Ref. Ares(2022)8556348 - 09/12/2022

Grant Agreement N°: 101004145
Topic: SPACE-29-TEC-2020

Dynamic spectrum sharing and bandwidth-efficient techniques for high-throughput MIMO Satellite systems

D2.6: Targeted performances

Revision: v.3.0

Work package	WP 2
Task	Task 2.2
Due date	30/11/2021
Submission date	30/11/2022
Deliverable lead	UNIBO
Version	3.0

Abstract

This deliverable provides the final outcome of Task 2.2 by providing: i) a detailed revision of the selected services based on the outcomes of D2.1 “NGSO based satellite access overview;” ii) an overview of the targeted performance of the DYNASAT system; iii) a qualitative list of the expected advantages introduced by the bandwidth-efficient and spectrum sharing techniques discussed in D3.1 “Bandwidth Efficient Techniques selection” and D4.1 “DSA for non-geostationary satellites,” respectively; and iv) a detailed system-level capacity assessment when no advanced technique is implemented. For the latter, the methodology of the simulation is thoroughly detailed.

Keywords: Non-Terrestrial Networks, Beamforming, MU-MIMO, spectrum sharing, NTN services, 3GPP

Document Revision History

Version	Date	Description of change	List of contributor(s)
V1.0	19/11/2021	Final version for SAB approval	UNIBO – TAS
V1.1	12/12/2021	Final version after SAB approval	UNIBO – SAB
V2.0	31/05/2022	Second version after the Y1 comments	TAS – UNIBO
V3.0	30/11/2022	Extension of the Executive Summary and clarification of the maritime scenario.	UNIBO, TAS-F

Disclaimer

The information, documentation, and figures available in this deliverable, are written by the DYNASAT (Dynamic spectrum sharing and bandwidth-efficient techniques for high-throughput MIMO Satellite systems) project Consortium under EC grant agreement 101004145 and do not necessarily reflect the views of the European Commission. The European Commission is not liable for any use that may be made of the information contained herein.

<table>
<tr><th colspan="3">Project co-funded by the European Commission under SPACE-29-TEC-2020</th></tr>
<tr><td>Nature of the deliverable:</td><td>R</td><td></td></tr>
<tr><td colspan="3">Dissemination Level</td></tr>
<tr><td>PU</td><td>Public, fully open, e.g. web</td><td>√</td></tr>
<tr><td>CI</td><td>Classified, information as referred to in Commission Decision 2001/844/EC</td><td></td></tr>
<tr><td>CO</td><td>Confidential to DYNASAT project and Commission Services</td><td></td></tr>
</table>

* *R: Document, report (excluding the periodic and final reports)*
DEM: Demonstrator, pilot, prototype, plan designs
DEC: Websites, patents filing, press & media actions, videos, etc.
OTHER: Software, technical diagram, etc

EXECUTIVE SUMMARY

This document reports the final outcomes of Task 2.2 “Targeted Performances.” The objectives are to: i) dimension the system to meet the targeted performance; ii) perform the link budget and system-level simulations to support the system dimensioning; iii) estimate the benefits of the considered bandwidth-efficient and spectrum sharing techniques on the targeted performance; and iv) assess the energy efficiency and life cycle of the satellite network infrastructure in order to quantify the environmental impact. In particular:

- The services detailed in D2.1 implying the use of one or more satellites in the NR RAN have been critically assessed taking into account the DYNASAT architecture, assumptions, and objectives. More specifically, each service has been classified taking into account: (1) the suitability to the DYNASAT architecture and assumptions, by considering the efficiency of the services provided through the NGSO mega-constellation; (2) the necessity for innovative bandwidth- efficient techniques and enhanced broadband connectivity; and (3) the necessity for spectrum sharing between the satellite and the terrestrial network component. Based on such prioritisation, the following services have been retained as of interest for the DYNASAT project: broadcast/multicast services via satellite, digital divide, coverage extension, and maritime coverage.
- An overview of the 3GPP TRs and TSs providing relevant information with respect to the definition of the KPIs to be considered for the DYNASAT services is detailed. Based on these, a set of economic and technical KPIs deemed of particular interest for the DYNASAT techniques has been reported.
- A qualitative assessment of the benefits that can be obtained by introducing bandwidth efficient techniques in the DYNASAT framework is provided provided. In particular: i) MU-MIMO is expected to significantly increase the achievable spectral efficiency and the throughput, while posing several challenges (*i.e.*, the need for CSI, on-board space limitations for the antenna array, and the limited amount of digital processing capabilities on-board) and additional costs (including, *e.g.*, the need for active antenna arrays and Doppler/delay compensation techniques at the user terminals); ii) Multi-Connectivity techniques would lead to increased throughput, better coverage, seamless mobility, and additional robustness, while posing challenges in terms of the selection of the operating bands and the variation of Doppler/delay impairments between the master and the secondary nodes, as well as additional costs (*e.g.*, increased cost of the user terminal and the need for the Xn Air Interface via ISL); and iii) coordinated and non-coordinated spectrum sharing techniques would lead to significant benefits in the exploitation of the spectrum, at various levels depending on the considered scenario, while introducing additional challenges and costs related to the management of the shared spectrum.
- The TRL for the considered techniques is extensively discussed. In particular, an update on the considered techniques (standalone or distributed MU-MIMO, MC, coordinated or non-coordinated DSA) has been reported with a plan related to the achievement of higher TRL values, when possible.
- A description of the system capacity simulation tool, with the assessment of the system-level capacity without the implementation of advanced techniques, is provided.

Based on the above, this deliverable provides a clear overview of the target services, benefits and challenges of the considered technologies, and expected TRL levels for the DYNASAT project.

It shall be mentioned that the Energy Efficiency and Life Cycle assessment is considered to be significantly related to the final system architecture and the related performance when bandwidth-efficient are implemented. As such, this topic will be covered later in the project activities and, in particular, as outcome of Task 2.4.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AWGN	Additive White Gaussian Noise
CA	Carrier Aggregation
CSI	Channel State Information
DC	Dual Connectivity
DSA	Dynamic Spectrum Access
FDD	Frequency Division Duplexing
FFR	Full Frequency Reuse
FR	Frequency Reuse
gNB	gNodeB
ISL	Inter Satellite Link
LEO	Low Earth Orbit
LOS	Line-of-Sight
LTE	Long Term Evolution
KPI	Key Performance Indicator
MBMS	Multimedia Broadcast Multicast Systems
MIMO	Multiple Input Mulitple Output
M-MIMO	Massive MIMO
MU-MIMO	Multi User MIMO
mMTC	massive Machine Type Communications
MN	Master Node
MNO	Mobile Network Operator
NB-IoT	NarrowBand Internet of Things
NGSO	Non-Geosynchronous Orbit
NR	New Radio
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
SISO	Single Input Single Output
SN	Secondary Node
SU-MIMO	Single User MIMO
SUE	Spectrum Utilization Efficiency
TDD	Time Division Duplexing
TN	Terrestrial Network
TR	Technical Report
UE	User Equipment
WI	Work Item

1 SERVICES AND REQUIREMENTS

The potential services have been detailed in D2.1, taking those reported in 3GPP TR 28.822 as a baseline. In this document, four services have been retained for further study during the project activities. In this Section, we will include:

- A short review of the selected scenarios.
- A set of target performance, for which 3GPP documents will be taken as a reference.

1.1 Service description

In D2.1, the following services were detailed based on an extension of those already provided in 3GPP TR 22.822, [1], which aim at providing service continuity, ubiquity, and scalability for 5G communications exploiting a non-terrestrial component:

- Smart good tracking (IoT via satellite).
- NB-IoT/mMTC global (IoT via satellite).
- Remote control and monitoring of critical infrastructure (IoT via satellite).
- Broadcast/multicast via satellite.
- 5G to premises.
- Emergency management.
- Optimal routing or steering over satellite.
- Global satellite overlay.
- Indirect connectivity.
- Satellite fixed/moving platform backhaul.
- Digital divide.
- Coverage extension.
- Maritime coverage.

