Ref. Ares(2022)4111340 - 02/06/2022

Grant Agreement N°: 101004145

Topic: SPACE-29-TEC-2020

DYNASAT

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

D2.1: NGSO based satellite access overview

Revision: v.2.0

Work package	WP 2
Task	Task 2.1
Due date	30/06/2021
Submission date	31/05/2022
Deliverable lead	TAS
Version	2.0

Abstract

This document provides a description of the 5G satellite access and its targeted services. It reviews the main parameters for the satellite system, as user equipment description and 5G-NR radio parameters needed to fit the retained services. An overview of reference architectures and scenarios is presented, with the related constellation solution analysis. It highlights the main features and constraints needed to apply bandwidth efficiency transmission and spectrum sharing techniques. Based on the first outcomes, some indicators are described in order to estimate the impact of such techniques.

Keywords: NGSO – 5G SATELLITE SYSTEM – ARCHITECTURE – SERVICES

Document Revision History

Version	Date	Description of change	List of contributor(s)
V1.0	17/06/2021	First version of the document	TAS / UNIBO / FS / UniPr
V1.1	03/12/2021	Second version of the document	TAS / UNIBO / FS / UniPr
V2.0	31/05/2022	Second release of the document after Y1 comments	TAS / UNIBO

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

EXECUTIVE SUMMARY

As one of the ambitions of DYNASAT, this document presents an overview of satellite based access for 5G non-terrestrial systems. It focuses on a satellite network infrastructure based on a constellation, which will take into account system constraints related to the application of bandwidth efficient transmission and efficient spectrum usage techniques.

An analysis of targeted services is detailed. The aim of such constellation is to serve mass market and professional 5G user equipment, and so the selected targeted services are broadcast/multicast via satellite, digital divide, coverage extension and maritime coverage. All services address pedestrians with class 3 handheld equipment, as described by 3GPP. They correspond to commercial smartphones, in FR1 (<6GHz), for direct access. The related satellite and NR radio parameters are also based on 3GPP requirements, for an S-band system, which are used to have a preliminary estimation of link budgets.

In order to evaluate the performance gain of the use of bandwidth efficient techniques on a NGSO-based 5G system, three reference architectures have been defined. Later, they will be compared through technical and economic indicators as data rate, served capacity or system CAPEX/OPEX, among others that are described in this document. The first architecture, called "5G baseline architecture", is based on a 5G constellation addressing handheld terminals but ensuring only simple visibility (each UE will have only one satellite in view). It corresponds to Release 17 approach in 3GPP and considers the RU on board (part of the transparent architectures in 3GPP NTN Rel.17 WI). This case is reworked in "DYNASAT A" architecture where the constellation design ambitions more satellites (at least 2) are viewed by a majority of UEs, making possible throughput enhancements with simultaneous dual (or multiple) link operations. Finally, "DYNASAT B" will be derived from "DYNASAT A" with restrictions to only shorter-term bandwidth advanced techniques and spectrum sharing.

Besides the number of satellites, other requirements are needed for the application of multi connectivity and enhanced MIMO techniques, as well as for dynamic spectrum sharing approaches. Coverage overlap, time synchronisation or sharing between TN and NTN have been described and may have an impact on DYNASAT architecture. Frequency reuse or possible band combination need also to be considered for payload definition, which could impact link budgets.

Finally, a baseline constellation is provided for DYNASAT solution. Based on a global coverage solution, satellites at around 600 km of altitude will ensure the required services.

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ABBREVIATIONS

CAPEX	Capital Expenditure
CC	Component Carrier
DC	Dual Connectivity
DCI	Downlink Control Information
DL	Downlink
DRA	Direct Radiating Array
EIRP	Equivalent Isotropic Radiated Power
eMBB	enhanced Mobile Broadband
FR	Frequency Range
gNB	next Generation Node B
gNB-CU	gNB Centralized Unit
gNB-DU	gNB Distributed Unit
IP	Internet Protocol
ISL	Inter Satellite Links
IRR	Interest Rate of Return
KPI	Key Performance Indicator
MCG	Master Cell group (3GPP acronym)
MIB	Master Information Block
MIMO	Multiple-input multiple-output
MN	Main Node
MRC	Maximal Ratio Combining
MR-DC	Multi-Radio Dual Connectivity
NG-RAN	Next Generation Radio Access Network
NTN	Non-Terrestrial Network
OPEX	Operational Expenditure
OSS	Operational System Support
PBCH	Physical Broadcast Channel
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
SCG	Secondary Cell Group (3GPP acronym)
SCS	SubCarrier Spacing
SFN	System Frame Number

SN	Secondary Node
SAB	Security Advisory Board
SNO	Satellite Network Operator
SoA	State-of-the-art
SRI	Satellite Radio Interface
SRM	Satellite system Resource Manager
SSB	Synchronization Signal Block
TCO	Total Cost of Ownership
TCP	Transmission Control Protocol
TN	Terrestrial Network
TR	Technical Report
TT&C	Telemetry Telecommand & Control
UE	User Equipment
UL	Uplink

1 TARGETED SERVICES

In this Section, we define and detail the target services that will be addressed during the DYNASAT Project. To this aim, Section 1.1 provides a list of potential use cases, based on an extension of those outlined in 3GPP TR 22.822 [1]. Then, the set of services retained for the project activities is identified in Section 1.2 based on 3 criteria: applicability to DYNASAT architecture and main assumptions, need for advanced bandwidth-efficient techniques and need for spectrum sharing between terrestrial and satellite systems.

1.1 Service description

As reported in [1], the added value that Non-Terrestrial Networks (NTN) can provide as additional/complementary Radio Access Network (RAN), compared to terrestrial only communications, is in terms of:

- Service **continuity**
  - Notably, terrestrial networks are deployed based on users' density (and service revenues) rather than on a geographical basis. This approach has led to the well-known Digital Divide problem, with geographical areas where access to 5G or, in general, broadband services is not possible based on terrestrial networks. In such situations, the User Equipments (UEs), which can be pedestrian or on moving platforms (terrestrial, airborne, or maritime), might end up during their movement in areas in which a single or a combination of terrestrial networks cannot provide coverage. In such situations, the possibility to roam to a satellite network can guarantee the continuity of the 5G service, complementing and extending terrestrial networks in unserved areas.
- Service **ubiquity**
  - Apart from economic reasons, leading to Digital Divide areas, terrestrial networks can also be temporary or geographically unavailable due to natural disasters (e.g., floods, earthquakes) or terrorist attacks, which fully or partially destroy the infrastructure(s). In this framework, satellite access might be the only viable solution to ensure not only consumer service provisioning, e.g., both broadband/IoT services in un-/under-served zones and the coordination of first responders on the disaster area.
- Service **scalability**
  - Compared to terrestrial networks, satellites inherently cover much larger areas, e.g., tens of thousands of terrestrial cells could fit into a single satellite field of view. This unique characteristic makes satellite extremely efficient in providing broadcasting and multicasting services, either the same content over a large area or specific user content to dedicated UEs. In addition, satellites can contribute to off-load the traffic of the terrestrial networks in peak hours.

1.1.1 Internet of Things via satellite

There are many potential services that can be provided in the context of Internet of Things (IoT) by means of a satellite RAN. Since they all share many aspects related to the infrastructure and the interaction with a terrestrial network, they are all categorized at high level as an IoT via satellite framework. The specific description of the different services that can be identified in this ecosystem is reported below.

1.1.1.1 Smart good tracking

In this scenario, a moving platform (ship, train, or cargo flight) or a truck are carrying goods which must be continuously monitored and localized. To this aim, it is required that the boxes or containers are equipped with sensors that provide: i) the location, as a mandatory parameter; and ii) an optional set of parameters that allow to remotely keep track of the status of the good (e.g., the temperature of the boxes in which COVID-19 vaccines are being transported).

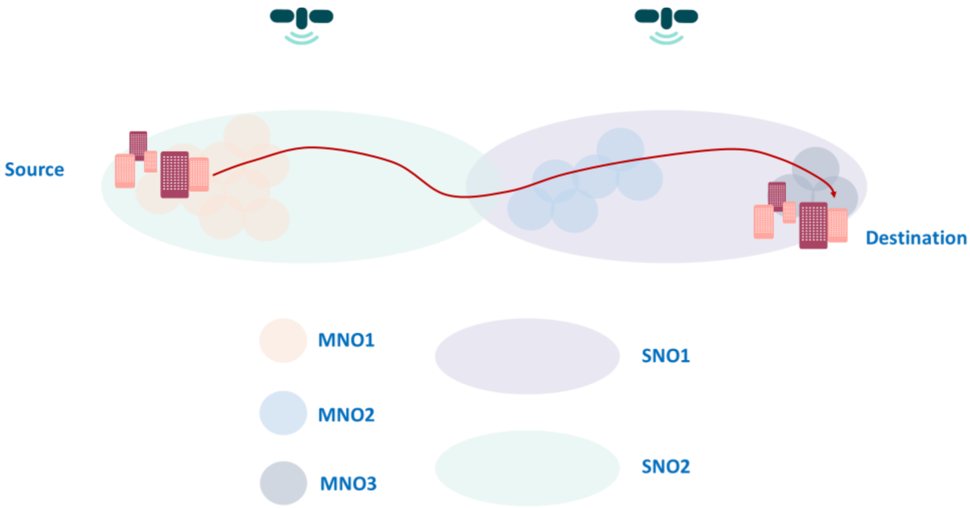


Figure 1: Smart good tracking: scenario.

Referring to Figure 1, a generic vehicle (maritime/airborne/train platform or truck) transporting the goods will move from the source to the destination on a path on which the continuous coverage from a single terrestrial network, or a combination of different networks, might be not guaranteed. For instance: i) a cargo flight will be able to connect to a terrestrial network while on-ground, but not during the flight time; ii) a train or vehicle will move across rural areas with no or limited population, where terrestrial Mobile Network Operators (MNOs) might not be encouraged to deploy an infrastructure; or iii) a ship can be connected to a terrestrial network when it is anchored or close to a harbour, but not off-shore. In this framework, the possibility to rely on satellite access through one or more Satellite Network Operators (SNOs) would actually guarantee service continuity. As for the latter, it is worth mentioning that, while the figure shows a single satellite per SNO for the sake of simplicity, when LEO constellations are exploited it is reasonable to assume that each UE/vehicle will be in the field of view of multiple satellites from the same SNO.

In order to provide the efficient and continuous possibility to roam between terrestrial and satellite networks, the following general requirements should be fulfilled:

- in order for the sensor to communicate the status of the goods, it is required that each box/container is equipped with a UE. In case this is not feasible, it might be envisaged to equip the container only with sensors, which then report their measurements to a Relay Node or to an active UE in order to connect to the network;
- each UE should have a subscription with at least one MNO (connection through other MNOs can then be guaranteed thanks to roaming contracts among the terrestrial operators);
- when the UE is not able to directly communicate with an MNO gNB or with an SNO satellite (e.g., it is at the bottom of a containers stack or in NLOS conditions), it shall have the capability to either connect to another UE (device-to-device) or, if available, to a Relay Node on-board the vehicle, which can gather the signals coming from all of the UEs and forward them to the network;
- roaming agreements are required among the terrestrial (MNO1, 2, and 3 in the example) and satellite operators (SNO1 and 2), so that the network reselection policies and techniques can be implemented.

The overall 5G system should thus provide connectivity by means of both terrestrial and satellite

Radio Access Technologies (RAT). When both options are available, advanced management techniques can be implemented so as to either route the traffic towards the best performing network or to implement Dual Connectivity (DC). In the latter case, it is worth mentioning that, when more than one satellite from the same network operator is visible, DC can be implemented as well. However, DC is a technique aimed at enhancing the capacity provided to the UEs; since in this scenario we are considering smart good tracking, which typically requires a limited amount of traffic per UE, it might be not necessary to implement advanced bandwidth-efficient techniques. Even assuming that a RN on-board the vehicle gathers the entire traffic before sending it through a MNO or SNO, the expected capacity requirements do not justify the implementation of advanced, and more complex, techniques.

1.1.1.2 NB-IoT/mMTC global coverage

This service aims at guaranteeing a continuous global coverage of NB-IoT or mMTC devices for any type of data transfer between the terminals and a central server, as long as non delay critical communications are involved.

