5G-IS
Space Infrastructure

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WHITE PAPER ON 5G SPACE-BASED INFRASTRUCTURE

Editors:
Anastasius Gavras, Eurescom GmbH
Helmut Zaglauer, Airbus Defense and Space GmbH

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1 Introduction

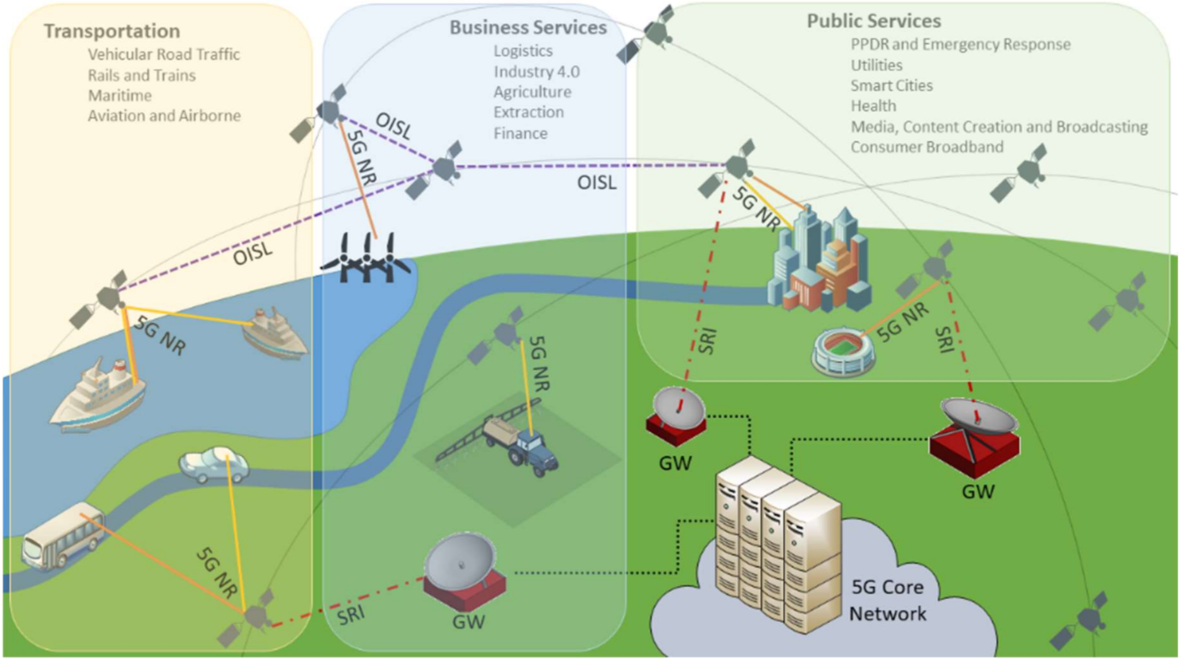
5G-IS; "5G system infrastructure study", is a study funded under the ESA ARTES Strategic Programme Line "5G/6G and Sustainable Connectivity". The study analyses and assesses different aspects of architecture design and related evaluation criteria, including key performance indicators, in order to identify potential system architecture options towards the deployment of a 5G space-based infrastructure (5GSBI – extending to beyond 5G and even 6G), complementing terrestrial next generation mobile networks. In a specific extension of the work, the focus of a dedicated deep dive was placed – with support of external partners BMW, Deutsche Telekom and Nokia – on 5G/6G satellite connectivity solutions for automotive/road transportation applications as one of the most promising market areas.

Recent advances in space technologies (including new launch and propulsion concepts) have helped to significantly improve the performance and reduce the deployment cost of space-based infrastructures. Collectively they have enabled a new generation of low earth orbiting satellites that allow to reduce round-trip air interface latency and make mega-constellations viable. The promise of service continuity, ubiquity and scalability that space-based assets can provide has drawn increased attention to the use of satellite communication technology as an inherent part of future communications infrastructures in the context of beyond 5G and 6G. 3GPP, the main standardisation body for 5G/6G mobile networks has recognised this development and made non-terrestrial networks (NTN) an integral part of its standards beginning with Release 17 and further expanding in scope and impact in the upcoming releases 18 and 19.