The above defined services imply the inclusion of one or more satellite into the New Radio (NR) Radio Access Network (RAN), providing significant benefits to the overall system. However, not all of these use cases can fit the DYNASAT architecture, assumptions, and objectives. Indeed, the DYNASAT project aims at developing and demonstrating advanced techniques for bandwidth–efficient spectrum usage in the framework of NGSO mega-constellations to serve mass-market and professional equipments. Since Low Earth Orbit (LEO) systems are considered, single link latency will be between 5-20 ms typically, according to altitude and elevation. In addition, crossing multiple ISL shall be considered and other delays apply : processing, buffering, crossing of ground network links, GW density, etc. This can easily lead to latencies between 20-50 ms which is enough for most of the 5G services. In particular, the selected services imply a pedestrian with a handheld equipment, such as a smartphone, that uses the 5G network. For example, considering a simple link from UE to satellite to GW (altitude of 600 km, 30° elevation and assuming the distances from UE to satellite and from satellite to GW are equal), the delay, as in geometrical delay, will be 7,2 ms. Access, buffering and processing times will lead to total latencies greater than 10 ms.

Along these lines, each of the above services is classified taking into account: (1) the suitability to the DYNASAT architecture and assumptions, by considering the efficiency of the services provided through the NGSO mega-constellation; (2) the necessity for innovative bandwidth-efficient techniques and enhanced broadband connectivity; and (3) the necessity for spectrum sharing between the satellite and the terrestrial network component.

In Table 1, the evaluation of each service provided in D2.1 is reported for the sake of completeness. The scores are assigned based on the matching level between the service and the selection criterion, *i.e.*, low (L) corresponds to a limited matching, while high (H) to very a good matching.

#	Service name	Architecture	Enhanced broadband	Spectrum sharing	Score
1.1	Smart good tracking	L	L	M	4
1.2	NB-IoT/mMTC global coverage	L	L	M	4
1.3	Remote control and monitoring of critical infrastructures	L	M	L	4
2	Broadcast/multicast via satellite	H	M	L	6
3	5G to premises	L	M	M	5
4	Emergency management	H	M	H	8
5	Optimal routing or steering over a satellite	M	H	H	8
6	Satellite transborder service continuity	H	H	L	7
7	Global satellite overlay	L	L	M	4
8	Indirect connectivity	L	M	M	5
9	Satellite fixed/moving platform backhaul	L	M	M	5
10	Digital divide	H	M	H	8
11	Coverage extension	H	M	H	8
12	Maritime coverage	H	M	H	8

Table 1 service classification. L: low (1); M: medium (2); H: high (3).

Therefore, based on the classification reported in Table 1, the DYNASAT studies will address the following services first:

- Broadcast/multicast via satellite.
- Digital divide.
- Coverage extension.
- Maritime coverage.

Regarding the broadcast/multicast service via satellite, it is well known that there is an ever-increasing capacity request of broadband connectivity. Hence, in the context of enhanced Multimedia Broadcast Multicast Systems (MBMS), satellite networks provide advantages, in terms of efficient access option, to the users located in un or under-served areas and to users with the required Quality of Services (QoS), when the MNO is suturing due to the huge traffic request. For this use case, it is required that (1) 5G system should support both satellite and terrestrial Radio Access Technologies (RATs); (2) the 5G should implement techniques and procedures to make more efficient the content distribution, especially when both the terrestrial and satellite options are available; and (3) the UE should be able to connect to both a terrestrial and a satellite 5G network. Thus, in this service a possible scenario applicable to DYNASAT could be that of reducing the size of the terrestrial cell with the aim to implement spectrum sharing with a certain extent. Regarding the architecture, since we focus on the handheld equipment, the application of NGSO mega-constellation with direct-access is definitely suitable.

Digital divide refers to the gap between those who have access to digital solutions, such as internet and mobile communications, and those who experience a lack of connectivity. In this context, satellite constellations provide broadband solutions to places where is not feasible to develop massive terrestrial infrastructures. In this service, two types of broadband digital divide use case can be distinguished:

- Fixed: users are households and enterprise premises in areas not covered by terrestrial networks;
- Mobile: users are considered as outdoor pedestrians, connected to the satellite by handheld equipment. Some 5G terrestrial relays can be necessary.

It is this second use case that is interesting for DYNASAT, not only because it meets all the requirements but also because it is an interesting economical use case. Indeed, digital divide implies very high deployment cost for terrestrial providers explaining why this is not a good business case for them. Satellite based access allows to overcome this.

Coverage extension, also known as broadband service continuity, covers all the users who have already everyday connectivity and move to under-served areas. It mainly focuses on pedestrian users with handheld devices, which rely only on NTN services. Even with the objective of exploiting terrestrial bandwidths, no interference arises, since are used in remote areas. It is worth highlighting that this service is able to cover service 5, *i.e.*, Optimal routing or steering over a satellite.

The scenario of maritime coverage provides connectivity to users located in cruise ships near the cost. Indeed, moving away from the coast for some km, users loose connection with the terrestrial network. Within this use case, it is possible to use the terrestrial bandwidth without interference constraints. Depending to the distance to the land, satellites could be connected to the gNB on the coast, thus preventing the need of Inter Satellite Links (ISLs).

1.2 Target performance

In terms of system requirements, there are several 3GPP TRs and TSs providing preliminary values and definitions that can be taken into account as a baseline to be tailored based on the DYNASAT system needs. These are reported in Table 2.

Document #	Title	Sections of interest	Comments
TS 22.105, [2]	Services and service capabilities (Release 16)	5.4: range of QoS requirements	- range of BER and latency values per operating environment, including satellite access, for both real-time and non-real-time applications
		5.5: supported end-user QoS	- summary of applications - tables with end-user performance expectations per application (conversational/real-time, interactive, streaming)
		B.2: QoS related performance requirements for example end user applications	- more detailed (in terms of description) requirements for conversational real-time, interactive,

			streaming, background services - sub-service types are listed
TS 22.261, [3]	Service requirements for the 5G system; Stage 1 (Release 18)	6: basic capabilities	- requirements, management, and constraints for several basic 5G capabilities - network slicing, mobility, multiple access, resource efficiency, connectivity model, etc.
		7: performance requirements	- section 7.4 reports the KPIs for 5G via satellite, providing the requirements per receiver mobility scenario
TR 38.811, [4]	Study on New Radio (NR) to support non-terrestrial networks (Release 15)	4.2: 5G use cases where NTN has a role	- satellite and aerial access
		5: deployment scenarios	- deployment scenarios (D1, D2, D3, D4, D5)
TR 38.821, [5]	Solutions for NR to support non-terrestrial networks (NTN) (Release 16)	B: KPIs and evaluation assumptions	- Table B.2-1: Non-Terrestrial network target performances per usage scenarios

Table 2: Summary of 3GPP references related to the performance tartgets and assessment.

Moving from the requirements that are already available in 3GPP documents, a number of technical and economical Key Performance Indicators (KPI) have been defined in D2.1 in order to define targets of performance improvements for the bandwidth efficient techniques that are studied in DYNASAT for the different services that have been selected in the previous chapter.

The performance targets defined in D2.1 and listed in Table 3 and Table 4 are equally applicable to the above services.