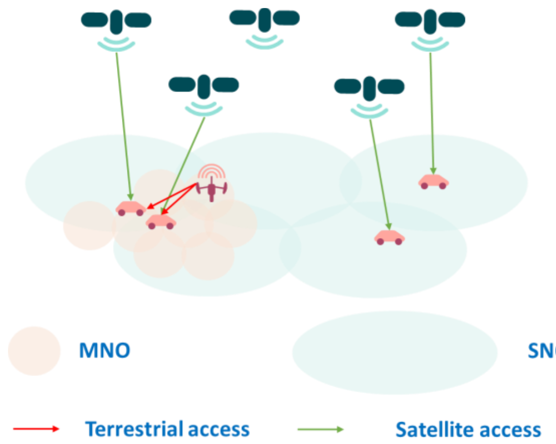


Figure 2: NB-IoT/mMTC global coverage: scenario.

As reported in Figure 2, a (mega-)constellation of LEO satellites can provide global coverage. The IoT terminals can be on moving platforms, e.g., vehicles, and, thus, can also experience the lack of a terrestrial infrastructure guaranteeing connectivity. In order to allow the IoT service provider to not interrupt its service, the satellite network can either directly provide the IoT service to the terminals in its coverage area or complement the terrestrial network(s) in un-/under-served areas by means of roaming agreements with the satellite network operator.

In terms of requirements, the following aspects can be identified:

- the 5G network shall support NB-IoT or mMTC services via satellite;
- the 5G system shall be capable of selecting the optimal access network to provide the required service (such selection can be based on, e.g., subscription contracts, terrestrial and satellite operator policies, or QoS settings);
- the UE shall be able to support NB-IoT or mMTC services through both a terrestrial and a satellite network infrastructure.

1.1.1.3 Remote control and monitoring of critical infrastructures

In this case, the 5G system aims at remotely controlling and monitoring critical infrastructures, as, e.g., an off-shore wind farm as shown in Figure 3. In general, independently from the specific application, the following traffic flows can be foreseen:

- remote monitoring and non-time-critical control of operations, with moderate capacity requirements and low latency (thus requiring HAPS or LEO);
- continuous data upload for data analytics, characterised by large capacity requirements

and no restriction on the latency;
- on-demand download of sensor data for remote analysis, which might involve large capacities and no restriction on latency;
- video surveillance during on-demand maintenance, with HD video transmission (large capacity) and low latency requirements;
- on-demand provision of information from the remote control center to on-site personnel, which might involve large capacity but no time criticality.

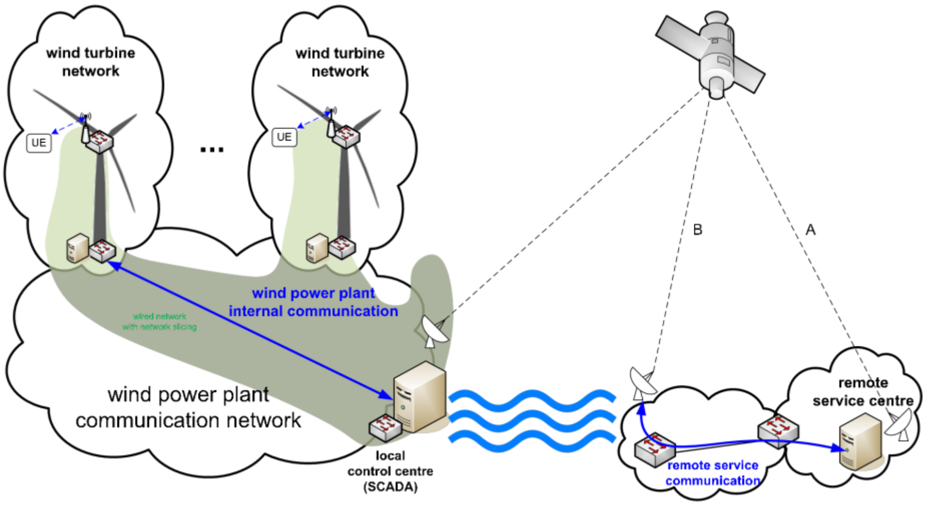


Figure 3: Off-shore wind power plant communication network connected to inland remote service centre via 5G satellite connection, [1].

To provide this type of service, the 5G system shall satisfy the following requirements:

- support uplink/downlink large data rates via satellite access;
- provide a large service availability, e.g., 99.99% or more;
- reconfigurability of the satellite access shall be ensured so as to satisfy different latency requirements.

1.1.2 Broadcast/multicast through satellite

In the context of enhanced Multimedia Broadcast and Multicast Systems (eMBMS), in which an ever increasing capacity request is being experienced (e.g., due to the increase in the number of UHDTV programs in broadcasting services, but in general this applies to all types of multicast/broadcast digital content), satellite networks provide an efficient access option to: i) serve users located in un-served areas, i.e., where no MNO is available; and ii) serve users with the required Quality of Service (QoS) when the MNO is saturating due to the large traffic requests, *i.e.*, for traffic off-loading.

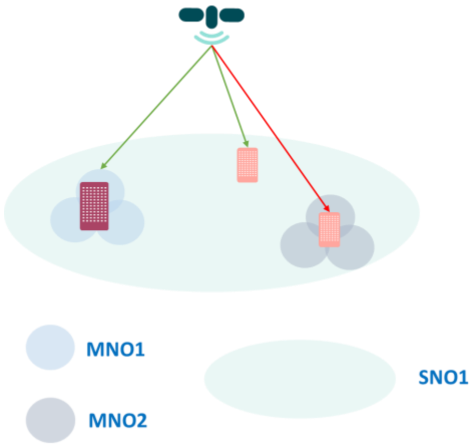


Figure 4: Broadcast and multicast with a satellite overlay: scenario.

Referring to Figure 4, the generic UE can be:

- indoor and, thus, it necessarily has to be served by means of a terrestrial network (as MNO2, in which the NLOS condition is highlighted in red);
- outdoor, in the coverage area of SNO1 only, thus requiring a direct connectivity to the satellite RAT;
- outdoor, in the coverage area of both MNO1 and SNO1. In this case, advanced techniques can be used to significantly enhance the capacity provided to the UEs as, for instance, Dual Connectivity among terrestrial and satellite networks or between multiple LEO satellites. This also corresponds to the case in which the satellite network can off-load traffic from the terrestrial one(s) during the most busy hours.

In terms of general requirements, the following can be identified:

- the 5G system should support both satellite and terrestrial RATs;
- the 5G system should implement techniques/procedures to optimise the content distribution, in particular when multiple options (terrestrial and satellite) are available;
- the UE should be able to connect to both a terrestrial and a satellite 5G network. Moreover, if DC solutions are envisaged, it shall also be able to actually receive parallel bearers from the satellite and terrestrial nodes.

1.1.3 5G to premises

This scenario is similar to the broadcast/multicast described above. However, in this case a terrestrial operator aims at gather traffic, including unicast, at an office gateway located in the area. The broadcasting/multicasting service will be provided over the satellite component, while, in general, unicast broadband services will flow through the terrestrial access. However, if latency is not critical, the satellite component can be used for unicast communications as well.

Similar requirements as those reported above for the multicast/broadcast scenario can be considered.

1.1.4 Emergency management

This scenario refers to situation in which a natural disaster or a terrorist attack destroy, fully or partially, part of the Radio Access Network or of the Core Network, which become unavailable as shown in Figure 5. Consequently, all of the services provided by one or more MNOs operating through the disrupted terrestrial infrastructure cannot be guaranteed anymore. Notably, the restoration of the communication infrastructure on the area is fundamental for both the population and, in particular, the first responders that need a telecommunication infrastructure to coordinate their efforts and to report to the command center the evolution of the rescue operations.

In this scenario, both LEO satellites or High Altitude Platform Stations (HAPS) can provide coverage with a sufficiently reduced latency. The MNOs in the target area would still be able to provide their services, with a limited capacity if needed so as to guarantee that all of their users can access the network and that rescue teams are guaranteed the priority, by means of roaming contracts with an SNO serving the area through a satellite network infrastructure. However, even in the absence of roaming contracts, the on-ground users can be granted direct access to the satellite infrastructure.

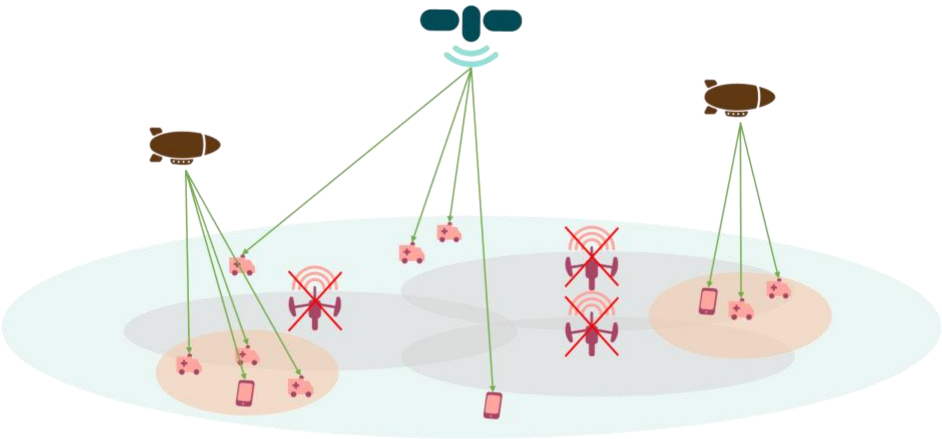


Figure 5: Emergency management scenario.

It is worth mentioning that the capacity requests in such scenario can range from very low values (e.g., simply reporting the locations of the different rescue teams to the command center, which can be in the same area or remote) to quite large (e.g., Augmented Reality helmets provided to the first responders, sending their videos to the command center).

The requirements for this service can be as follows:

- the 5G systems shall guarantee connectivity through a satellite component when the terrestrial infrastructure is not available;
- mission-critical communications shall be granted priority and, in case enough capacity is available, part of it can be allocated to routing baseline services (voice, SMS, limited data traffic) to other users
- in case AR connectivity is to be provided, DC or other advanced techniques that can exploit multiple satellites/HAPS can be used to enhance the capacity. In this case, the UE shall have the capability to rely on these techniques.

1.1.5 Optimal routing or steering over a satellite

In this service, it is envisaged that there is the need to monitor and/or control a fully/partially factory/farm/plantation in a remote area, which can be close to the edge of a terrestrial 5G network or even in an un-served area, as shown in Figure 6.

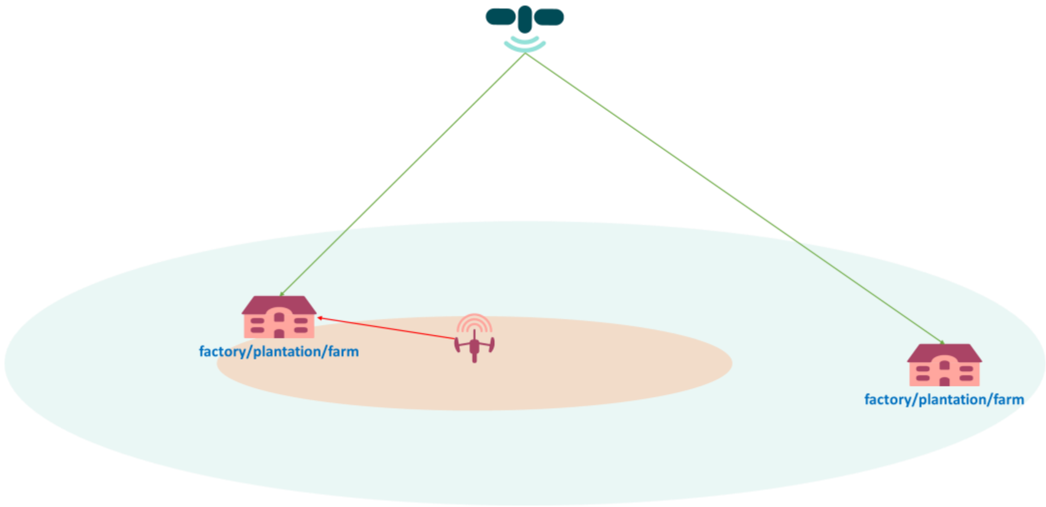


Figure 6: Optimal routing or steering over a satellite: scenario.

Even for a remote site located in the coverage area of a terrestrial network, during the traffic peak hours it might be difficult to achieve the required performance for broadband access for remote operations. However, in this case it is possible to implement DC or other bandwidth-efficient techniques to enhance the capacity. When the site is outside of the coverage of a terrestrial network, advanced techniques can be used only through the satellite network.

It is also worth mentioning that the UEs located indoor (e.g., in a factory, rather than a plantation) might have some issues in directly connecting to the satellite. In these situations, a Relay Node, providing gNB-like functions to the UEs, can be located in LOS with the satellite.

In terms of requirements, it is expected that the UEs shall be capable of implementing DC or other advanced bandwidth-efficient techniques combining terrestrial and satellite radio access.

