a satellite it has to be removed from its orbit within a certain timeframe. For older LEO satellites, this has been rather relaxed as the timeframe was as long as 25 years, which was achieved naturally when the fuel needed for orbit maintenance is fully consumed. New rules require to de-orbit no later than five years after end of service. This means to provision extra fuel for active de-orbiting. This is an important step for a sustainable usage of LEO as more and more satellites and objects in this orbit range increase the risk of collisions, which in the worst case becomes uncontrollable and might make a whole range of orbits unusable for a long time, which is referred to as the Kessler effect.

Another important aspect concerning the de-orbiting relates to the materials the satellite is composed of. It needs to be analyzed if the satellite burns completely in the atmosphere during re-entry. If this is not the case, specific care needs to be taken that the remaining parts of the satellite do not cause any harm once impacting on-ground, i.e., they need to land above the ocean. However, besides the safety issue of what is left from a satellite after re-entry into the atmosphere and falling back onto the earth surface, it has been recently shown that aluminum and other metals originating from the burn-up of satellites as well as rocket stages can be found in the stratosphere with a yet unknown influence on the properties of stratospheric aerosol [42].

Additionally, the large and increasing number of satellites in low-earth orbit cause issues in the astronomy community, which negatively affects acceptance of mega constellations. This can partially be alleviated by selecting materials with low reflectance on the earth-pointing surface of the satellites.
At the time of writing, there is a multitude of satellite constellations in LEO at different stages between planning, deployment, and extension. However, they are currently completely independent from each other and building upon proprietary technologies. Considering the above-mentioned congestion issues, as well as the fact that it may be not economically possible for each of these constellations to achieve full global coverage on their own, it should also be looked at the possibilities to interconnect different satellite constellations and combine their capacities similar to terrestrial backbone networks that are interconnected via internet exchange points. This requires in addition to standardized radio access technologies as done in 3GPP, also the standardization of inter-satellite links.

HAPS platform
As the HAPs platform operates above main weather systems, solar power can be utilized more effectively than on ground altitudes, particularly in equatorial areas. In the long run, hybrid solutions using hydrogen will extend the operational range/coverage to higher latitudes. Lifetime of HAPs platform is expected to be 10+ years, and allows convenient upgrades of payload system.

9 Conclusion

This deliverable addresses specific system aspects of NTN, with a focus on communication for terrestrial users. The network design and architecture for NTN to support terrestrial users presented in this deliverable is a recommended system-level design of 6G NTN for terrestrial coverage. Regarding the functional split design, among the potential options for 6G architecture, the RRH on board and the gNB on board appear to be the most promising options. The deliverable also presents that a UAV supported SAGIN can improve the data rate in the backhaul link of IoRT devices, which provides a solution for 6G IoT NTN.

The integration of TN and NTN brings new opportunities for achieving global coverage but also challenges to the design of the system. The interferences considering different victims has been discussed in the deliverable. For interference mitigation, we have studied MMSE-IRC and MRC algorithms, which can be used for antenna weight calculation to improve the system performance. The simulation results indicate that MMSE-IRC outperforms MRC algorithm by leveraging the interference information obtained from the channel measurements. We have also discussed the spectrum sharing possibilities between the TN and NTN. Based on the state-of-the-art, we have provided some recommendations for spectrum sharing of TN and NTN.

Overall, the proposed architecture and design aspects presented in this report serve as a valuable input for evaluation in Task 4.2 and future study. The future of 6G NTN for terrestrial coverage looks promising with the proposed architecture and design aspects presented in this deliverable.

10 References

[1] "6G for Connected SKY," [Online]. Available: https://www.6g-sky.net/.
[2] Q. Duan, "Intelligent and autonomous management in cloud-native future networks—A survey on related standards from an architectural perspective," Future Internet, vol. 13, p. 42, 2021.
[3] P. Kaliyammal Thiruvasagam, V. Venkataram, V. Raja Ilangovan, M. Perapalla, R. Payyanur and V. Kumar, "Open RAN: Evolution of Architecture, Deployment Aspects, and Future Directions," arXiv e-prints, 2023.
[4] A. Vanelli-Coralli, A. Guidotti, T. Foggi, G. Colavolpe and G. Montorsi, "5G and Beyond 5G Non-Terrestrial Networks: trends and research challenges," in 2020 IEEE 3rd 5G World Forum (5GWF), 2020.
[5] R. Campana, C. Amatetti and A. Vanelli-Coralli, "RAN Functional Splits in NTN: Architectures and Challenges," arXiv preprint arXiv:2309.14810, 2023.
[6] L. M. Larsen, A. Checko and H. L. Christiansen, "A survey of the functional splits proposed for 5G mobile crosshaul networks," IEEE Communications Surveys \& Tutorials, vol. 21, pp. 146--172, 2018.
[7] S. Antipolis, "Study on new radio access technology: Radio access architecture and interfaces, V14.0.0 (2017–03)," 3GPP Rep. TR 38.801, France, 2017.
[8] "Small Cell Virtualization Functional Splits and Use Cases, Release 7.0," Small Cell Forum, 2016.
[9] A. Alabbasi and C. Cavdar, "Delay-aware green hybrid CRAN," in 2017 15th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), 2017.
[10] "Access to Space for All Latest Information," UNOOSA, [Online]. Available: https://www.unoosa.org/oosa/en/ourwork/access2space4all/index.html. [Accessed 25 04 2023].
[11] "SpaceX Website," [Online]. Available: https://www.spacex.com/. [Accessed 25 04 2023].
[12] "OneWeb website," [Online]. Available: https://oneweb.net/. [Accessed 25 04 2023].
[13] H.-W. Lee, S. Liao, C.-C. Chen, I.-K. Fu and H.-Y. Wei, "Rate region and Interference impact analysis for spectrum sharing in 6G NTN-TN networks," in 2023 XXXVth General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS), 2023.
[14] L.-H. Shen, Y. Ho, K.-T. Feng, L.-L. Yang, S.-H. Wu and J.-M. Wu, "Hierarchical Multi-Agent Multi-Armed Bandit for Resource Allocation in Multi-LEO Satellite Constellation Networks," arXiv preprint arXiv:2303.14351, 2023.
[15] H. Martikainen, M. Majamaa and J. Puttonen, "Coordinated Dynamic Spectrum Sharing Between Terrestrial and Non-Terrestrial Networks in 5G and Beyond," arXiv preprint arXiv:2304.12112, 2023.
[16] H. Kokkinen, A. Piemontese, L. Kulacz, F. Arnal and C. Amatetti, "Coverage and interference in co-channel spectrum sharing between terrestrial and satellite networks," in 2023 IEEE Aerospace Conference, 2023.
[17] Y. Cho, W. Yang, D. Oh and H.-S. Jo, "Multi-Agent Deep Reinforcement Learning for Interference-Aware Channel Allocation in Non-Terrestrial Networks," IEEE Communications Letters, vol. 27, pp. 936--940, 2023.
[18] "6G White Paper - MediaTek's vision for the next-generation of cellular mobile technologies," 31 1 2022. [Online]. Available: https://www.mediatek.com/blog/6g-whitepaper.