Measure	Indicators	Target
Performance with single radio link	*Link margin*	Up to a factor 10 of increased throughput, user density, link availability or mix
Experienced data rate with Power class 3 devices (SoA: 2 Mbps (DL), 0.25 Mbps (UL))	*Data rate*	Up to 20 Mbps (DL), 2.5 Mbps (UL)
Frequency re-use factor SoA: 3 in MSS, as per 3GPP TR 38.821 in clause 6)	*Frequency re-use factor*	1 (full re-use of spectrum in all beams)
Spectral efficiency SoA: 1 bps/Hz (DL), 0.5 bps/Hz (UL)	*Spectral efficiency in UL & DL*	Up to 3 bps/Hz (DL), 1.5 bps/Hz (UL)

Access to spectrum for satellite network infrastructure Spectrum allocated to Mobile Satellite Services	*Frequency bands allocation*	Spectrum allocated to Mobile Satellite Services as well as Mobile Services (Cellular)
Served capacity density	*Capacity per km²*	Up to 10 kbps/km² (DL), 5 kbps/km² (UL)
Percentage of capacity demand actually served	*% of total capacity*	20% for high-bandwidth demand services 100% for low-bandwidth demand services
Percentage of served service areas	*% service areas*	100% of service areas
Coverage improvement with protection areas	*Improvement compared to non-co-operative non coordinated spectrum sharing*	20 % smaller protection area
Spectrum Utilization Efficiency (SUE)	*Improvement compared to non-co-operative non coordinated spectrum sharing*	20 % higher SUE
Capacity in fully overlapping networks	*Improvement compared to non-coordinated spectrum sharing*	20 % higher capacity for satellite without losing mobile capacity

Table 3 Technical KPIs indicators and targets.

Measure	**Indicators**	**Target**
System CAPEX	*Given as variation in % to a reference CAPEX value of a reference system*	No more than x2 increase compared to 5G baseline architecture.
System OPEX	*Given as variation in % to a reference OPEX value of a reference system*	No more than x2 increase compared to 5G baseline architecture.
System TCO	*Given as variation in % to a reference TCO value of a reference system*	No more than x2 increase compared to 5G baseline architecture.
System Revenues	*Given as variation in % to a reference Revenues value of a reference system*	At least x2 increase compared to 5G baseline architecture.
IRR (Interest Rate of Return)	*Given as variation in absolute value (expressed as a %) to a reference IRR value of a reference system*	More than +3% variation compared to the IRR of the 5G baseline architecture.

Table 4 Economical KPIs indicators and targets.

2 BANDWIDTH-EFFICIENT AND SPECTRUM SHARING TECHNIQUES: EXPECTED BENEFITS

Satellite systems are expected to play a crucial role in the future 5G networks, [6]. The main motivation is that, thanks to their inherent characteristics, satellite systems can extend the terrestrial coverage, and internet access can be provided to rural areas and emerging countries, and in general to all scenarios where no terrestrial connectivity is available. Satellite systems can act as a backup network in case of terrestrial network outage and alleviate the need of network densification on the ground. Moreover, satellite communications can improve 5G network management, synchronization, and signalling, and allow efficient backhauling. In this chapter, the qualitative benefits and challenges obtained with the introduction of advanced bandwidth-efficient and spectrum sharing techniques are discussed.

In this section, an detailed overview of the qualitative benefits that are expected from bandwidth efficient and spectrum sharing techniques is provided, taking into account the peculiarities of the DYNASAT concept. The considered techniques are extensively described and characterised in D3.1, [7], and D4.1, [8], respectively.

2.1 Performance gain achievable with bandwidth efficient transmission techniques

In the last years, the 3GPP standardization group has promoted intense activities to study the integration of NTN in 5G systems (Release 15 [9] and Release 16 [10]). There is an on-going Release 17 standardization activity in 3GPP to specify the enhancements of NR to support NTN systems [11]. The objectives of this Work item (WI) are to address issues due to long propagation delays, large Doppler effects, and moving cells, which have been identified during the NTN Study Item (SI) [12]. The considered scenarios show a high interference level because several beams are originated from the same satellite. Therefore, scenarios applying frequency reuse 3 or a combination of polarization reuse and Frequency reuse 2 have been discussed by the 3GPP standardization group. Transmissions with one transmit and one receive antenna (SISO) are considered. During the Study Item, system-level simulation results have been provided for single satellite systems.

The grand challenge for future 5G networks is to satisfy the increasing request of new services by living with the scarcity of the frequency spectrum. The study of more efficient ways to exploit the available bandwidth is therefore of paramount importance and resource sharing is probably the only option. In the context of satellite communications, the leading design paradigm has historically been based on interference avoidance. By transmitting signals that are separated in the time and/or frequency domains, it is ensured that a simple receiver structure can effectively recover the transmitted information. However, to meet the increasing requirements, the attention of the research community has recently shifted toward the interference management and exploitation paradigm. Interference is not avoided by design anymore, but a certain amount of controlled interference is intentionally introduced and mitigated or exploited, both at the transmitter and at the receiver sides, using specifically designed transceiver architectures. In the literature, it has been shown that this change of paradigm can allow to reach extremely high gains with respect to the interference avoidance approach of traditional systems.

For satellite systems, several bandwidth efficient techniques to be applied at the transmitter and/or at the receiver can be adopted. In this project, we study **bandwidth efficient transmission techniques** based on the interference management and exploitation paradigm, such as cooperative and coordinated precoding methods that leave unmodified the user terminal receiver on the ground, for application in advanced mega-constellations of NGSO satellites. The expected gain that can be achieved with the adoption of these techniques in the context of satellite networks is in terms of capacity for unicast and broadcast applications.

Multi-satellite MIMO cooperation techniques and interference mitigation techniques are considered in satellite scenarios with aggressive frequency reuse. Multibeam satellite architectures allow to reuse the same bandwidth in different beams. The service area is divided into small beams in order to reuse the frequency spectrum and hence to improve the spectral efficiency. Figure 1 schematically shows the forward link of a multibeam satellite system.

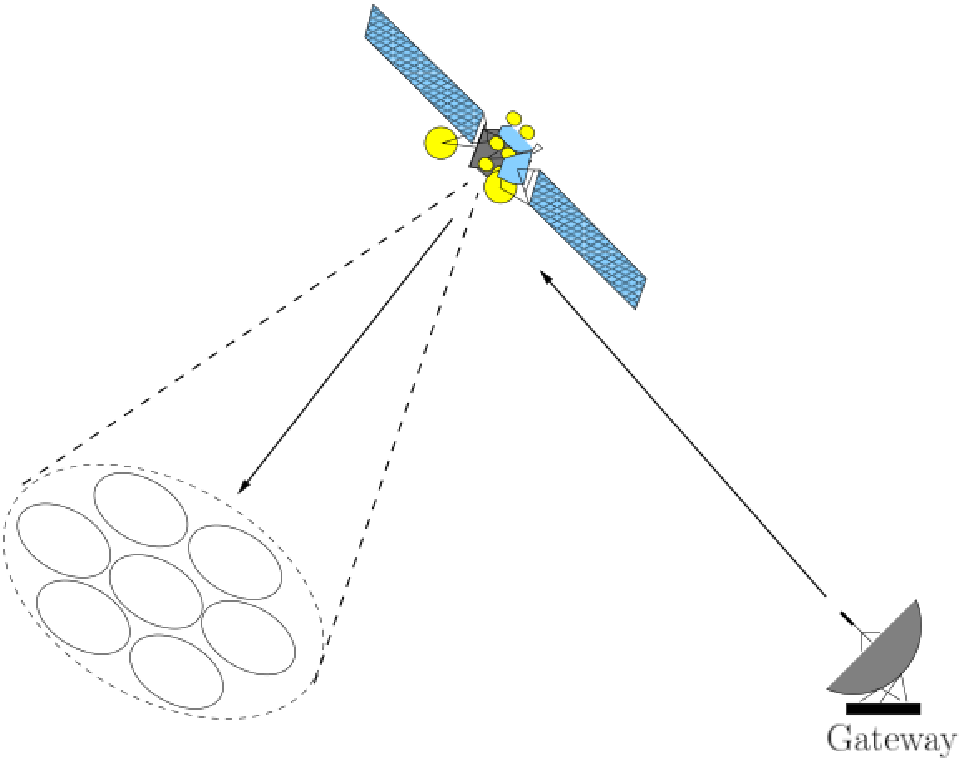

Figure 1: Forward link of a multibeam satellite system.