1.1.6 Satellite transborder service continuity

In this scenario, two satellites are deployed providing a partially overlapped coverage (SA and SB) in correspondence of a border. In addition, there are also two terrestrial networks, TA and TB, providing coverage in their corresponding countries. In this context, the satellite access network can be:

- a single satellite network (single satellite or constellation), which extends the coverage of the available terrestrial 5G networks;
- a satellite network providing connectivity between the terrestrial networks and the core network;
- a standalone satellite network, which in any case can have roaming agreements with the terrestrial ones.

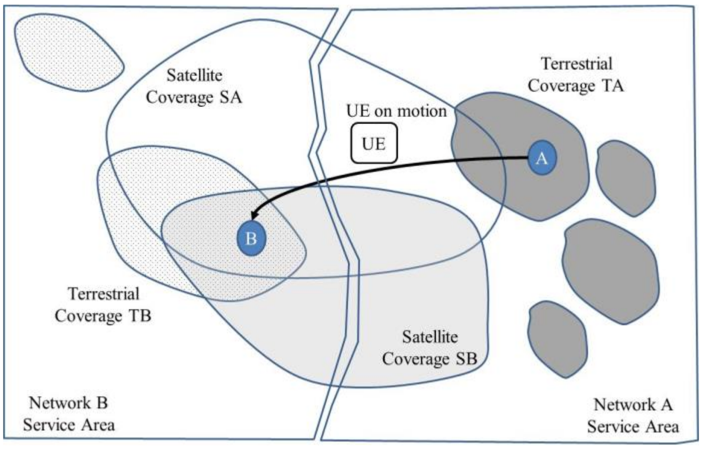


Figure 7: Satellite transborder service continuity scenario, [1].

This service allows a UE in motion to connect through the satellite RAT when the terrestrial connection is not available or for off-loading purposes. Even after passing the border, before the destination network operator, which shall have access to both SA and SB, can take in charge the UE traffic and ensure the service continuity. Once the terrestrial network in the destination country is available, the UE can be connected to TB. IT is worth mentioning that DC and other bandwidth-efficient techniques can be used to significantly enhance the capacity provided to the UEs. Several requirements shall be fulfilled to allow this service:

- the 5G system shall support the core network sharing and the possibility to have different MNOs, from different countries, attached to the same network;
- the satellite access network shall comply with the regulatory requirements of different countries;
- roaming shall be supported, also involving MNOs from different countries, guaranteeing the QoS.

1.1.7 Global satellite overlay

Notably, the propagation delay on satellite links is limited by the speed of light, while on fiber optics links, as reported in [xx] and [yy], it is limited by 2/3 of the speed of light. Thus, a delay equal to 1 ms can be obtained either through a 300 km satellite link or a 200 km fiber link. However, when the distance between the source and the destination increases, it can be more convenient (from a latency point of view) to consider NTN rather than a terrestrial connection.

In this framework, a (mega-)constellation of regenerative LEO satellites with gNB capabilities (either full gNB or the distributed unit in case functional split is implemented) can provide an overlay mesh network for all applications requiring long-distance connections with tight latency requirements. To this aim, it is also required that the satellites in the constellation can communicate with each other, i.e., Inter-Satellite Links (ISLs) can be established. Examples of applications requiring this type of network infrastructure are High Frequency Trading (HFT), and Banking or Corporate communications.

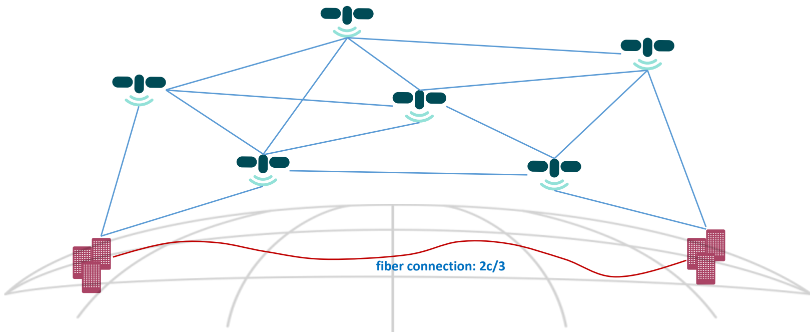


Figure 8: Global satellite overlay scenario.

In this context, the network operator can select different routes for the time-critical information to be sent, terrestrial or satellite based. Based on the network monitoring, the best performing route is selected on a case-by-case basis. The system requirements are as follows:

- the 5G system shall be able to select the communication link that provides the best QoS (latency, jitter, bit-rate);
- meshed connectivity (fully or partially connected, as in Figure 8) has to be supported in the space segment.

1.1.8 Indirect connectivity

In this scenario, the satellite network ensures service continuity for UEs located in remote un-served areas and to users that are on moving platforms which pass through such zones. These UEs might not have satellite access capabilities. Thus, indirect access should be provided by means of Relay Nodes, which shall be equipped with satellite access capabilities. Depending on the payload capabilities, two architectures can be defined as shown in Figure 9 and Figure 10 for transparent or regenerative payloads, respectively.

It is worth mentioning that a set of RNs can be accessing the 5G network through the same satellite, but from different countries, due to the large coverage potentially provided by a single satellite. Another possibility is that the RN itself can be located on a moving platform, e.g., cruise ships or aircrafts, and, thus, cross the border between two countries while providing continuous connectivity to its associated UEs. Notably, in this scenario, the UEs should not expect any difference in the type of services and the related QoS compared to a traditional terrestrial access.

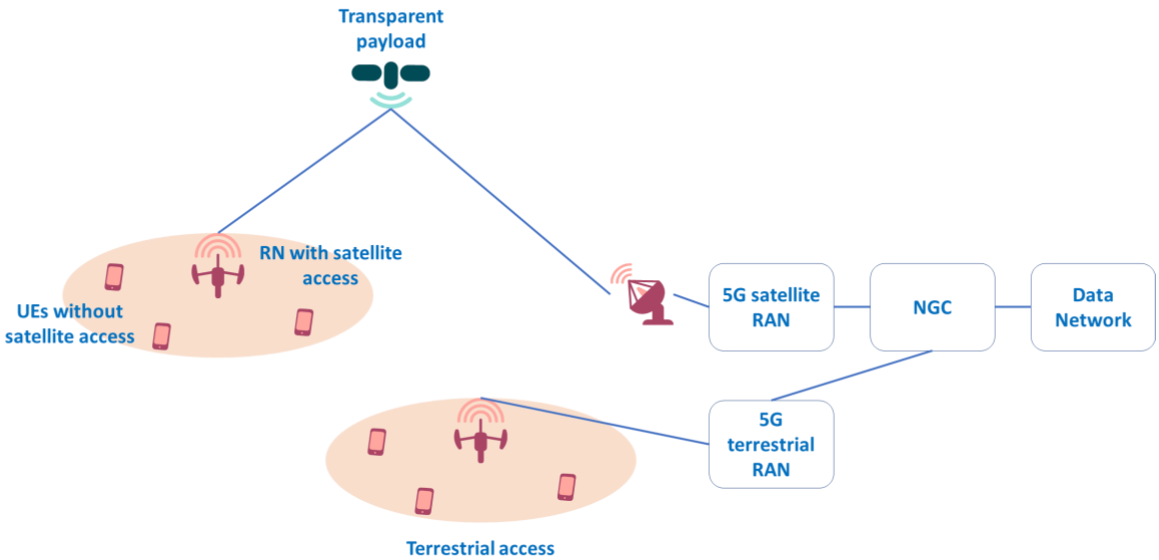


Figure 9: Indirect connectivity: transparent payload.

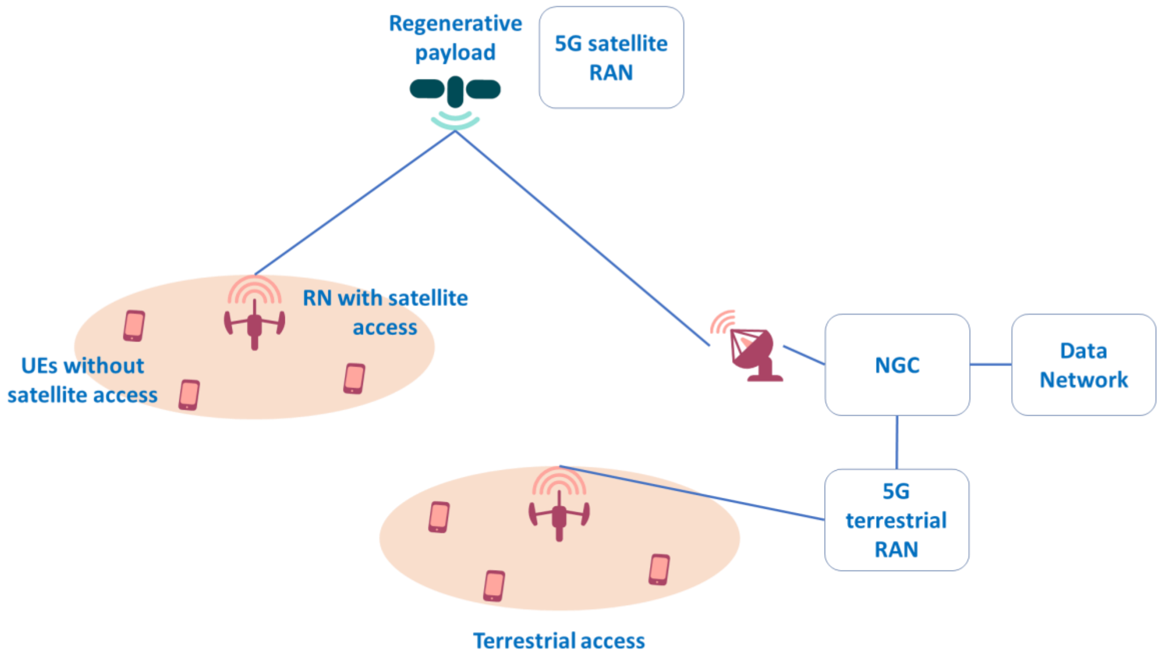


Figure 10: Indirect connectivity: regenerative payload.

A preliminary set of qualitative requirements can be as follows:

- the RN can be fixed, extending the coverage in remote areas and, thus, provide connectivity to a few UEs. However, when the RN is or a long-haul aircraft or a cruise ship, it can be expected that the number of required connections can be as large as a few hundreds or thousands, respectively;
- the RN shall continuously provide the required services to the attached UEs even during its roaming from one country to another, which might be non-trivial in order to be seamlessly performed from the UEs' perspective;
- the minimum QoS requirements that can be guaranteed should take into account the connectivity through a satellite, but the security performance for any UE should be the same as if it were connected to a terrestrial 5G RAN.

1.1.9 Satellite fixed/moving platform backhaul

In this scenario, one or more gNBs are located in remote, currently un-served areas or on-board moving platforms in order to extend the coverage of the 5G network by providing backhaul connectivity between the remote RAN and the Next Generation Core network (NGC). Clearly, the 5G system shall support satellite connectivity inside between the NGC and the RAN, or, possibly, also between elements of the NGC in order to enhance the deployment flexibility.

1.1.10 Digital divide

Digital divide refers to the gap between those who have access to digital solutions, as internet or mobile communications, and those who don't. Different reasons drive the lack of connectivity, mostly economic rationales, sometimes related to the low terrestrial infrastructure and so huge costs of new development. While in some countries of the world everything is digitally connected and seems not working without it anymore, others are still waiting for the accessibility.

Several worldwide initiatives exist to close the gap of digital divide. Indeed, only in Europe, 20% of EU citizens never used the internet, while 72% of EU citizens use internet at least once a week[1]. These figures are even worst in other countries, and open up new opportunities for bridging this division with global solutions.

As mentioned above, sometimes massive terrestrial infrastructures development could not be considered, and a satellite constellation could provide broadband solutions.

In this service, it can be distinguished two types of broadband digital divide use cases, fixed and mobile:

- Fixed: users are households and enterprise premises, for consumer or B2B markets, in areas not covered by terrestrial networks.
- Mobile: users are considered as outdoor pedestrians, connected to the satellites through handheld equipment. Some 5G terrestrial relays can be necessary.

1.1.11 Coverage extension

Also known as mobile broadband service continuity, this scenario covers the users that have already everyday connectivity and move to areas that are not covered by terrestrial networks. It focuses on pedestrian users with handheld equipment, only being connected through NTN services.

1.1.12 Maritime coverage

This scenario concerns users in cruise ships near the coast, for maritime leisure or cruise/commercial. Indeed, when moving some km far away the coastline, users loose connexion with terrestrial networks. This kind of use cases represent a good opportunity to use the terrestrial bandwidths without interference constraints. Direct connectivity to handheld could be offered, as well through a small 5G customer relay. Depending to the distance to the land, satellites could be connected to gNB in the coast.