2 Vertical markets

A thorough analysis of 15 vertical markets identifies a large number of use cases that benefit or even require satellite connectivity and are therefore accessible to space-based communication services. The top-level architecture for a 5GSBI that could serve the three identified vertical market clusters is shown in Figure 1, with a selection of typical use cases and usage scenarios. The assessment of the requirements per use case is partly based on the accepted key performance indicators (KPIs) defined by ITU-T and positions each use case in classes for end-to-end (E2E) latency, user experienced data rate, peak data rate, area traffic capacity, connection density, reliability, availability and support for mobility at speed. Furthermore, the requirements are categorised in classes that can be considered as a starting point for the definition of service profiles. These classes reflect business and societal needs that cannot be measured via a standard KPI metric – addressing among others network resiliency, energy consumption, territorial coverage, traffic predictability, as well as technical and business fit for non-terrestrial network services and technologies. The analysis identifies use cases that could be implemented almost immediately and ones that face significant technical or business obstacles before they would become accessible. In addition, it provides a clustering of use case based on commonalities that allow these use case clusters to be served by the same space-based architecture.

In a first step a thorough analysis of the "traditional" vertical market clusters transportation, business services and public services was conducted collecting all the use cases and their requirements and consolidating them in agreement with industry stakeholders and regulators. In addition, new innovative terrestrial use cases and convergence of 5G/6G with space functions were assessed. The transversal analysis across the vertical markets provides the overall business perspective for 5G/B5G NTN identifying commonalities and clusters of related use cases as a basis for deriving mission and architecture scenarios.



GW: Gateway, NR: New radio, OISL: Optical inter-satellite link, SRI: Satellite Radio interface

Figure 1: Vertical market clusters with selected use case examples supported by a 5GSBI.

In total 77 use-cases from 15 vertical markets in three mentioned vertical market clusters: Transportation, Business Services and Public Services, could be identified where satellite access can bring benefit. For each use-case the following parameters were assessed: latency, user experienced data rate, area traffic capacity, connection density, reliability, availability, mobility, user equipment (UE) type, location characteristics, traffic and connectivity profiles, implementation timeline, technical and market fit. Each parameter was categorized in a range from 1 to 5 with 1 being most challenging, e.g. highest data rates, lowest latency, etc. to 5 being least challenging, e.g. low data rate, no latency constraints, etc. A clustering of the use-cases based on data rate, latency and UE type has been presented at EuCNC special session “NTN in 5G and beyond: Multi orbit architectures” [1].

Further results of the vertical market analysis are displayed in Figure 2. Plots a) to c) show the technical vs. market fit for the three vertical market clusters. The axes correspond to the average of assessing five subcategories in each case on a scale from 1 (worst fit) to 5 (best fit). Technical fit categories are availability of suitable UE, ease of implementation of satellite radio access, availability of cost-efficient payload, core network integration and seamless integration with TN. Market fit categories are market maturity (including willingness to utilize NTN), benefit of using satellite networks, accessible market size, TN competition, and confidence about viability of the market.