Signals are generated at the gateway (or at multiple gateways), then are sent to the multibeam satellite, that forwards the signals to the beams on the surface of the Earth, where the user terminals are located, represented by ellipses in the figure. A four-color scheme is the commonly adopted solution in most systems, as it ensures a low level of interference, whereas the more aggressive schemes, with a lower number of colors, ensure a more efficient usage of the bandwidth, at the price of an increased interference, which has to be managed at the receiver and/or at the transmitter to achieve the required performance. As an example, a 4-color frequency reuse scheme is shown in Figure 2, where beams with the same color use the same bandwidth. In a 4-color frequency reuse scheme, the interference is very limited and can be neglected at the receiver. A more **aggressive frequency reuse** can be adopted with the aim of improving the **system spectral efficiency**. Figure 3 depicts the case of a 2-color frequency reuse scheme, while Figure 4 is for the case of 1-color frequency reuse, also known as full frequency reuse (FFR) scheme. In this project, we study transmission techniques that allow to use FFR. We consider advanced precoding/beamforming techniques for MIMO schemes.

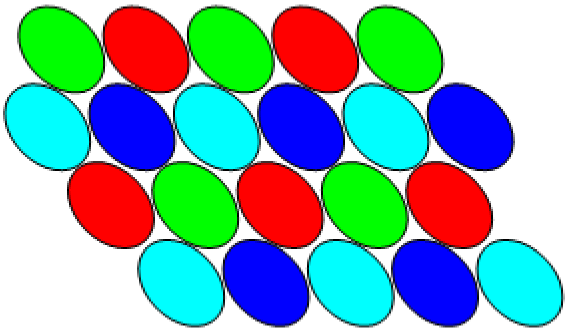

Figure 2: 4-color frequency reuse scheme (FR4).

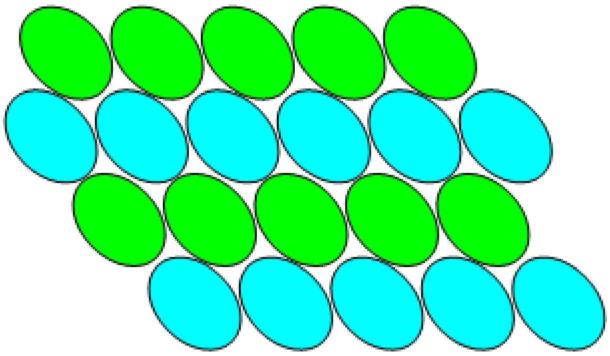

Figure 3: 2-color frequency reuse scheme (FR2).

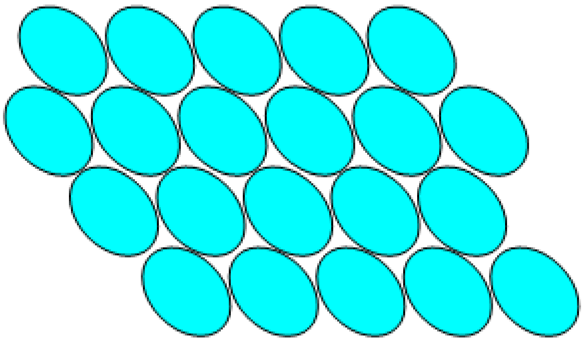

Figure 4: 1-color frequency reuse scheme (FR1).

The adoption of MIMO technology to satellite systems has been much slower than in terrestrial communications [13]. The shortcomings of the application of SU-MIMO to fixed satellite systems are due to the LOS channel, the space limitations on board a single satellite which do not allow for adequate antenna spacing or because the employment of more satellites gives rise to waste of spectrum, lack of synchronization in reception and high implementation cost. On the other hand, broadband fixed interactive multibeam satellite system accommodating a large number of fixed terminals within its multiple beams can benefit from the MU multiplexing gain when MU-MIMO precoding techniques are applied. MU-MIMO precoding techniques are in fact less sensitive to LOS or antenna correlation and allow for spatial multiplexing gain without necessitating satellite terminals with multiple antennas. This comes at the cost of the necessity of CSI at the transmitter, which is not an easy task in SatCom. In fact, it is not possible to use Time Division Duplexing (TDD) schemes to ease channel estimation because of satellite frequency regulation restrictions in millimeter wave bands. The adoption of M-MIMO in broadband satellite networks pose further challenges [14], such as difficulties from the implementation point of view, *i.e.*, wide adoption of transparent payloads with distributed gateways and four colors frequency reuse schemes not compatible with M-MIMO, very limited adoption of active array antennas with many radiating elements, and limitations in the amount digital processing implementable on-board. Moreover, benign channel model (essentially Additive White Gaussian Noise (AWGN) with no multipath fading) reduces the potential M-MIMO performance gain.

Recently, increased interest in MIMO transmission for NGSO satellite communications is emerging [15], [16]. This is due to the fact that LEO satellite communications are expected to be incorporated in future wireless networks and to some advantages with respect to the GEO counterpart, such as much less stringent requirements on power consumption and transmission signal delays. But most of the existing works on downlink precoding in multibeam satellite communications rely on exact instantaneous CSI. This assumption is not so realistic because of the long propagation delay between a satellite and UEs and the mobility of user terminals and satellites. In particular, for TDD systems, the coherence time of the channel is usually shorter than the transmission delay, while in FDD systems, it requires UL feedback from UEs, which introduces a great amount of training and feedback overhead due to mobility of UEs and more importantly could become outdated as a result of the long propagation delay.

In Dynasat, we will also investigate whether asynchronous NR-NR Dual Connectivity (DC) and Carrier Aggregation (CA) [17],[18],[19] would be beneficial for NTN and whether some enhancements are needed. In general, in Multi-connectivity defined by 3GPP the UE is able to utilize radio resources provided by multiple distinct schedulers located in two different NG-RAN nodes. We can define one Master Node (MN) and a Secondary Node (SN), connected via Xn interface. At least the MN is connected to the core network. Three cases of Multi-connectivity may be considered: involving TN and NTN access, involving NTN access inter-satellite and involving NTN access intra-satellite. When both MN and SN are NTN-based at least a partial coverage area overlap is required.

Multi-connectivity enhances performance in terms of data rate and reliability of the connection, providing additional robustness. Moreover, it provides seamless mobility by eliminating handover interruption delays, avoids the need to synchronize gNBs, and allows non-co-located deployments.

The satellite system considered in this project is a LEO constellation providing a global land and ocean 5G coverage. The constellation will be based in Mobile Satellite System (MSS) S band for service link and it will provide 5G services to UE be fix or mobile (*e.g.*, cars, vessels, …).

The bandwidth efficient techniques that are considered in this project can be divided in three main categories, *i.e.*, short, medium and long term techniques. For the short term, techniques with features that have little impact specifications to contribute to 3GPP Release 18 will be considered. In particular, Multi-connectivity techniques and MU-MIMO precoding techniques that do not rely on CSI knowledge at the transmitter will be evaluated. The techniques of interest for medium and long term are precoding techniques that rely on the knowledge of the CSI at the transmitter, and that can exploit the presence of two or more satellites. Massive MIMO techniques from terrestrial networks will be also extended to the mega-constellation scenario. The main issue to be solved in this case is the problem of obtaining channel state information at the transmitter in satellite frequency division duplex schemes. We expect a large gain in terms of system capacity with the adoption of such techniques.