1.2 Service selection

The above defined services, in which we re-envisaged part of those identified by 3GPP and reported in [1], show that the inclusion of one or more satellites into the New Radio (NR) Radio Access Network (RAN) can provide significant benefits. In this section, we identify a subset of these services that will be kept for further analyses in the DYNASAT Study.

To this aim, it is worth to recall that the DYNASAT Project aims at developing and demonstrating innovative techniques for bandwidth-efficient transmission and efficient spectrum usage to serve mass-market and professional equipment, in particular focusing on NGSO mega-constellations. As LEO orbits are targeted, latency will be of maximum of 6ms (and compatible with the constellation design described in Annex B), and so enough for most of the 5G NR networks (see requirements for each service[2], regulated by [2]). In particular, selected services are those that a

[1] https://digital-strategy.ec.europa.eu/en/library/eu-digital-divide-infographic

[2] https://5g-tools.com/qos-for-5g-nr/

pedestrian with a handheld equipment (typically an smartphone), will use through the 5G network. Thus, each scenario is classified based on the following criteria:

- Applicability to the DYNASAT architecture and assumptions, i.e., feasibility and efficiency in providing the considered service through a mega-constellation of NGSO satellites. In this case, it is worth recalling that direct connectivity is considered as RAN access method and that handheld terminal is foreseen, for the moment being.
- Need for advanced bandwidth-efficient techniques and enhanced broadband connectivity.
- Need for spectrum sharing between the satellite and the terrestrial network component.

Table 1 reports the evaluation of each service according to the above defined criteria. In particular, a low (L) evaluation corresponds to a limited matching between the service and the selection criterion, while high (H) implies a very good matching.

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

#	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

The scoring is then simply based on sum obtained for each criterion, equally weighted.

The following observations were made when classifying the services:

- Services related to the IoT are not considered as primary, due to the fact that they usually require a limited amount of data to be sent/received, i.e., low broadband classification. It can be considered as an opportunity, in the case where the satellites capacity is not completely saturated by other services. For example service 1.3, in which it is possible that high resolution video feeds are to be sent to a central control station. In terms of spectrum sharing, services 1.1 and 1.2, in which the IoT device is moving and often will see both a satellite and a terrestrial network, it is possible to foresee the implementation of spectrum sharing techniques, but with a limited impact since the capacity requirements are limited. In service 1.3, spectrum sharing is unlikely to be required, since the remote station to be controlled and monitored is likely to be in a remote zone without a terrestrial infrastructure.

- With respect to service 2, the off-loading case might have a limited interest in terms of spectrum sharing: in fact, if the terrestrial spectrum is saturated by the excessive traffic, it is unlikely that a MNO will share its spectrum with a satellite operator. In this context, a possible scenario could be that of reducing the size of the terrestrial cell in order to implement spectrum sharing to a certain extent. In terms of architecture, as long as we focus on handheld devices, the usage of NGSO mega-constellations with direct access is definitely applicable. Indoor could be considered only in the case where the satellite antenna is large enough to close the link budgets (several dB of margin).
- In service 3, it shall be noticed that we have a traffic aggregator located at the gateway, which can be implemented at the MNO office. Thus, in this case we do not have a direct access scenario, but rather a scenario in which Relay Nodes (RN) or Integrated Access and Backhaul (IAB) nodes are present. In terms of capacity request and spectrum sharing, the backhauling of a large quantity of aggregated traffic can be indeed redirected through a non-terrestrial constellation.
- The emergency management scenario (service 4) can be indeed of interest, in particular when considering LEO satellites rather than HAPS. More specifically, in terms of architecture a mega-constellation of LEO satellites providing direct access to handheld terminals can rapidly provide connectivity over an area in which a natural or man-made disaster occurred. Moreover, the capacity requests can be large, in case high resolution videos or Augmented Reality services are to be guaranteed to the first responders. Finally, in case the terrestrial infrastructure is not completely disrupted, advanced spectrum sharing techniques can be beneficial both in terms of capacity and reliability.
- In service 5, the scenario in which the terminals are indoor is not of interest, since this would require a traffic aggregator (RN/IAB), i.e., non-direct access. The service can be of interest only in case that the control and monitoring of the remote facility is to be performed through outdoor terminals. This makes the applicability in terms of the architecture a bit limited; however, assuming an area in which both terrestrial and a satellite connectivity is possible, a solution could be to make outdoor terminals to be served by the satellite components while the indoor terminals would be served by terrestrial. This would provide a significant benefit through enhanced broadband capacity and spectrum sharing techniques. Note also this adds requirements by means of channel estimation and/or localization, also involving possible exchange between the terminal and the RAN infrastructure.
- In service 6, different scenarios could be imagined. Either to protect MNO's of neighboring countries or to provide service in the frequency bands of each country, there will be an impact on the satellite architecture.
- In service 7, it shall be mentioned that in DYNASAT we are not considering ISLs for the moment being and, thus, the applicability in terms of architecture is limited. With respect to spectrum sharing, such techniques would only be implemented close to the source and the destination, while along all of the ISL hops no terrestrial network is present. Finally, the amount of traffic required for the applications that would be exploiting this type of service (e.g., High Frequency Trading or Banking or Corporate communications) is typically limited.
- For both service 8 and 9, it shall be mentioned that no handheld terminals are considered for the moment being, while in terms of capacity and spectrum sharing with terrestrial networks we might indeed have some benefit. By the way, a huge band will be needed in

order to consider backhauling, so more likely FR2 bands than FR1, which is also one of the main hypothesis of DYNASAT.

- Digital divide (service 10) is of particular interest considering mobile use case. Further, it responds also to an interesting economical use case.
- Coverage extension (service 11) is a global use case covering un-served areas for pedestrians. Even with the objective of using terrestrial bandwidths, no interferences are expected as they are used in remote areas. We can consider that this service could cover also service 5 use cases.
- Finally, maritime coverage (service 12) is particularly interesting to exploit sea areas. In the case that it concerns near coastal zones, satellite could cover them and connect its feeder link to the lands, thus preventing ISL need, in this specific case. Therefore the service would be limited coverage extension from the 5G terrestrial service (e.g. 700 MHz). Beyond a certain distance depending on the satellite altitude and other system factors, the coverage could not be ensured and ISL would then be required.

In conclusion, based on the above considerations and on the classification reported in Table 1, the following services are to be considered as primary for the DYNASAT studies:

- Broadcast/multicast via satellite, Section 1.1.2
- Digital divide, Section 1.1.10
- Coverage extension, Section 1.1.11
- Maritime coverage, Section 1.1.12

2 5G SATELLITE ACCESS

In the following are presented some initial performance or characteristics to consider for the system. Next work phases may refine, discuss, or propose alternatives to these baseline.

2.1 Frequency Bands

Initial assumption for satellite access in a legacy Mobile Satellite Service band compatible in FR1 < 6 GHz, and suitable for Handheld devices. The MSS "S-Band" is selected as baseline for the satellite operations for Dynasat. S-band is referred to in 3GPP works (TR 38.821 [3]).

More insights of band selection, constraints and alternative options are presented in document D2.3 [9]. In particular, the analysis of neighbor terrestrial channels will also be considered.

The downlink and the uplink frequency, respectively 2,17 and 1,98 GHz are used in the initial link budget analysis presented in the Appendix A of this document.

2.2 Satellite parameters

The antenna hypothesis will be derived from the antenna solutions described in [9] with DRA and beamforming capabilities.

The complete list of the parameters is given in the Appendix B of [9]. There are three types of antennas, which vary in size.

To perform initial sizing based on link budget, the Type 1 antenna performance in S-Band was considered.

Other satellite constraints (mass, power, etc.) are not specified at this stage.

2.3 5G-NR radio parameters

2.3.1 Introduction

In 5G-NR, there are three physical channels for each of the uplink and downlink: the Physical Broadcast Channel (PBCH) that forms part of the synchronization block and provides the UE with the Master Information Block (MIB), the Physical Downlink Shared Channel (PDSCH), the main physical channel used for unicast data transmission but also for transmission of paging information, random-access response messages, the Physical Downlink Control Channel (PDCCH), the physical channel used to transmit Downlink Control Information (DCI) messages that contain PDSCH and PUSCH transmission resource scheduling information for one or multiple user equipment, the Physical Random Access Channel (PRACH) used for the initial channel access, the Physical uplink shared channel (PUSCH) the uplink counterpart to the PDSCH, and the Physical uplink control channel (PUCCH) that carries the uplink control data.

2.3.2 Reference SCS and preamble configuration for DYNASAT

In 5G-NR several choices of the subcarrier spacing (SCS) are available. The choice of the SCS depends on the operating band and on the channel type. For data transmission, 5G-NR operating bands in FR1 (frequency < 6GHz) shall be operated based on low SCS i.e. 15 kHz, 30 kHz and 60 kHz. In FR2 (frequency > 6 GHz), the SCS of 60 kHz and 120 kHz are deployed.

For the S-band analysis, 15 kHz subcarrier spacing is considered (recommendation for increasing the robustness with respect to timing tracking errors and channel time dispersion, according to prior Thales internal work). A Physical Resource Block (PRB) contains 12 OFDM sub-carriers in the frequency domain, which gives a total bandwidth of 180 kHz per PRB to be taken into account on link budget computations. User data on the uplink is carried on PUSCH physical channel and on PDSCH physical channel on the downlink.

On the downlink, the initial cell search and acquisition are enabled by the Synchronization Signal Block (SSB). The SSB spans four OFDM symbols in the time domain and 240 subcarriers in the frequency domain. The SSB possible subcarrier spacing are summarized in the table below

Table 2: SSB subcarrier spacing and corresponding frequency range

Subcarrier spacing (kHz)	SSB bandwidth (MHz)	Frequency range
15	3.6	FR1 (< 6 GHz)
30	7.2	FR1
120	28.8	FR2
240	57.8	FR2

Once the SSB has been detected, the UE can acquire the framing structure and use the SSB as a reference for internal frequency adjustment. From a system point of view, once the PBCH has been demodulated, the UE can derive the system frame number and the cell identity and decode the Master Information Block (MIB). The MIB provides essential information to enter the network.

Moreover, in order to synchronize on the uplink, i.e., to establish a new connection with the gNB, a preamble is sent over PRACH channel. 13 types of preamble formats are supported. They can be segmented into two categories: long preambles and short preambles.

- Long preambles have a sequence of length $L_{RA} = 839$. There are four different long preamble formats: 0, 1, 2 and 3. Note that they can only be used for FR1 frequency bands and do not share the same SCS as standard NR data numerologies, with SCS=1.25 kHz or 5 kHz. For numerology µ = 0 the PRACH SCS is set to 1.25 kHz . In other words, if we consider it in terms of 15 kHz spacing, a long preamble with this numerology occupies approximately 6 RB in the frequency domain (839*1.25 kHz ≈ 6*15kHz*12). The long PRACH formats are presented in the Table 3 from [3] [TS 38.211]

Table 3: PRACH preamble formats for $L_{RA} = 839$ *and* $\boldsymbol{\Delta f}^{RA} \in \{\mathbf{1.25}, \mathbf{5}\}$ *kHz*

Format	L_{RA}	Δf^{RA}	N_u	N_{CP}^{RA}	Support for restricted sets
0	839	1.25 kHz	24576κ	3168κ	Type A, Type B
1	839	1.25 kHz	$2 \cdot 24576\kappa$	21024κ	Type A, Type B
2	839	1.25 kHz	$4 \cdot 24576\kappa$	4688κ	Type A, Type B
3	839	5 kHz	$4 \cdot 6144\kappa$	3168κ	Type A, Type B

- Short preambles have a sequence of length $L_{RA} = 139$. There are nine different short preamble formats: A1, A2, A3, B1, B2, B3, B4, C0 and C2. The short preamble formats SCS is aligned with the normal NR SCS (15, 30, 60, 120kHz). These new short preamble formats with larger subcarrier spacing and shorter sequences have been introduced to enable new use cases, such as low-latency and high-speed transmissions. Table 4 summarizes the short PRACH preambles

Table 4: Preamble formats for $\boldsymbol{L_{RA}} \in \{\mathbf{139, 571, 1151}\}$ and $\boldsymbol{\Delta f^{RA}} = \mathbf{15 \cdot 2^{\mu}}$ kHz where $\boldsymbol{\mu} \in \{\mathbf{0, 1, 2, 3}\}$