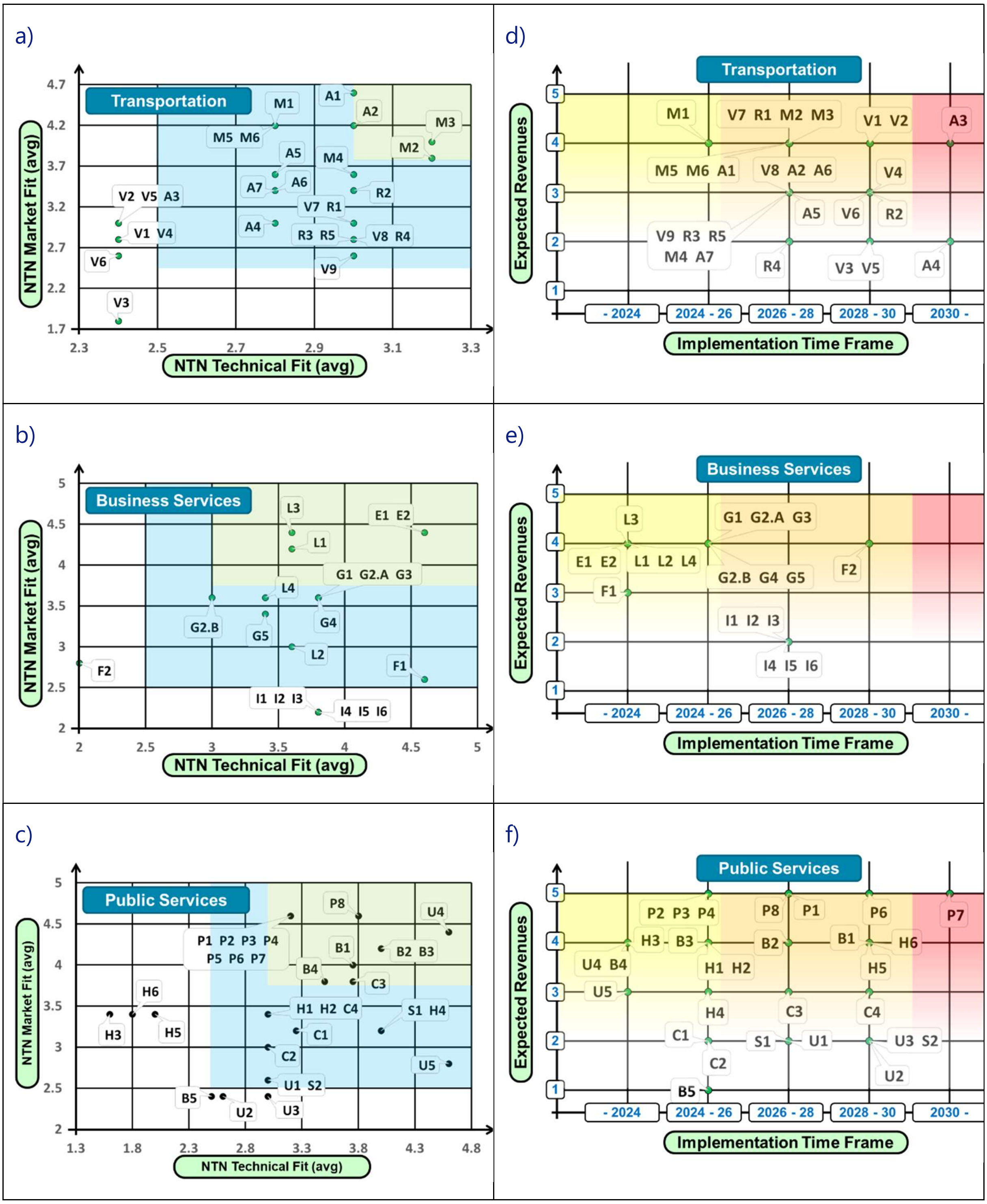
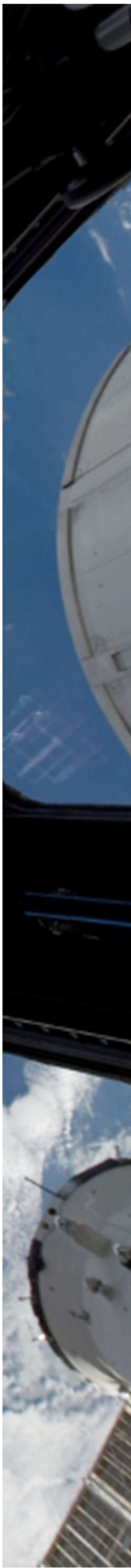