Technique	Gain	Challenges	Cost
MU-MIMO precoding	-frequency reuse 1 -increased spectral efficiency -increased throughput -MU multiplexing gain	-CSI knowledge at the transmitter -space limitations on board a single satellite -limited amount of digital processing implementable on-board	-adoption of active array antennas with several radiating elements -implementation of user scheduling algorithm -Doppler and delay compensation at the user terminal -channel estimation at the user terminal
Multi-connectivity	-increased throughput -better coverage -seamless mobility -additional robustness	-different delay/delay variation between the MN and the SN -operating bands selection	-partial coverage area overlap -UE implementation cost -setting up and maintaining Xn via the ISL

Table 5: Qualitative performance gain, challenges, and implementation cost of the considered bandwidth efficient techniques.

Table 5 summarizes the qualitative performance gain, challenges, and implementation cost of the aforementioned bandwidth efficient techniques.

2.2 Performance gain achievable with spectrum sharing techniques

When we study the benefits of spectrum sharing, we can identify two different spectrum sharing options in Dynasat: coordinated and non-coordinated spectrum sharing. In non-coordinated spectrum sharing, the transmissions of the sharing systems are white noise to each other, and the spectrum users have a strict priority order. The secondary users are only allowed to transmit, when they do not cause harmful interference to the primary users. The metrics to evaluate the performance of a sharing arrangement are coverage, capacity and Spectrum Utilization Efficiency. By coverage, we mean the geographic area where a radio station can communicate. Capacity is the amount of traffic that a network can handle at any given time, and the Spectrum Utilization Efficiency (SUE) is expressed as a formula:

$$SUE=M/BST,$$

where M is the amount of information transferred over distance, B is frequency bandwidth, S is geometric space (usually area), and T is time denied to other potential users [20].

If we assume, that the primary use has discrete boundaries in time, frequency or geographic domain, all additional (coordinated or non-coordinated) spectrum use by the secondary user always improves coverage, capacity and spectral utilization efficiency. If non-coordinated spectrum sharing only brings benefits without any negative effects, shouldn't we use spectrum sharing in all bands and everywhere. Although the benefits are clear in the cases where the primary has discrete boundaries, another way to look at the question is to consider a case where the primary use does not have boundaries. In mobile networks, this case is in the coverage band deployments below 1 GHz. In those bands, the mobile networks cover the whole or almost fully the landmass of a country. Splitting the band to smaller frequency bands, time periods or geographic areas requires protection margins in all dimensions between the sharing networks and decreases the coverage, capacity and SUE.

The coordinated spectrum sharing is a middle ground between block licensed nation-wide networks and non-coordinated spectrum sharing. The transmissions of coordinated networks can overlap in frequency, time and geographic domains as long as they are coordinated. The benefit of coordination is that the margins in frequency, time and geographic domains are significantly smaller than in non-coordinated spectrum sharing. Coordination is very efficient when two cells are coordinating with each other: when one network is idle, the other network can transmit. Sharing becomes less efficient when one network covers several cells of the other network, as in order to transmit in the larger network, all cells which are covered by the larger network must be idle at the same time. In coordination, there can be several levels, a simple form of coordination is used in the European private LTE/5G networks, where the license terms often include a requirement for TDD synchronization.

The applicability of coordinated and non-coordinated spectrum sharing and benefits or negative impacts to the primary and secondary network or the total system are scenario dependent. In the following scenarios, we assume that both networks operate in the same frequency band and continuously. The first scenario is that the primary network has discrete boundaries, and the secondary network only fills gaps of the primary network with minimal or no overlap. For the primary network, there is no coverage, capacity or SUE impact. The coverage of the secondary network is improved in the areas where the primary network is not deployed, and it also gets full capacity and SUE improvement. Considering the whole area and both networks, coverage, capacity and SUE are improved significantly. The difference between coordinated and non-coordinated approaches is that the coordinated sharing has smaller geographic margins, and on the system level the coverage, capacity and SUE improvements are higher than in non-coordinated sharing (Figure 5).

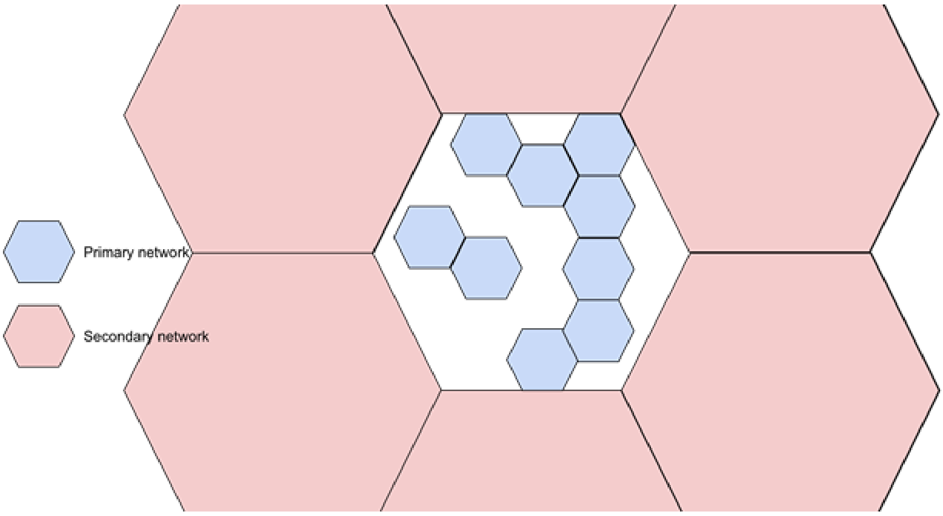

Figure 5: Secondary networks filling the gaps of the primary network.

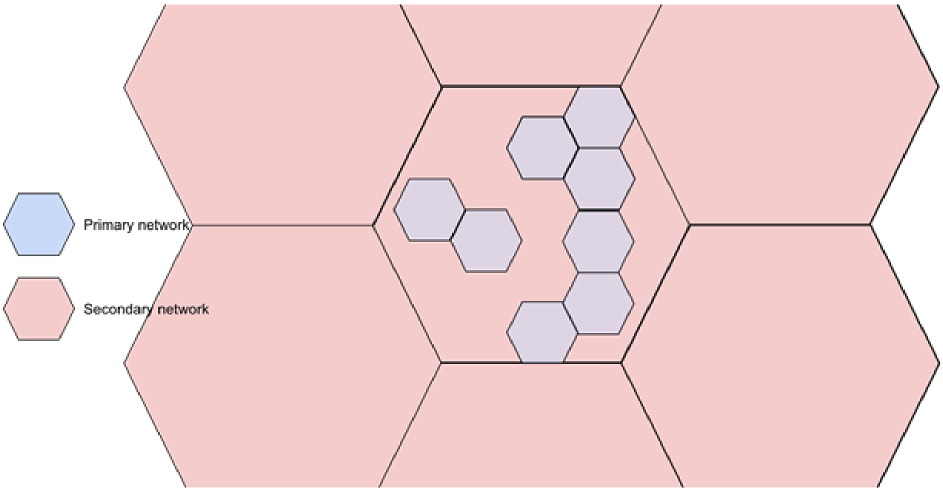

Figure 6: Secondary network with full coverage.

In the second scenario, the primary network has discrete boundaries, and the secondary network has the full coverage of the area. This scenario is only possible to deploy using coordinated spectrum sharing. The primary network has roughly the same coverage as without sharing. For simplicity, we neglect the decrease of coverage area due to increased interference from the secondary network. Capacity and SUE of the primary are decreased. The secondary network gets full coverage improvement and partial capacity and SUE improvement, depending on the amount of capacity available from the primary network. On the system level, taking into account both networks, the coverage is improved to maximum, but both capacity and SUE are decreased significantly due to fewer cells serving the time and frequency domain resources that are available for the secondary network (Figure 6).

In the last scenario, we assume that both networks cover the whole study area. The positive and negative effects for the primary and secondary networks are the same as in the previous scenario. On the system level, there is no coverage improvement and both capacity and SUE are decreased (Figure 7).