Format	L_{RA}			Δf^{RA}	N_u	N_{CP}^{RA}	Support for restricted sets
	$\mu \in \{0,1,2,3\}$	$\mu = 0$	$\mu = 1$				
A1	139	1151	571	$15 \cdot 2^{\mu}$ kHz	$2 \cdot 2048\kappa \cdot 2^{-\mu}$	$288\kappa \cdot 2^{-\mu}$	-
A2	139	1151	571	$15 \cdot 2^{\mu}$ kHz	$4 \cdot 2048\kappa \cdot 2^{-\mu}$	$576\kappa \cdot 2^{-\mu}$	-
A3	139	1151	571	$15 \cdot 2^{\mu}$ kHz	$6 \cdot 2048\kappa \cdot 2^{-\mu}$	$864\kappa \cdot 2^{-\mu}$	-
B1	139	1151	571	$15 \cdot 2^{\mu}$ kHz	$2 \cdot 2048\kappa \cdot 2^{-\mu}$	$216\kappa \cdot 2^{-\mu}$	-
B2	139	1151	571	$15 \cdot 2^{\mu}$ kHz	$4 \cdot 2048\kappa \cdot 2^{-\mu}$	$360\kappa \cdot 2^{-\mu}$	-
B3	139	1151	571	$15 \cdot 2^{\mu}$ kHz	$6 \cdot 2048\kappa \cdot 2^{-\mu}$	$504\kappa \cdot 2^{-\mu}$	-
B4	139	1151	571	$15 \cdot 2^{\mu}$ kHz	$12 \cdot 2048\kappa \cdot 2^{-\mu}$	$936\kappa \cdot 2^{-\mu}$	-
C0	139	1151	571	$15 \cdot 2^{\mu}$ kHz	$2048\kappa \cdot 2^{-\mu}$	$1240\kappa \cdot 2^{-\mu}$	-
C2	139	1151	571	$15 \cdot 2^{\mu}$ kHz	$4 \cdot 2048\kappa \cdot 2^{-\mu}$	$2048\kappa \cdot 2^{-\mu}$	

Due to the small SCS, the long formats with Δf^{RA} = 1.25 kHz are less robust to Doppler offsets than the short formats. However the format 2, the longest available preamble format, is more suitable for low SNR levels with four repetitions. Its important CP length makes it very robust to timing errors. The short format B4 is also to be investigated since it is suitable for low SNR levels. It occupies twelve resource blocks in the frequency domain. It is more robust to Doppler offsets. Compared to the format 2, it facilitates the on-board processing since it allows the receiver to use the same FFT for data and random access preamble detection.

2.1 Radio environments and deployments

UEs of interest, for which satellite operations are envisaged, are always considered being in **outdoor conditions.**

Further, the satellite constellation coverage is assumed to co-exist with terrestrial 5G cellular networks. Identification of the possible regimes of coexistence, their performances and constraints are analyzed in the project.

Co-existence with another LEO system is not considered in this work.

2.2 User Equipment characteristics

DYNASAT consider all category of 5G UE in satellite Direct Access of potential interest except the most tiny devices for specific IoT services . However a strong focus is put on Handheld.

All considered UEs are assumed to comply with 5G NR air interface. Unless specified or discussed, UEs has access to a location service that can be based on GNSS.

2.2.1 Handheld UEs

The User Equipment considered is a class 3 Handheld in FR1 bands (< 6 GHz) and with non-directional antenna. These handhelds correspond to commercial smartphone performances for eMBB services in Direct Access. The UE characteristics are based on 3GPP standard and legacy of UE development. A best case and a worst case for UE have been derived.

Table 5: Performances of the User Equipment (S-band)

PARAMETER	UE Best case	UE Worst case	UNITS
UE Type	Handheld		
Antenna Type Configuration	(1,1,2) with omni-directional antenna element (linear polarization) (*)		
Antenna Gain	0	-3	dBi
Tx Power Max	23	23	dBm
EIRP	-7	-10	dBW
NF	7	7	dB
G/T	-34,62	-37,62	dB/K

(*) : (1, 1, 2) configuration means: 1 line; 1 column; 2 polarizations (V/H)

2.2.2 Other UEs

Characteristics of other UE types will be provided as needed in the relevant analysis.

3 REFERENCE ARCHITECTURE & SCENARIOS

3.1 System mission and overview

DYNASAT system will be mainly composed by a 5G LEO constellation **providing global services for all the Earth (0-90° latitude range)**. The purpose is to take advantage of advanced bandwidth techniques and spectrum sharing in order to increase capabilities. The DYNASAT mission is to provide a satellite component for a 5G Direct Access service to serve handheld terminals, **in outdoor conditions**.

Key design principles are:

- Minimise the impact on the bill of material of mass market user equipment
- Minimise the impact on 5G network infrastructure
- Scale the capacity with the traffic demand

System architecture will be composed of several segments:

- Space segment: constellation, satellite platform and satellite payload
- Ground Segment: NTN-GWs, gNBs, ground distribution network, CN, UEs (User Equipment)
- Mission and Operations segment: SOC (Satellite Operations Centre) and NOC (Network Operations Centre) which consist of redundant facilities to control and operate the satellite constellation (mission ; payload and platforms) and the satellite network resources.

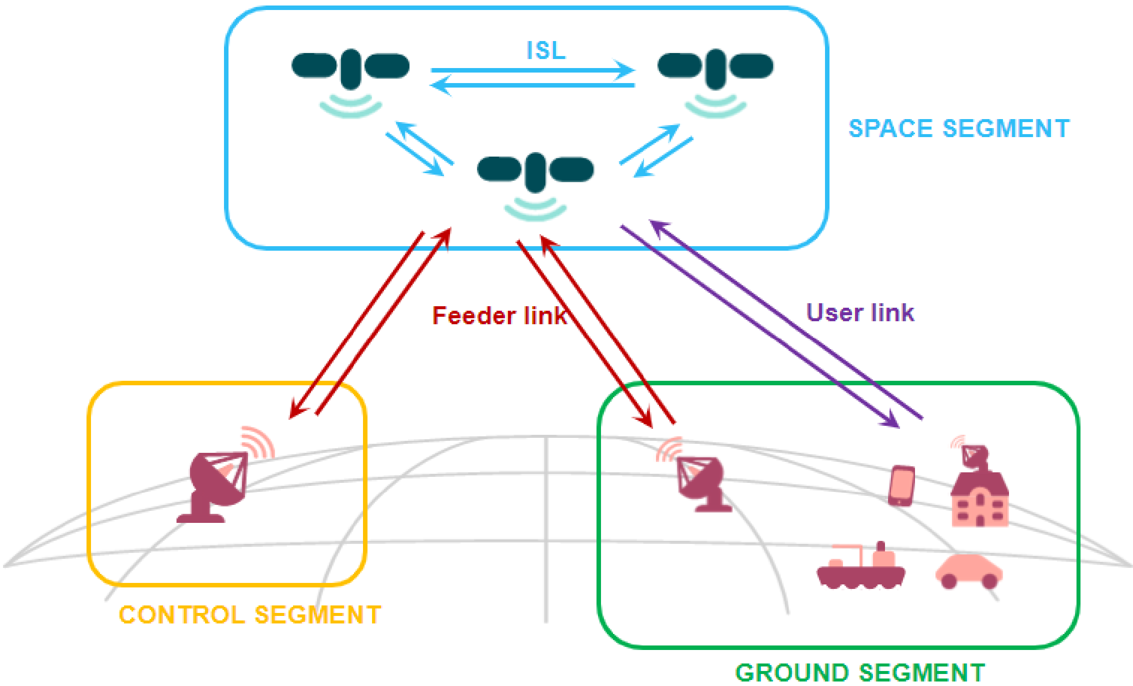


Figure 11: Satellite system segments.

Note:

Thanks to ISL, the actual Feeder Link used for a given UE access may not necessarily be established by the same satellite(s) in visibility of UE

Satellite RAN is composed by the satellites' payloads, NTN-GWs and gNBs.

Satellites could be interconnected through ISL (Inter Satellite Links). In addition, the payload includes OBP, clock, ISL transmitters/receivers, DRA antenna for User Segment (UE side) , and feeder link transmitters/receivers. Satellite TT&C link interface is also present.

The NTN-GWs provide the interconnectivity between the satellite constellation, the satellite NOC/SOC, the gNBs and CN through the ground distribution network.

The System architecture will be able to support native service in non roaming case for its own subscribers, and/or roaming with a visited CN and RAN sharing with a direct satellite RAN interface to MNO's CN. However the technical aspects of this topic will not be developed further in the project.

The Mission and Operations segment will count with:

- a TT&C link interface from the SOC to the satellite platform
- a M&C interface from the NOC to the satellite payload and RAN & CN OSS
- an external interface to terrestrial management systems from other MNO's through the NOC

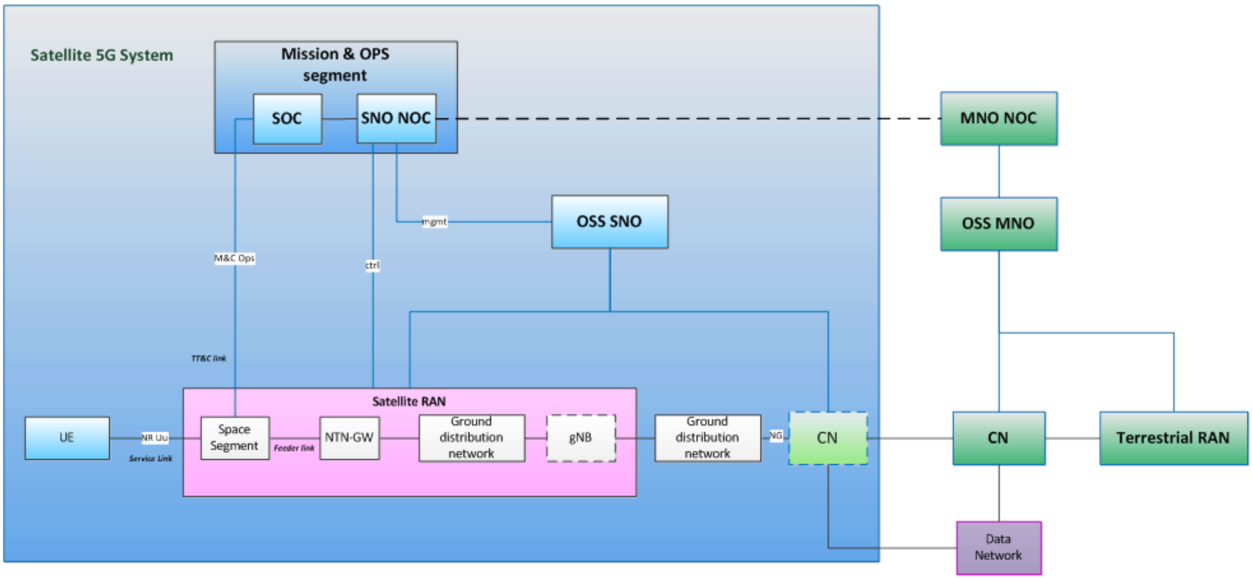


Figure 12: System functional breakdown architecture

The system functional breakdown will take into account the mixed architecture of non-roaming, RAN sharing & roaming compatibility and the gNB functional split on board / ground (several options). The gNB on board (or part of gNB in case of split) will determine the functions in the satellite OBP, as well as the exact protocol stack on the NTN-GW interface. Splitting options are discussed in the next section.

The routing function, spread over the OBP and ground network will allow to route data and control traffic to the proper destination through the constellation and ground distribution network. Note that in addition "Flow steering" (routing at service level) may also be managed at CN (at UPF).

The System M&C is split between the Satellite 5G NOC and SOC. The NOC configures, controls and monitors the satellite RAN, including the Payload and OBP, NTN-GW and gNB, and the satellite CN. The SOC configures, controls and monitors the satellite platform (satellite management). The NOC provides the human interface to network operators and externally the MNOs-NOC. The SOC is the interface to satellite operators.

In this model , the SNO also endorses a full 3GPP “MNO” role. Key points of the proposed architecture are:

1) SNO manages an independent 5G Core Network encompassing UE service management as well as satellite resource management and gNB-level resource management related to NR waveform. The 5G Core Network, also labelled CN in the figure, is expected to remain compatible with 3GPP specifications (i.e. standard UPF, AMF, and SMF, etc.). The UEs and gNBs interoperate with the 5G Core Network following 3GPP standard protocols (compatible with NTN features)

2) Also as a standard case in 3GPP architecture, the core network is also the interface to the (external) data networks (Public Internet; Public Switched Telephone Network; SIP networks…)

3) The SNO may provide “RAN sharing” capability to one ore multiple national MNOs. RAN sharing would allow for example the service of a terrestrial MNO to serve UEs located in the MNO country, without registering to the SNO Core Network. This would typically require prior MNO-SNO agreements.