Figure 2: Results of the vertical market analysis



Legend for use-case identifiers: Vx – Vehicle, Rx – Rail, Mx – Maritime, Ax – Aviation, Lx – Logistics, Ix – Industry 4.0, Gx – Agriculture, Ex – Extraction, Fx – Finance, Px – PPDR, Ux – Utilities, Sx – Smart cities, Hx – Health, Bx – Broadcasting, Cx – Consumer

Use cases in the upper right-hand corner have the best fit, while the ones in the lower left-hand corner need to be developed further both with respect to market and technical maturity. Significantly, for the Transportation Market Cluster the technical fit is still relatively low. This is mostly connected to the accommodation of the user terminals on the (moving) platforms. This also slightly reflects into the market fit as there is still some hesitation about the perspective of satellite connectivity from the associated vertical markets and use case owners. In the Business Services Market Cluster there is a significant number of use cases at or above a fit of 3.5 on the market and technical side, showing significant maturity. Some specifically for the Industry 4.0/Manufacturing market are still very low on market fit. In the Public Services Market Cluster there is an even larger number of use cases with high scores, specifically from the public protection and disaster relieve (PPDR) and Media/Broadcasting but also from the Utilities and Consumer Broadband vertical market. To emphasize this, two areas have been highlighted in the respective diagrams:

- High fit (light green colour) with market fit > 3.75 and technical fit > 3. For these use cases the market is already well positioned to adopt 5G NTN with good business prospects and the technological maturity promises a rather quick implementation
- Good fit (light blue colour) with market and technical fit both > 2.5. For these use cases both market and technology still need a little bit more maturation, but implementation with a manageable time horizon is foreseeable.

Plots d) to f) of Figure 2 show the time perspective for possible implementation and servicing of each use case through satellite networks compared with their expected revenues. Expected revenue is categorized from 1 (lowest) to 5 (highest) and corresponds to the previously mentioned accessible market size from the NTN market fit assessment.

Here the use cases in the upper left-hand corner are the most interesting ones - the "low hanging fruit" - with regards to high revenue expectation and quick realization opportunities. As already deduced in the market/technical fit assessments, the Transportation Market Cluster has still some more development needs - with an implementation perspective at earliest in the second half of this decade. Clearly, the market perspective - with a total of 11 use cases on level 4 of the expected revenues - warrants to strongly pursue this market cluster further albeit with some patience. In the Business Services Market Cluster quick implementation seems more readily possible - driven specifically by Logistics and Extraction, but also by Agriculture. The Public Services Market Cluster shows a very broad spectrum. Some use cases appear very immediate, some are becoming viable in the mid-term and some are only long-shots. Most of the use cases also promise quite significant market prospects and revenue expectations. To emphasize this, two areas have been highlighted in the respective diagrams:

- Up to 2025 period (light yellow colour) - for these use cases a very quick implementation seems possible
- 2025 - 2030 period (light orange colour) - with a mid-term perspective for implementation
- Beyond 2030 period (light red colour) - with use cases that are foreseen to only be implemented in the long term

The initial work on the vertical market clusters was extended to conduct a deep dive into the specifics of the vehicular road transport market segment as one of the most promising and impactful verticals since providing sufficient connectivity is one of the core challenges the automotive industry faces today. Extensive, in-depth studies of automotive (Vehicle-to-Everything V2X) connectivity use cases as well as the requirements and architecture enhancements for the implementation of suitable services have been conducted by the 5G Automotive Association (5GAA) – a global cross-industry organization of companies from the automotive, technology and telecommunications industry. Clearly, the customer demand for connectivity will increase with specific emphasis on higher data rates and volumes as well as increased reliability and availability. The intensifying deployment of autonomous vehicles and self-driving cars will accelerate this trend as near permanent connectivity will significantly enhance their efficiency, performance and even safety through vastly improved situational awareness.