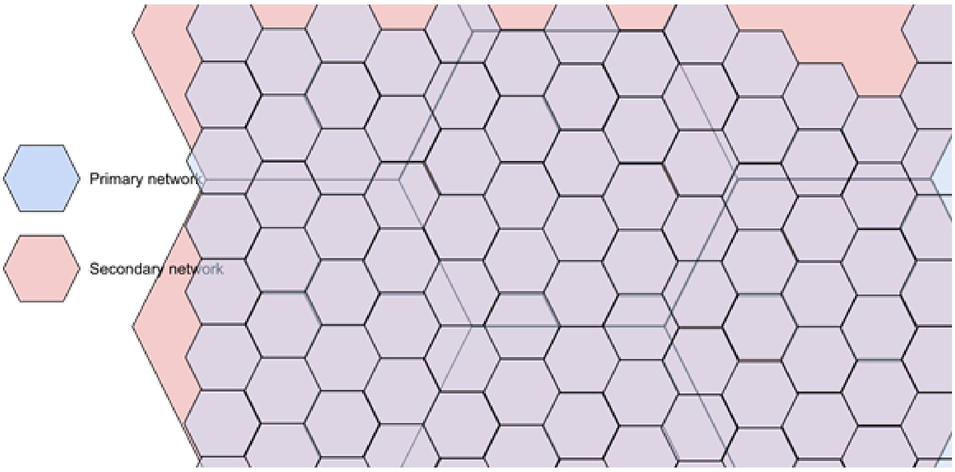

Figure 7: Both primary and secondary networks with full coverage.

As discussed above, the benefits depend on the scenario and environment. When the sharing networks use the same technology, *e.g.*, 3GPP or IEEE 802, coordinated spectrum sharing could be applied. On contrary, the non-coordinated spectrum sharing must be used between the different technology families. Non-coordinated spectrum sharing can only be applied where the primary and secondary users can be separated in frequency, time or geography. Also, in that case, coordinated spectrum sharing has provides more benefits than non-coordinated spectrum sharing by having smaller margins in frequency, time and geographic domains which result higher coverage, capacity and SUE improvement compared to non-coordinated spectrum sharing. Although coordinated spectrum sharing can be deployed for overlapping networks, the overlap should be minimized as it decreases capacity and SUE improvement of the combined network system. In practise, this limits the spectrum sharing to capacity bands, which are above 1 or 2 GHz or to the areas where there is no mobile coverage, like high seas.

3 TRL ASSESSMENT

The aim of this section is to define which TRL levels are considered in DYNASAT for each technology used in the scope of the project. It refers to the current TRL as well as the target/expected TRL afterwards.

3.1 BANDWIDTH-EFFICIENT TRANSMISSION TECHNIQUES

3.1.1 Multi-User MIMO (MU-MIMO)

Technology family	Selected technologies	Expected TRL at the end of the project	Effective TRL at the end of the project	Means/Way forward to achieve TRL 5	Leaders
MU-MIMO Single satellite	MB CSI-based MMSE SS-MMSE LB-MMSE	4	4	Motivations discussed below.	UNIBO

As reported in D2.6 (second version after the Y1 review meeting), two ESA studies had targeted the implementation of precoding in Satellite Communication systems, i.e., PreDem (Precoding Demonstrator for Broadband System Forward Links) and LiveSatPreDem (Live Satellite Demonstration of Advanced Interference Management Techniques). These studies aimed at implementing and demonstrating the achievable spectral efficiency with MU-MIMO techniques over the DVB-S2(X) Air Interface. The latter one, i.e., the LiveSatPreDem project which is an evolution of PreDem, provided a precoding demonstrator with a precoding enabled GW, a satellite MIMO channel emulator, and a set of UEs. Thus, the final TRL of the LiveSatPreDem project reached TRL 4, in a scenario represented by the DVB-S2X air interface, a single GEO satellite, a single GW, the use of beam space precoding, and CSI-based MIMO.

DYNASAT addresses significantly different scenarios and assumptions, that do not allow to apply the TRL 4 techniques developed by the two described ESA studies and set back TRL of the addressed scenarios to 2. Infact, Dynasat addresses:

a) the 3GPP NR interface, which was originally developed neither for satellite nor for precoding, instead of the DVB-S2X air interface that is satellite native and has a superframe mode specifically designed to support precoding from satellite;

b) S-band spectrum usage instead of the Ka-band spectrum of the ESA studies;

c) LEO satellites instead of GEO, moving users instead of fixed, feed-space instead of beam-space techniques, and both CSI and location-based solutions instead of CSI-based MIMO, only.

It shall be noted that the technology to perform the CSI estimation is already available and deployed, based on Pilot Aided approaches. When considering the 5G New Radio Air Interface, this shall be performed by means of the CSI-RS signals already defined in the 3GPP specifications. In this framework, it shall be noted that, in a single NR cell per beam scenario, MIMO is already allowed by the standard. The only aspect that needs to be considered is related to the number of beams generated by the satellite; in fact, as long as 64 or less beams are generated, all of them are managed by a single cell, *i.e.*, with a single Physical Cell ID. Considering that channel estimation or location estimation and the MMSE algorithms have been assessed in a PoC for a limited number of operating frequency bands and with Gaussian Channel model in S-Band, the MMSE based solutions have reached the TRL 3. They could reach the TRL 4, providing the assessment for other Operating Frequency Lower Bands and a realistic Channel Model for each of the targeted band.

Consequently, for the single-satellite MU-MIMO techniques addressed in DYNASAT the following applies:

- Starting TRL: 2
- Current TRL: 3; taking into account also D3.3 to be delivered in November 2022, which reports considerations on the required signalling and measurements, for both CSI-based and location-based techniques.
- End of the project TRL: 4 for a single-satellite MU-MIMO LEO scenario on the basis of the laboratory demonstration described in D5.5.

Means/Way forward to achieve TRL 5 for single-satellite MU-MIMO:

Dynasat developed techniques can be brought to TRL 5 by providing an implementation of several set of beamforming configurations per satellite (up to 64 beams), and real connectivity tests with handheld terminals. The control of beamforming shall also be implemented either on-board or in the ground segment (in a SCC – Satellite Control Center - under the supervision of the MCC – Mission Control Center – passing through a SES – Space to Earth Station – or “Gateway”). It shall be noted that, in case more beams are needed, then beam management and Bandwidth Part association aspects shall be taken into account in order to manage the procedures and control of the mapping between terrestrial NR cells (PCI), NR beams, and satellite beams. Currently, 3GPP specifications refer to Rel. 15 solutions for NTN beam management and further analyses are not planned, for the moment being.

With respect to MIMO, it shall be noted that additional evaluations in a laboratory environment should be considered with respect to the channel model (a more realistic S-band model compared to the 3GPP one) and other candidate operating bands (*e.g.*, L-band handheld terminals). Thus, despite a TRL 4 is achieved in the proposed conditions, it is important to underline that additional demonstrations should be performed to achieve the same TRL in all of the scenarios of interest, which are not targeted by Dynasat.

The above considerations and TRL analysis are in line with the DYNASAT DoA Part B (page 6), with respect to the possibility of achieving (partly) TRL: “*[…] significantly increasing the Technology Readiness Level (TRL) of the designed techniques and concepts from the current level 2 up to level 4, and partly 5 […]*.”

Technology family	Selected technologies	Expected TRL at the end of the project	Effective TRL at the end of the project	Means/Way forward to achieve TRL 5	Leaders
MU-MIMO Multiple satellites	MB	3/4	3/4	Motivations discussed below.	UNIBO
	CSI-based MMSE				
	SS-MMSE				
	LB-MMSE				

Regarding the multiple-satellites MU-MIMO, based on the above observations for the single satellite scenario, the following applies:

- Starting TRL: 1
- Current TRL: 2, taking into account also D3.3 to be delivered in November 2022, which reports considerations on the required signalling and measurements, for both CSI-based and location-based techniques.
- End of the project TRL: 3.