3.2 gNB description and splits

Cellular base station (gNB in 5G) is obviously the critical functions and equipments in 3GPP networks.

Its splitting is made possible with new reference interfaces introduced by 3GPP for 5G. The terminology is as follows:

- gNB-CU (Central Unit): logical node that includes gNB function to transfer user data, mobility control, radio access network sharing, positioning, SDAP and PDCP-U session management and related encapsulation, …
- gNB-DU (Distributed Unit): logical node that includes the subset of gNB functions depending on the exact functional split option. It implements roughly the “baseband” functions.
- gNB-RRU or -RRH ((Remote) Radio Unit / Radio Head): gNB functions that correspond to RF and Low-PHY

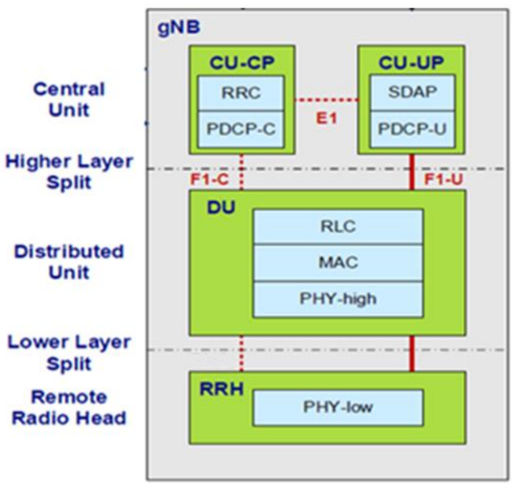


Figure 13: Interfaces between gNB components.

The interface between gNB-CU and gNB-DU is the F1 interface defined by 3GPP [4]. F1 can even be split for User plane and Control plane (F1-C and F1-U). gNBs-CUs will be able to interface with each other via the Xn interface defined by 3GPP.

The functional on board/ground gNB split will determine the gNB functions on board and on ground and the interface protocol through the feeder link. The UE communicates with the gNB through the satellite and NTN-GW. The UE will be connected via NR Uu interface through the service link to the satellite.

The link between the gNB and 5G Core will be via standard NG interface. Note that the NG interface is mapped onto the core network reference points N2 (control plane) and N3 (user plane). A gNB can interact with other gNBs (e.g. for handover purposes) over the Xn interface.

Ground distribution network provides the infrastructure required to interconnect all ground segment elements and provide interconnection to external interfaces (e.g. MNO CN, MNO NOC).

On this basis, different splits of the 5G functionalities between satellite and ground can be considered:

- Transparent payload / gNB fully on ground
- Split RU on board / DU and CU on ground
- Split RU/DU on board / CU on ground
- Full gNB on board
- Full gNB + UPF (or : 1 UPF instance) on board

This splitting is further discussed in next section.

In 3GPP Rel-15 and Rel-16 specifications, the reference point for the UL/DL frame timing on the NR Uu is the antenna port of the gNB (TRP). The alignment is ensured by the gNB by controlling the timing advance (using MAC-CE commands) that the UE has to apply to the UL transmissions so that the UL transmissions of the UE are received at the right time at the reference point. This does not apply to the PRACH transmission since the UE has no means to estimate the delay to the RU (there is a guard period reserved in the UL frame to cope with the largest possible propagation delay between UE's and the gNB). The gNB sends in the answer to the PRACH the uplink timing adjustment to be applied by the UE in the next transmissions.

In 3GPP Rel-17 it has been decided that for NTN, the reference point for UL/DL frame timing can be either on the ground or at the satellite. When establishing the connection with a PRACH, the UE has to pre-compensate the delay on the service link based on the UE-satellite distance (and additionally the delay on the feeder link if indicated by the gNB in the SIB). In connected mode, the UE may also have to continue compensating autonomously this delay (open-loop timing adjustment) in order to avoid that the gNB has to send many MAC-CE commands (close-loop timing adjustment) to correct the timing alignment (still TBD in 3GPP).

3.3 Spectrum sharing interface

In architectures where Dynamic Spectrum Sharing will be considered between the satellite system and the terrestrial systems, an additional logical interface will be implemented (not shown in the previous reference figure).

Different solutions will be analysed and discussed:

- Interface using or adapting the existing 3GPP framework, or implementation-level interface
- gNB, Core Network, and/or satellite NOC (or SRM subfoncton) originating/terminating interface

3.4 Reference architectures

A progressive approach is proposed in order to compare the advantages of DYNASAT as further explained in this section.

3.4.1 Definitions

Note:

No consensus also prevails today in 3GPP on how to map usual 5G NR concepts of cells, beams, … with satellite NTN. The following definitions are pending to currently incomplete work. This section will be updated in the version of the document.

The following terminology is introduced:

Antenna port

- As per TS 38.331 an antenna port is defined such that the channel over which a symbol on the antenna port is conveyed can be inferred from the channel over which another symbol on the same antenna port is conveyed.
- Simply put, it is a logical entity distinguished by a separate Reference Signal sequence
- UE / gNB has knowledge of Antenna port

(Satellite) NR Beam

A satellite resource related to the characteristics of the satellite antenna(s) to accommodate gains within the geometry. Usually each satellite manage multiple beams falling in the complete satellite Field of View. Beams are either steerable to keep pointing the same area center(s) (fixed ground beam), or may be moving relative to Earth (antenna may then be non-steerable). In the 5G NTN context, a (satellite) NR Beam :

- involves a dedicated set of NR subcarriers
- is considered to be formed with steerable antenna, such that it can keep serving a fixed "satellite cell" . The satellite cell may be served by one or more satellite beams belonging from different satellites at a time.

Satellite beam

A radio beam created by Satellite Active Antenna System. A satellite beam may not be directly identified by the NR UE (unless a single beam it is mapped to an antenna port and/or NR beam).

Cell

Definition of NTN cell should encompass the usual notion of cell in TN. Basically a cell is a fixed portion of a service volume or more simply area on ground, where a 3GPP service is provided. Actually the notion of cell must be a bit more elaborated:

Geographic Cell: Earth tessellation leads to thousands of earth fixed cells associated to a specific terrestrial coverage area. We proposed these cells are referred to by the term *Geographic cells*.

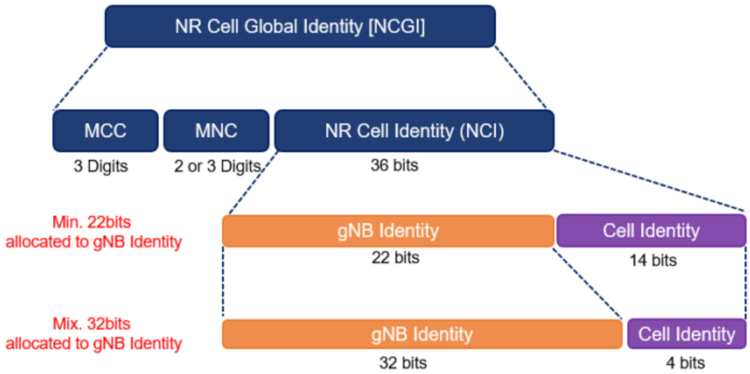
Physical Cell / Identifier (PCI): In 5G there are 1008 unique PCIs given by the PSS (Primary Synchronization Signal) / SSS (Secondary Synchronization Signal) sequence indexes broadcasted in the cell.

NR Cell / Identifier (NCI): Each logical cell is identified by an NCI (broadcast on SIB1) and contains the gNB ID.
It can handle one or several PLMN (broadcast in SIB1). These "PLMN-logical cells" are called "global cells" and identified by a NR CGI (composed of the PLMN ID and NCI, also called NCGI). NCI is 36-bit encoded.

(Local) cell / Identifier (loc cell ID):. Local cell Id may vary from 4 to 14 bits

gNB / Identifier (gNB ID): It is used to identify gNBs within a PLMN. The gNB ID is contained within the NCI of its cells. gNB Id may vary from 22 to 32 bits

NR Cell Global / Identifier (NCGI): NGCI is the concatenation result of a NCI + PLMN ID (=Mobile Country Code + Mobile Network Code)



Global gNB ID: used to identify gNBs globally. The Global gNB ID is constructed from the PLMN identity the gNB belongs to and the gNB ID. The MCC and MNC are the same as included in the NCGI.

From that definitions it is proposed in the following to assume a DYNASAT cell is either a TN or NTN cell, and can be identified and discovered by UE through the standard 3GPP method. What is exactly a DYNASAT cell vs 3GPP related cell objects will have to be further defined.

More definitions, related to Multi-Connectivity are also provided in Section 3.6.

3.4.2 3GPP 5G baseline architecture

In a first step, a "simple" 5G satellite constellation can be considered, called "5G baseline architecture". This system would address handheld terminals, in direct access, ensuring <u>only a simple visibility.</u> It means, each UE will receive only one satellite link. Of course, no other advanced techniques are used in this kind of architecture. This could correspond to application of Release 17 approach in 3GPP.

This baseline architecture corresponds to a case with the least functions for satellite payload. The selected functional split considered as baseline solution is:

- the RU on board
- gNB-CU and gNB-DU are on ground.

Note that this option is part of the transparent architectures (not transparent payload) included in the 3GPP NTN Rel.17 WI ; eCPRI shown in the figure is a possible method to transport the 5G NR signal over RU on-board satellite using the radio timing Reference Point (RP). Use of any air interface other than NR over the feeder link naturally prevents the deployment of a transparent satellite payload.

Hence, the satellite implements:

- native 5G NR (NTN) waveform at Uu user side interface. The specific satellite/ground repartition choices of the of 5G functions shall never impact the logical and control parameters exchanged over 5G uu interface, neither the functions not the algorithms implemented in UEs
- any desired air interface at GW side (called also Satellite Radio Interface (SRI) later in the document). Air interface itself transport 5G NR digitalized interface samples as network PDUs. For example, the waveform can be based on the DVB-S2 / RCS2 family.

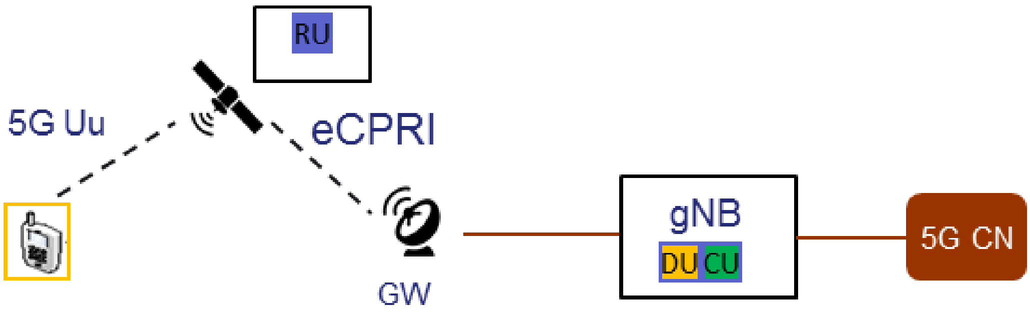


Figure 14: RU on-board with DU and CU on the ground.

The RU is ideally integrated with a Digital Beamforning Network (DBFN) that is suited for DRA antenna and will perform the beam steering in the frequency domain (before the 5G NR iFFT), according to prior Thales work analysis.

The eCPRI protocol is considered between the satellite and the gNB-DU and has to be conveyed on the feeder link. Since the RU is the time reference point, it is possible to absorb the variation of the delay between the RU and the DU: buffering is done at the RU so that frames are sent at the right time on the Uu interface. eCPRI can also be less bandwidth demanding on the feeder than the 5G NR signal because only the PRB's containing user data are transmitted (transmission of IQ samples in the frequency domain is considered, not in the time domain like with CPRI or eCPRI split 8).

The DU and CU may be localized at the NTN-GW site or not. Most probably the gNB-DU will be close to the NTN-GW, while a gNB-CU could be considered to coordinate several gNB-DUs. This will be part of the analysis for system dimensioning.

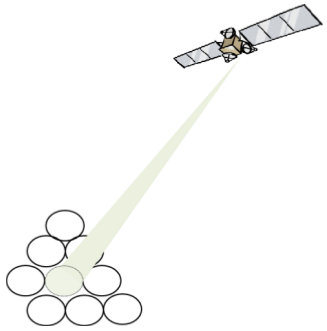


Figure 15: 5G baseline architecture, each TN cell (and UEs in that cell) is served by only one satellite

3.4.3 DYNASAT A

As explained before, one of the objectives of DYNASAT is the utilisation of advanced techniques in order to optimize bandwidth use. To this end, more than one satellite link in visibility is needed, in order for example to take advantage of several links to increase throughput among others. Advantages of using more than one satellite link will be developed further in WP3.

That leads us to a specific constellation, which needs to be defined with the constraint of having more than one satellite in visibility per user.