[19] "MediaTek website," MediaTek, [Online]. Available: https://www.mediatek.com/.
[20] G. Geraci, D. Lopez-Perez, M. Benzaghta and S. Chatzinotas, "Integrating Terrestrial and Non-terrestrial Networks: 3D Opportunities and Challenges," IEEE Communications Magazine, 2022.
[21] A. Guidotti, A. Vanelli-Coralli, A. Mengali and S. Cioni, "Non-Terrestrial Networks: Link Budget Analysis," in ICC 2020-2020 IEEE International Conference on Communications (ICC), 2020.
[22] "3GPP TSG-RAN WG4 Meeting # 100-e R4-2115750," 19th – 27th May 2021. [Online]. Available: https://www.3gpp.org/ftp/tsg_ran/WG4_Radio/TSGR4_100-e/Inbox/Drafts/%5B100-e%5D%5B313%5D%20NTN_Solutions_Part2/Round%202/Draft_R4-2115750_Simulation%20assumptions%20for%20NTN%20co-existence%20study_ZTE.docx.
[23] "Solutions for NR to support Non-Terrestrial Networks (NTN)," 3GPP TR 38.821.
[24] "Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) system scenarios," 3GPP TR 36.942.
[25] "Non-terrestrial networks (NTN) related RF and co-existence aspects," 3GPP TR 38.863.
[26] Y. Huang, W. Lei, C. Lu and M. Berg, "Fronthaul functional split of irc-based beamforming for massive mimo systems," in 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), 2019.
[27] I. Bozsóki. [Online]. Available: https://www.itu.int/en/ITU-D/Regional-Presence/CIS/Documents/Events/2018/09_Almaty/Presentations/ITU%20Workshop%2018.09.2018%20-%20Istvan%20Bozsoki%20presentation%202.pdf.
[28] [Online]. Available: https://digital-strategy.ec.europa.eu/en/news/5g-planes-wi-fi-road-commission-decision-opens-new-opportunities-innovation.
[29] [Online]. Available: https://docdb.cept.org/download/4234.
[30] [Online]. Available: https://ast-science.com/spacemobile-network/direct-connection/).
[31] [Online]. Available: https://direct.starlink.com/.
[32] [Online]. Available: https://docs.fcc.gov/public/attachments/DOC-391236A1.pdf.
[33] "Laser Inter-Satellite Links in a Starlink," [Online]. Available: https://arxiv.org/ftp/arxiv/papers/2103/2103.00056.pdf.
[34] [Online]. Available: https://connectivity.esa.int/sites/default/files/ASCENT%20strategic%20recommendations%20-%20Whitepaper.pdf.
[35] [Online]. Available: https://www.itu.int/en/ITU-R/software/Pages/gibc.aspx.
[36] [Online]. Available: https://www.itu.int/en/mediacentre/backgrounders/Pages/Earth-stations-in-motion-satellite-issues.aspx.
[37] H.-W. Lee, A. Medles, V. Jie, D. Lin, X. Zhu, I.-K. Fu and H.-Y. Wei, "Reverse Spectrum Allocation for Spectrum Sharing between TN and NTN," in 2021 IEEE Conference on Standards for Communications and Networking (CSCN), 2021.
[38] R. K. Saha, "Spectrum Sharing in Satellite-Mobile Multisystem Using 3D In-Building Small Cells for High Spectral and Energy Efficiencies in 5G and Beyond Era," IEEE Access, vol. 7, pp. 43846--43868, 2019.
[39] "The 17 Goals," sustainable development, [Online]. Available: https://sdgs.un.org/goals.
[40] "Committed to connecting the world," ITU, [Online]. Available: https://www.itu.int/en/Pages/default.aspx. [Accessed 25 04 2023].
[41] "Analysis of 6G architectural enablers' applicability and initial technological solutions," Hexa-X, 2022.
[42] D. M. Murphy, M. Abou-Ghanem, D. J. Cziczo, K. D. Froyd, J. Jacquot, M. J. Lawler, C. Maloney, J. M. Plane, M. N. Ross and G. P. a. o. Schill, "Metals from spacecraft reentry in

stratospheric aerosol particles," Proceedings of the National Academy of Sciences, vol. 120, p. e2313374120, 2023.