The lower TRL for the multiple-satellites scenario is justified by the fact that, in order to provide a lab demonstration, multiple emulators for the different satellites are needed; with respect to the ISLs among different satellites, they might require an optical/RF channel emulator; a simpler assumption can be made by initially assuming ideal links or on-ground recombination. The above motivates at least a TRL 3 for the distributed MIMO solutions achievable by DYNASAT. Furthermore, since the technologies discussed in DYNASAT are mature enough to support a laboratory demonstrator in case the above elements are available, e.g., ISLs emulators, a TRL 4 can be partially achieved.

3.1.2 Multi-Connectivity (MC)

Technology family	Selected technologies	Expected TRL at the end of the project	Effective TRL at the end of the project	Means/Way forward to achieve TRL 5	Leaders
Multi-connectivity	Bandwidth Efficient Techniques - Multi-Connectivity	4	4	See text below.	MAGISTER

Multi-Connectivity (MC) has been implemented in the NTN System Level Simulator (SLS), which has been calibrated based on 3GPP TR 38.821. The channel model is specified in 3GPP TR 38.811. In addition, the simulator models the different protocol levels from the application to the PHY layers in detail. The implemented MC basic functionality is based on specific NR MC signalling. The proposed and implemented new MC signalling is utilizing the existing Xn air interface and it does not require significant new technologies to be implemented in a real environment. The demonstration scenario models 7 beams per satellite with traffic and, in addition, there are 12 beams per layer introducing interference in the system. Based on the above observations, we consider the current TRL level to be 4, as the focus of the MC demonstration is at protocol level and the SLS can be seen as a laboratory environment for protocols.

Means / Way forward to achieve TRL 5:

In order to achieve TRL 5, the following improvements and adjustments are needed.

> The channel of the NTN SLS should be replaced with a real channel emulator. NTN SLS is an ns3 simulator variant and this kind of real channel emulation on top of ns3 has been done previously with many simulators, but not with NTN SLS. This requires that all the control messages of the NR-NTN are implemented in detail so they can be passed over the emulated channel.

3.2 SPECTRUM SHARING TECHNIQUES

3.2.1 Non-Coordinated DSA

Technology family	Selected technologies	Expected TRL at the end of the project	Effective TRL at the end of the project	Means/Way forward to achieve TRL 5	Leaders
Non-Coordinated DSA	Spectrum management system for Non-Coordinated DSA of NTN - TN sharing	4	4	See text below.	FairSpectrum, MAGISTER

Based on the TRL definition, we assess the Non-Coordinated DSA solutions at TRL 3 (experimental Proof of Concept). This is motivated by observing that the spectrum management function has been designed to work with a large number of satellites, but it has only been demonstrated with two satellites. The implemented channel model is the one defined in 3GPP TR 38.811 and it supports the identified NTN frequency bands. The satellite antenna model is defined in ITU-R M.2101 and ITU-R F.1336, which have been designed for coexistence studies and Dynamic Spectrum Access is a system implementing coexistence rules.

Means/Way forward to achieve TRL 4 for Non-Coordinated DSA technology

According to the constellation simulations (capacity tool), the ephemeris of the LEO satellites and the beam/NTN cell mapping, the considered scenario entails a number of satellites interfering over the same area larger than two used to achieve TRL3 (see the previous section). Therefore, to achieve TRL4, the design of the spectrum management function has been extended so as to work with a large number of satellites. By the end of the project, the Non-coordinated DSA will therefore be demonstrated considering number of satellites reflecting the actual coverage configuration.

Means/Way forward to achieve TRL 5 for Non-Coordinated DSA technology

Achieving TRL 5 for the Non-Coordinated DSA technology requires the following.

1) The Non-Coordinated DSA spectrum management system for NTN - TN sharing shall be connected to real databases of terrestrial MNOs.
    - The TN connectivity is partially implemented in DYNASAT as the TN sites are real MNO mobile sites in France. At the same time, the TN site information should be more accurate in separating the different bands, not just the technology. The site information should also include the operating parameters of the site, like transmit power, antenna height, antenna type, and antenna direction and tilt.
2) The connection of the ground segment to the satellites in the constellation shall be provided.
    - In the NTN connectivity, the ground segment connectivity and parameter exchange on the feeder link have not been discussed, yet, and shall be therefore addressed.
3) The spectrum use information for the NTN component shall be extended to a worldwide coverage.
    - The spectrum use information of the MNO network is implemented in the DYNASAT project. The spectrum use of the NTN component implemented in DYNASAT is limited to the selected demonstration area (France). It shall be extended to the global LEO satellite system, including more than 600 satellites.
4) The interference between the sharing spectrum users shall be computed.

- We assess that the techniques for interference computation developed by DYNASAT can already be used in a system demonstrator at TRL5.

5) A spectrum use controller shall be implemented.
   - The spectrum control use implemented in the DYNASAT project for the TRL4 demonstration shall be extended to implement the ground segment and the information formats used in a real LEO satellite system environment.

3.2.2 Coordinated DSA

Technology family	Selected technologies	Expected TRL at the end of the project	Effective TRL at the end of the project	Means/Way forward to achieve TRL 5	Leaders
Coordinated DSA	Spectrum management system for Coordinated DSA of NTN - TN sharing	3	3	See text below.	FairSpectrum, MAGISTER

Coordinated-DSA has been implemented in the NTN System Level Simulator (SLS), which has been calibrated based on the specifications in 3GPP TR 38.821. The channel model is the one specified in 3GPP TR 38.811. The NTN SLS is an extension of the NR and LTE modules of ns-3 (Magister Solutions). As such, the application and radio protocol layers are thoroughly modeled. A significant exception is given by the control channel modeling, which is error-free and is assumed to follow the same frequency limitations as the data channels. On the other hand, the traffic, load measurements, and spectrum management server behavior are modeled in detail. There is only a single NTN beam in the scenario, but this scenario is focused on the edge of the NTN network, and, due to the frequency re-use in satellite systems, the neighboring beams are not interfering with the same resources. Based on these observations, we assess the C-DSA to be a TRL 3 technology.

Means/Way forward to achieve TRL 4 for Coordinated DSA technology

Achieving TRL 4 for the Coordinated DSA technology requires that:

1) the scenario should be larger to evaluate how a frequency reuse scheme with 3 colors in the NTN component impacts the C-DSA technology. This is planned to be implemented by the end of the project;
2) large-scale network coordination issues, e.g., how to determine which NTN beams and TN cells are interfering with each other and thus should be coordinated, should be addressed. Moreover, also how these aspects change as the constellation moves is an aspect to be taken into account;
3) coordinated-DSA would be able to configure the control planes of the TN and the NTN so as to allow spectrum sharing without harmful interference and without losing system capacity due to resource sharing.

In the current NTN simulator, the spectrum management function can control the scheduling limitations so that coordinated spectrum sharing would be possible without harmful interference and without losing system capacity due to sharing. The simulation solution does not include all issues related to sharing and all parts of the frame structure, but it assumes that the control signals can be limited to the same frequencies as data frequencies. The challenges which should be solved in a real system have been identified, but they have not all been solved in the DYNASAT project.

Means/Way forward to achieve TRL 5 for Coordinated DSA technology

Achieving TRL 5 for the Coordinated-DSA technology would mean that:

1) the Coordinated-DSA spectrum management system for NTN - TN sharing is connected to the real control plane management of the TN network;
2) the Coordinated-DSA is connected to the control plane management of NTN network;

the frame control includes all parts of the TN and NTN frames, and the spectrum management system is able to dynamically control these elements.