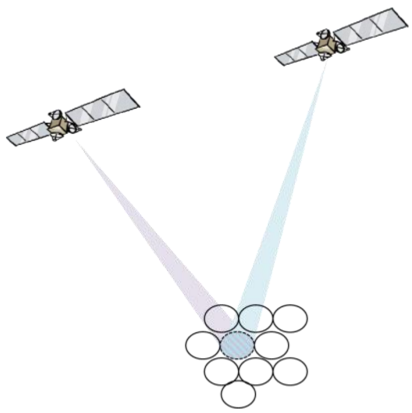


Figure 16: DYNASAT constellation, with several satellites serving the same NTN cell.

For means of simplicity on the comparison with the first architecture, even if the constellation is adapted to take into account the advantages of several satellites in visibility, we may consider that the advanced techniques are not activated. This will be considered a first step of comparison of 2 satellites constellations, with similar capabilities in terms of payload. This architecture will also permit to compare the gain of the application (or not, in this case) of the advanced techniques.

Here, the split could be challenged in the case the improvement techniques need more processing onboard, and in this case full gNB could be envisaged. As an option UPF (part of CN) could even be envisaged.

Data exchange may also be considered between satellites through ISL and could have an impact on ISL dimensioning.

Anyway, one must be aware that this should be considered carefully and only if there is no satisfying mean to have processing on ground mainly for latency reason.

It may also be a trade-off between satellite complexity and feeder/ISL throughputs.

For instance, MRC solution could be used to improve reception performances. Two approaches could be envisioned:

- MRC is performed on board a master satellite and other satellites send its received signal samples through ISL;
- To perform MRC on ground and each satellite send its contribution down to earth at the expense of multiplying the throughput for a dedicated cell reception by the number of satellites involved.

3.4.4 DYNASAT B

DYNASAT B considers the same constellation and payload solution than DYNASAT A, but applying short-term bandwidth advanced techniques and spectrum sharing constraints, namely Multi-Beam precoding ; sCSI based precoding) as it will be developed in WP3.

This kind or solution is proposed looking to Rel-18 horizon.

3.5 DYNASAT constellation design: mega constellation or not ?

3.5.1 State-of-the-art of Megaconstellation

Many companies tend to launch mega constellation. Amongst them, we can cite OneWeb, SpaceX, Kuiper… Those constellations have in common that they use high frequencies: Ku or Ka band on the user link. The consequence of this is that they allow high throughputs (up to several 100's Mbps per beam) but require on ground a high gain antenna. One of the goal of such constellations is to address a large consumer market. So there are constraints on the terminals. In particular, those terminals must be cheap (or at least not too expensive) and easy to install. Parabolic dishes offer a cheap and efficient way to get a high gain antenna, but in the case of a constellation they need to be articulated to track satellites as they move on their orbits. Moreover, to offer a constant link, a terminal needs to have two antennas : one that tracks the satellite currently serving the terminal, the second one being used to anticipate handovers. Indeed, mechanical movement of antennas are relatively slow and handing over from one satellite to another with a single dish would result in an interruption of traffic of several seconds every 5 to 10 minutes, and this is not acceptable from a user point of view.

For those reasons, **flat panel antennas** with electronic steering are often chosen. Indeed, this allows easy installation: just put the terminal on a table and it works… However, this kind of antenna shows poor performance at low elevation angles. The first reason is that the effective area that can catch signal is multiplied by the cosine of elevation toward satellite. That is to say that the lower the satellite above the horizon, the lower the effective antenna area, and hence its gain. Moreover, there is a tradeoff to make on the size of the radiating elements of the antenna. The larger the radiating elements, the cheaper the antenna (indeed, for a given antenna area, we need less radiating element if they are large). The counterpart of this low number of elements is twofold: first for high depointing angles, the individual gain of the radiating elements will decrease (independently from the cos(elevation) we have already discussed), and hence, the overall antenna performance degrades quickly at low elevation; second, grating lobes can appear, that is antenna can have a high gain in the direction of the pointed satellite, but also in another direction. The gain in this other direction may even be higher that the gain toward the satellite. Thus resulting on grating lobes that the terminal can be interfered or even jammed by other satellites, and the terminal itself can interfere or jam other satellites (or systems). So for those constellations in high frequency bands, the best choice for terminals is to have low off axis angle, that is to say to have a high minimal elevation. For instance, OneWeb has chosen 50° minimal elevation, leading to a minimal number of 540 satellites.

The second reason that can make a system to choose a megaconstellation is to have small and low capacity satellites. The total capacity of the system being increased by launching and launching new satellites.

3.5.2 Dynasat case

The case for DYNSAT is actually different from the VSAT targeted by those mega-constellation systems, with omni-directional antenna equipping handheld-type UEs (See Appendix B).

In Appendix B are presented and discussed the main drivers and the high-level constellation parameters:

- orbits (altitude, planes, inclination …) with baseline chosen at 600 km
- orbit plane population and total number of satellites
- coverage: minimal served elevation & latitude
- statistics on number of satellites in visibility

As baseline, the same constellation will be analysed for the references architectures identified in Section 3.4.

3.6 System architecture for Multi-Connectivity cases

3.6.1 Introduction to 3GPP Dual Connectivity and Multi-connectivity

In the frame of NR transmissions, hence fully applicable to DYNASAT project, we will use Multi Connectivity and Dual Connectivity interchangeably.

Multi-connectivity as defined in 3GPP standard is a "*mode of operation whereby a multiple RX/TX UE in the connected mode is configured to utilize radio resources provided by multiple distinct schedulers located in two different NG-RAN nodes connected via a non-ideal backhaul*" [R2-165931]. TS 37.340 complete this definition by adding "*(..) one providing NR access and the other one providing either E-UTRA or NR access)*". One node acts as the Master Node (MN) and the other as the Secondary Node (SN). The MN and SN are connected via a network interface (i.e. Xn interface) and at least the MN is connected to the core network.

Multi-connectivity enhances UE throughput and/or the reliability of connection to improve the Quality of Service (QoS). This technique also provides seamless mobility by eliminating handover interruption delays and errors, and optimizes capacity, coverage and mobility.

As per the late drop of 3GPP Release 15, NG-RAN supports NR-NR Dual Connectivity (NR-DC), in which a UE is connected to one gNB that acts as a MN and another gNB that acts as a SN. NR-DC is a subset of the Multi-connectivity feature. The master gNB is connected to the 5GC via the NG interface and to the secondary gNB via the Xn interface. The secondary gNB might also be connected to the 5GC via the NG-U interface. In addition, NR-DC can also be used when a UE is connected to two gNB-DUs, one serving the MCG and the other serving the SCG, connected to the same gNB-CU, acting both as a MN and as a SN.

In addition, NR-DC can also be used when a UE is connected to a single gNB, acting both as a MN and as a SN, and configuring both MCG and SCG.

The targeted services described in Section 1 may benefit from the use of Multi-Connectivity to meet the targeted service performances in terms of data rate and/or reliability. The Secondary Node (SN) Addition procedure, described in [5], is initiated by the Main Node (MN) and is used to establish a UE context at the SN to provide resources from the SN to the UE when the required signal level is achieved. the UE may simultaneously receive or transmit on multiple Component Carriers (CCs) depending on its capabilities. Regarding the system information handling, the SN is not required to broadcast system information other than for radio frame timing and SFN. System information for initial configuration is provided to the UE via the MN. The UE acquires, at least, radio frame timing and SFN of Secondary Cell Group from the SSB of the secondary cell. The impact of different delay/delay variation between the MN and the SN is to be investigated in the WP3.

3.6.2 Application to DYNASAT constellation

Next section discuss two possible (high-level) approaches of Multi Connectivity in DYNASAT.

3.6.2.1 Architectures and Cases relevant 3GPP Multi-connectivity

Globally speaking, 3GPP Multi-connectivity involving NTN is, to date, not to be expected to be possible before Rel. 19.

For that reason, we can say this approach is more relevant to DYNASAT A architecture.

Three cases of DC, depicted in Figure 17 and detailed in [**Error! Bookmark not defined.**], may be considered: DC involving TN and NTN access (a), DC involving NTN access inter-satellite (b) and DC involving NTN access intra-satellite (c). DC where both MN and SN are NTN-based require at least a partial coverage area overlap.

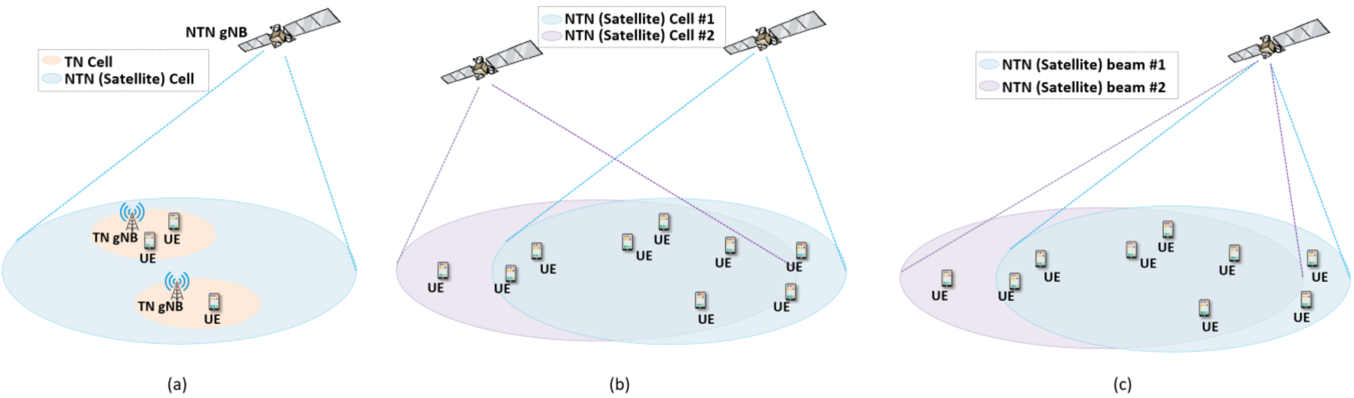


Figure 17: Dual Connectivity possible combinations between TN and NTN based access.

Note that if we can map satellite beam to NTN cell (1:1), cases (b) and (c) would actually reflect versy similar case at 3GPP RAN level.

As described in [**Error! Bookmark not defined.**], in Multi-Radio Dual Connectivity (MR-DC), the UE may be connected and served simultaneously by at least

- One NTN-based access and one terrestrial-based access where both gNB of the NTN or the gNB of the TN may be selected as master node. The UE may be connected to a 5G Core Network via simultaneously a **transparent** NTN-based NG-RAN and a cellular NG-RAN as illustrated in Figure 18. Another case may be considered in this study where the UE is connected to a **regenerative** NTN-based NG-RAN (gNB-DU on board) and a cellular NG-RAN (Figure 19)

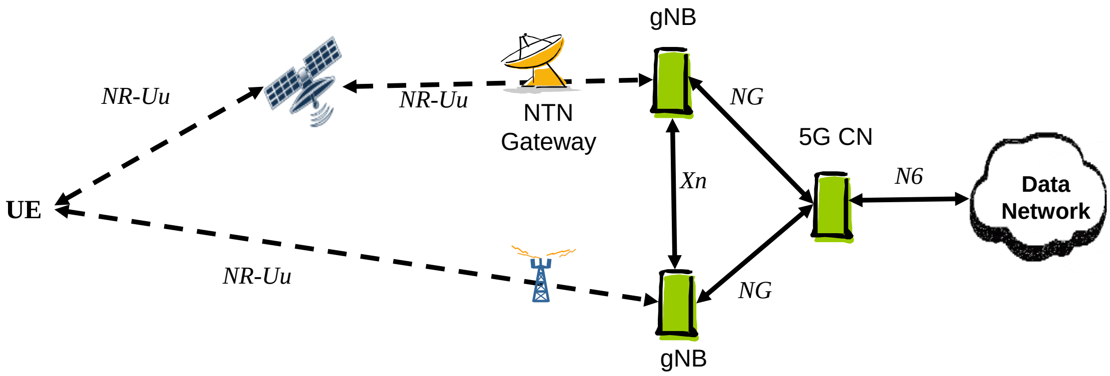


Figure 18: Multi connectivity involving transparent NTN-based NG-RAN and cellular NG-RAN[1].