3.3 Prototyping

In terms of the demonstrations/prototyping done within WP5, three demonstrations over two separate software components are considered:

1. Multi-Connectivity over 5G NTN system level simulator and Magister SimLab simulation service developed by Magister Solutions

2. Coordinated Dynamic Spectrum Allocation (C-DSA) over 5G NTN system level simulator and Magister SimLab simulation service developed by Magister Solutions

3. Non-Coordinated Spectrum Sharing over a web service developed by Fairspectrum.

Demonstrations 1 and 2 are planned to be developed on top of the "5G NTN" packet-level system/network level simulator, which is operating in a non-real time mode. Together with Magister SimLab simulation service they form so called RAN Lab Demonstrator of DYNASAT project. 5G NTN system level simulator models the NR/NTN user plane protocol stack with sufficient accuracy as well as relevant parts of the NR/NTN control plane protocols.

With these assumptions, the target TRL of WP5 demonstrations is TRL 3.

Demonstration 3 will be developed as a cloud service just like a commercial system would be deployed. The interface to incumbent (TN OAM) will be similar to a commercial system i.e. a list of TN base stations and their operating parameters. The exact form of the list and the method to retrieve will be country specific, so that will be finalized in the system integration phase of a commercial deployment. The control of the licensee system (NTN OAM) will be carried out through 3GPP LSA - OAM interface. The interface has been developed for terrestrial networks, which have fixed base station locations.

If the required information from the spectrum management (LSA Controller) to the NTN OAM is just geographically defined beam availability, we can get relatively close to a potential commercial interface. If the required information includes satellite constellation, orbits, timing and other NGSO specific information, a significant change to the LSA – OAM interface will be required.

The same applies to the developed spectrum management system. As we do not have any base stations or OAM in DYNASAT, the TRL level of Non-coordinated DSA will be 4. The demonstration will be carried out as a proof-of-concept spectrum management system instead of a simulation system like in coordinated spectrum sharing. The incumbent and licensee interfaces to the system will be web user interfaces.

Table 6: TRL assessment for the technologies studied in the DYNASAT project

Technology	Beginning of the project	Expected TRL at the end of the project
MU-MIMO standalone	TRL 2	TRL 4/5
MU-MIMO multiple	TRL 1	TRL 3/4
Multi-Connectivity	TRL 3	TRL 4
Coordinated DSA	TRL 2	TRL 3

Non-Coordinated DSA	TRL 3	TRL 4

4 CONCLUSIONS

In this document, we summarized the outcomes of Task 2.2 “Targeted Performances.” More specifically, the following contributions have been provided:

- The description of the services considered of potential interest for the Project activities and highlighted those that will be retained for future activities.
- An overview of the 3GPP TRs and TSs providing relevant information with respect to the definition of the KPIs to be considered for the Dynasat services. Based on these, we also listed a set of economic and technical KPIs deemed of particular interest for the Dynasat techniques.
- A qualitative assessment of the benefits that can be obtained by introducing bandwidth efficient techniques in the Dynasat framework. In particular, MU-MIMO, DA, and CA.
- An overview of the gain that can be obtained with spectrum sharing techniques in terms of the Spectrum Utilization Efficiency in different spectrum sharing scenarios.
- A description of the system capacity simulation tool, with the assessment of the system-level capacity without the implementation of advanced techniques.

It shall be mentioned that the Energy Efficiency and Life Cycle assessment is considered to be significantly related to the final system architecture and the related performance when bandwidth-efficient are implemented. As such, this topic will be covered later in the project activities and, in particular, as outcome of Task 2.4.

REFERENCES

[1] EC SPACE-29-TEC-2020 Project DYNASAT (Dynamic spectrum sharing and bandwidth-efficient techniques for high-throughput MIMO Satellite systems), Deliverable D2.1, “NGSO based satellite access overview,” June 2021.
[2] 3GPP TS 22.105 V16.0.0, “3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Services and service capabilities (Release 16),” July 2020.
[3] 3GPP TS 22.261 V18.3.0, “3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Service requirements for the 5G system; Stage 1(Release 18),” June 2021.
[4] 3GPP TR 38.811 V15.4.0, “3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on New Radio (NR) to support non-terrestrial networks (Release 15),” September 2020.
[5] 3GPP TR 38.821 V16.1.0, “3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Solutions for NR to support non-terrestrial networks (NTN) (Release 16),” May 2021.
[6] A. Guidotti et al., "Architectures and Key Technical Challenges for 5G Systems Incorporating Satellites," in IEEE Transactions on Vehicular Technology, vol. 68, no. 3, pp. 2624-2639, March 2019.
[7] EC SPACE-29-TEC-2020 Project DYNASAT (Dynamic spectrum sharing and bandwidth-efficient techniques for high-throughput MIMO Satellite systems), Deliverable D3.1, “Bandwidth Efficient Techniques selection,” May 2021.
[8] EC SPACE-29-TEC-2020 Project DYNASAT (Dynamic spectrum sharing and bandwidth-efficient techniques for high-throughput MIMO Satellite systems), Deliverable D4.1, “DSA for non-geostationary satellites,” May 2021.
[9] 3GPP TS 38.811, "Study on new radio (NR) to support non terrestrial networks (Release 15)", Sophia Antipolis Cedex, France, TR 38.811, Sept. 2019 (Rapporteur: Thales/Nicolas Chuberre).
[10] 3GPP TR 38.821, "Solutions for NR to support non-terrestrial networks (NTN) (Release 16)", Sophia Antipolis Cedex, France, TR 38.821, Dec. 2019 (Rapporteur: Thales/Nicolas Chuberre).
[11] RP-193234, "Solutions for NR to support non-terrestrial networks (NTN)", Thales, 3GPP TSG RAN meeting #86, Sitges, Spain, December 2019.
[12] RP-191600 Multi-RAT Dual-Connectivity and Carrier Aggregation enhancements.
[13] P. Arapoglou, K. Liolis, M. Bertinelli, A. Panagopoulos, P. Cottis and R. De Gaudenzi, "MIMO over Satellite: A Review," in IEEE Communications Surveys & Tutorials, vol. 13, no. 1, pp. 27-51, First Quarter 2011.
[14] P. Angeletti, R. De Gaudenzi, "A Pragmatic Approach to Massive MIMO for Broadband Communication Satellites,"IEEE Access, vol. 8, 2020.
[15] L. You, K. -X. Li, J. Wang, X. Gao, X. -G. Xia and B. Ottersten, "Massive MIMO Transmission for LEO Satellite Communications," in IEEE Journal on Selected Areas in Communications, vol. 38, no. 8, pp. 1851-1865, Aug. 2020.
[16] A. Guidotti, M. Conti, A. Vanelli-Coralli, "Distributed Beamforming in LEO Constellations for NB-IoT Services in 6G Communications," submitted to Globecom 2021.
[17] RP-182863 Enhancements on MIMO for NR.
[18] RP-193133 Further enhancements on MIMO for NR.

[19] RP-191600 Multi-RAT Dual-Connectivity and Carrier Aggregation enhancements.

[20] ITU-R SM.1046-1. Definition of spectrum use and efficiency of a radio system. 1997. https://www.itu.int/dms_pubrec/itu-r/rec/sm/R-REC-SM.1046-1-199710-S!!PDF-E.pdf

[21] T. Chen, W. Wang, R. Ding, G. Seco-Granados, L. You and X. Gao, "Precoding Design for Joint Synchronization and Positioning in 5G Integrated Satellite Communications," 2021 IEEE Global Communications Conference (GLOBECOM), 2021, pp. 01-06, doi: 10.1109/GLOBECOM46510.2021.9685480.

[22] D. Peng, Y. Li, S. Chatzinotas and B. Ottersten, "Hybrid Analog-Digital Precoding for mmWave Coexisting in 5G-Satellite Integrated Network," 2020 IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications, 2020, pp. 1-6, doi: 10.1109/PIMRC48278.2020.9217237.