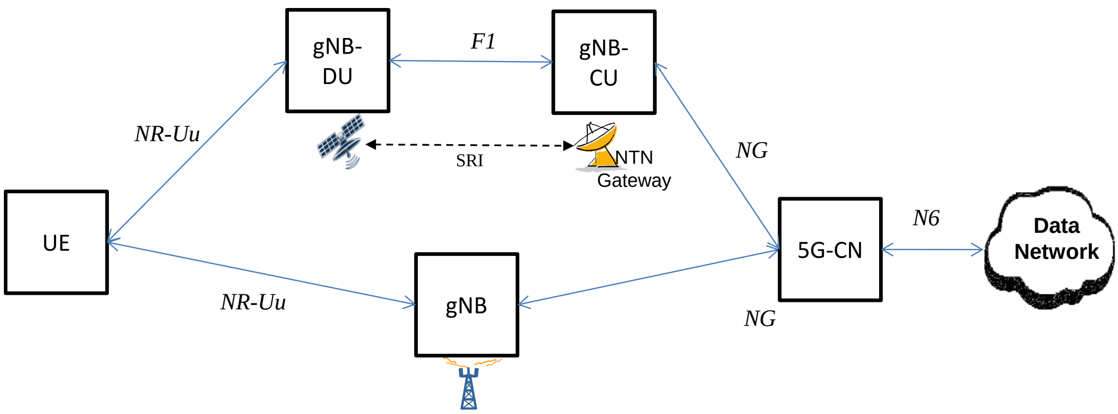


Figure 19: Multi connectivity involving regenerative NTN-based NG-RAN (gNB-DU) and cellular NG-RAN [1].

- Two NTN-based access. This case is beneficial in order to provide service to UEs in unserved areas or to enhance throughput in served areas. This case may refer to the combination of two **Transparent** NTN-based NG-RANs and is illustrated in Figure 20. The combination of two **regenerative** NTN-based NG-RAN (gNB on board) will be also considered as depicted in Figure 21

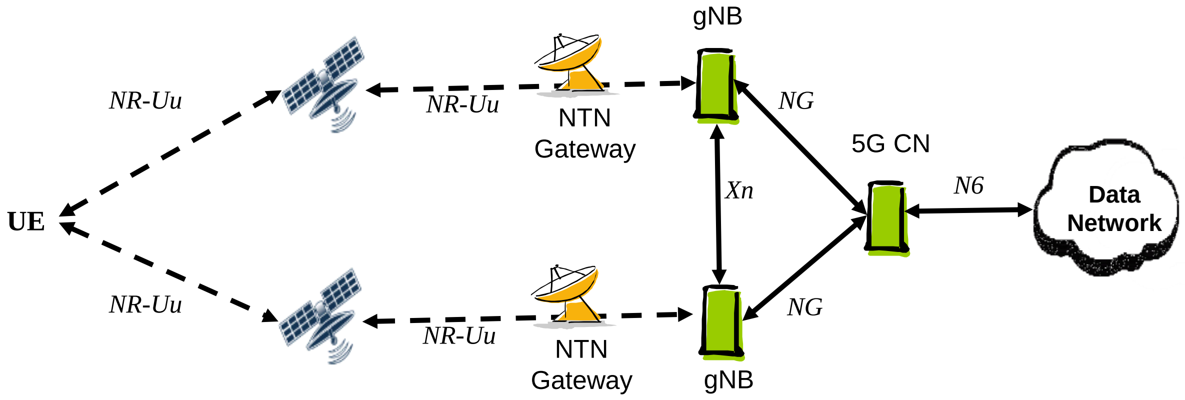


Figure 20: Multi connectivity between two transparent NTN-based NG-RAN [1].

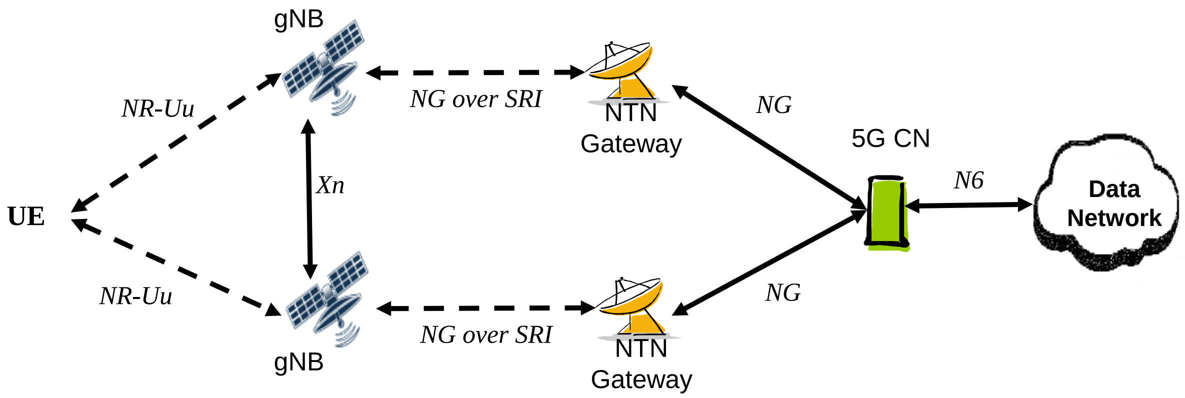


Figure 21: Multi connectivity between two regenerative NTN-based NG-RAN (gNB on board) [1].

The gNB of the MN and the gNB of the SN shall communicate via the Xn interface. In case of DC involving regenerative NTN-based NG-RAN with on board gNB, handling Xn interfaces toward terrestrial gNBs over the feeder link would require all the corresponding traffic to be transported over the Satellite Radio Interface (SRI) relevant to the satellite-hosted gNB. This may be a challenge. In this case, setting up and maintaining Xn via the Inter-Satellite Links (ISL) shall be investigated.

It should be noted that the implementation of the Multi-Connectivity will have an impact on the operating bands selected in D2.3. In fact, the possible band combination sets for DC are defined in Section 5.5B of [6].

3.6.2.2 Architecture and Cases relevant to “transmission-level” Multi-connectivity

A second approach which is not directly relying on a 3GPP concept is also proposed.

This second approach is suitable to both DYNASAT A and DYNASAT B architectures.

What is considered here is another form of MC oriented towards **transmission techniques** based on the interference management and exploitation paradigm. This can be applied to scenarios of terrestrial cells potentially served by several satellites with overlapping covering regions, i.e., to advanced mega-constellation architectures. The common approach in satellite communication is that of transmitting signals that are separated in the time and/or frequency domains. On the contrary, here, we consider multi-user MIMO (MU-MIMO) and interference mitigation techniques that can be effective in satellite scenarios with aggressive frequency reuse, i.e., **frequency reuse 1**. An important constraint that we will impose is to consider **cooperative and coordinated precoding methods** that are transparent from the user point of view, leaving substantially **unmodified the user terminal on the ground**. With reference to the forward link, the transmitted signals can be jointly designed employing precoding to manage the interference and allowing full frequency reuse. Moreover, multibeam satellite system accommodating many terminals within its multiple beams can benefit from the MU multiplexing gain when MU-MIMO precoding techniques are applied. The main constraints in the application of such techniques are:

- use of aggressive frequency reuse. *Hence this requires minimal good enough C/I performances between the cells*
- adoption of active array antennas with several radiating elements,
- on-board digital processing to reduce the delay,
- implementation of scheduling algorithm to avoid to deal with too similar users channel vectors in the same time/frequency resource.

More details on the implementation of precoding techniques in satellite systems are given in D3.1.

As already mentioned, the main architectural changes needed for the application of the considered bandwidth efficient techniques involve the non-terrestrial network segment. The impact on the complexity of the user equipment is limited and consists on:

- the possibility to combine signals coming from multiple antennas and/or satellites (NB: option Not in the scope of the current NTN Work Item Description)

- performing channel estimation to provide user feedback in satellite Frequency Division Duplexing scheme (NB: option already supported)

- eventually performing Doppler and delay compensations to simplify the UL/DL transmission designs (NB: discussed as part of Rel-17 for NTN).

MU-MIMO techniques allow for spatial multiplexing gain without necessitating satellite terminals with multiple antennas. On the other hand, the gain that can be obtained by supplying more antennas to the user equipment can be also investigated.

How MU-MIMO could be implemented with 3GPP framework will be later defined

4 KPI DESCRIPTION

Different reference architectures and main parameters of a satellite system have been defined in precedent chapters. In order to estimate the impact of DYNASAT improvements, we can define several technical and economic indicators (KPI) which will permit to estimate gains, with the correspondent targets (see Table 6 and Table 7):

- Performance with single radio link: this indicator will permit to compare the gain of the multiple satellites in visibility with DYNASAT constellation, without and with bandwidth efficient techniques and sharing application.
- Experienced data rate: one of the principal objectives of DYNASAT, to improve the data rate of the majority of the users.
- Frequency re-use factor: thanks to the studied techniques, we could expect to have a high frequency reuse factor and avoid interference between beams, fully optimizing the use of the band.
- Spectral efficiency: information rate that can be transmitted over the bandwidth. It is related to the modcod used for the communication, depending also on link budget.
- Access to spectrum for satellite network infrastructure: possibility of spectrum sharing between terrestrial and satellite, thanks to the application of improvement techniques.
- Served capacity density: number of Mbps served in a considered geographical area in average. We may consider infinite power availability at satellite level in order to estimate the impact of bandwidth and sharing efficient techniques independently of satellite limitations.
- Percentage of capacity demand actually served: ratio (percentage) between total capacity demand and capacity actually served by the satellite (some zones with high demand, satellite may not be able to serve all the users).
- Percentage of served service areas: percentage of the total of areas where service is demanded and satellite can provide at least a part of the service demand
- Coverage improvement with protection areas: A typical way to protect other spectrum users in non-coordinated spectrum sharing is to define exclusion areas around the protected spectrum user. The larger the exclusion areas, the larger spectrum capacity is lost.
- Spectrum Utilization Efficiency (SUE): SUE=C / (B*S*T), where C is capacity, B is bandwidth, S is space and T is time.
- Capacity in fully overlapping networks: Capacity in non-coordinated fully overlapping networks is decreased due to interference, and in coordinated networks capacity is lost due to inefficiency of the coordination method.
- System CAPEX: Capital expenditures (CAPEX) are the funds used by the considered business entity to acquire the considered system. It does include recurring costs and non-recurring cost such as R&D cost for the full system and each of its component. In this study context, the CAPEX is mainly made of satellites cost (development, manufacturing, etc…), launch costs, ground segment costs (gateways site and antennas, baseband and core networks software and hardware,…). System CAPEX will be provided as the sum of the annual CAPEX over the system lifetime.
- System OPEX: Operating expenditures (OPEX) are the expenses that incurs through the normal operations of the considered system. System OPEX will be provided as the sum of the annual OPEX over the system lifetime.
- System TCO: it is the sum of CAPEX and OPEX.
- System Revenues: it is the sum over the system lifetime of all services revenues that are sold to customers of the same considered business entity as the one considered for OPEX and CAPEX. In case the end users of the services are not the customers (for instance in case an indirect sales mechanism is considered), the considered revenues are the one from the customers to the business entity operating the system. These revenues can be named wholesale revenues, by opposition to the retail revenues that are the revenues obtained from the end users.

- <u>IRR (Interest Rate of Return)</u> : IRR is the metric that estimates the profitability of potential investments. IRR is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis. In the context of this study, IRR will be computed using the annual values of CAPEX, OPEX and Revenues over the project lifetime from beginning of the system development phase up to the end of the system lifetime.

Measure	Indicators	Target
Performance with single radio link	*Link margin, Throughput*	Up to a factor 10 of increased throughput, , 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 or User Density (if the demand is fixed per UE)*	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 6 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 7 Economical KPIs indicators and targets.

These indicators will be further evaluated during DYNASAT analysis. Indeed, we cannot commit on lower bound gaps on these tables at this stage of the project. Those values are meant to be high-level objectives at the beginning of the study. Objectives of assessment activities will be to get those achievable results and conditions for which they can be met. This is why the target specified in the third column doesn't correspond to an operational target but more to a target reachable under favoured conditions or environments.

5 CONCLUSIONS

5G satellite access network infrastructure for mass market service has been presented, with related targeted services. A focus on **direct access with handheld equipment** have been prioritized, retaining broadcast/multicast via satellite, digital divide, coverage extension and maritime coverage uses. Mainly based on 3GPP requirements, S-band satellites at around 600 km of altitude have been described, with the correspondent 5G-NR radio parameters. Related preliminary link budgets have been annexed. In order to estimate the performance gain of bandwidth efficient transmission and spectrum sharing techniques, three architectures are presented. They will be further detailed in next deliverables, based on the analysis of system constraints. A list of technical and economic indicators (KPI) have been also provided, and will be fill for each architecture in next steps. Finally, a preliminary constellation analysis shows a promising solution to achieve the requirements of global coverage with multiple satellites in view.

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[6] 3GPP TS 38.101-1 V17.1.0 (2021-03) « 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone (Release 17) »