Consequently, many of these automotive V2X use cases will significantly benefit from or even require the improvement in coverage and the enhanced ubiquity and continuity that non-terrestrial networks promise to provide as a complement to existing terrestrial networks. These automotive NTN use cases were identified, assessed with respect to their key performance parameters and characterized using the established 5GAA roadmaps both:

- from the business-oriented perspective targeting the service implementation driven primarily by the 5GAA and distinguishing between use cases in joint public and private interest, those focusing on OEM Services everywhere and those providing Premium Customer services as well as
- from the technology-oriented perspective targeting the E2E system and space infrastructure design based on the traditional KPIs downlink and uplink data rates and time delay/latency as well as preliminary estimates on the criticality and frequency of occurrence of the use cases

Based on these analyses the use cases could be combined into three clusters that could correspond to subsequent implementation waves of suitable 5GSBIs. This was translated into a mid-term portfolio comprised of narrowband applications that could be available as early as 2025-2028, an early long-term portfolio comprised of wideband or low broadband use cases for a 2029 – 2032 realization timeline with full broadband services expected to be available after 2032.

Given the constraints on timeframe and available resources, the results of the study are preliminary and need to be detailed and matured further. Nevertheless, the study provides a first end-to-end assessment of all the relevant issues upon which more detailed future development and implementation activities for an E2E 5GSBI to complement terrestrial networks in providing connectivity services for automotive applications can be built.

3 From Mission and User Requirements to System Configuration

In a second step a number of distinct sets of scenarios (cf. Table 1) based on a selection of use cases to be covered were identified. For each of these scenarios a consistent set of mission and user requirements derived from the functionalities, features and KPIs of the selected use cases were provided.

These mission and user requirements were developed based on generic requirements that every 5GSBI system needs to abide by and that are supposed to cover all aspects of a potential mission with strong influences from the 3GPP standards in particular but not limited to: TS 22.261 [2] and TS 23.501 [3] for technical specification group (TSG) Services and System Aspects and TS 38.108 [4] and TS 38.101-5 [5] for TSG RAN.

From the generic requirements, specific ones for each of the described scenarios are derived with possible modifications, exclusions and additions as appropriate.

Table 1: Top-level definition of scenarios

Mid-term scenario	Enhanced mid-term scenario	Long-term scenario
5G Advanced – Rel. 17/18	5G Advanced – Rel. 17/18; possibly Rel. 19	Towards 6G – Rel. 19 – 22
Limited set of use-cases	Ambitious set of use-cases	Full set of use-cases
Transparent payload	Regenerative payload	Regenerative payload
No intersatellite links	In-plane intersatellite links	Multi-orbit mesh network

Requirements are grouped into the following areas:

- General system/infrastructure features,
- Business Requirements, including the identification of the use cases that shall be served by the 5GSBI
- Security and Regulatory aspects,
- Service Requirements such as
    - Network Selection and Routing,
    - Service Continuity and Roaming,
    - Backhaul and Relay,
    - Sharing and Slicing,
    - Content Delivery with Broadcast/Multicast,
    - Positioning and Localisation,
    - UE aspects and
    - Mobility
- System Performance and quality of service (QoS) Requirements, both generally and with specific regard to the use cases that shall be served
- Management and Orchestration - covering both the network and the space system
- Radio Access Technologies and Networks
- and are as specific as possible at the present stage of the standardization and system conceptualisation process.

The requirements of the specific vertical markets will be in particular reflected in the business requirements including the specifics of the use cases perhaps also with some impact on regulatory aspects and system performance/quality of service. The general features of the service requirements, the network management and orchestration as well as the radio access will be the same for the different vertical markets perhaps with some minor specializations, i.e. reduction in the number of options and focus on specific implementations. For instance, for automotive applications the use cases identified together with 5GAA will be prominently featured together with the associated performance requirements, a full TN/NTN integration will be highly desired and all mobility aspects need to be taken into consideration.

Specifically for the mid-term automotive 5G NTN use case portfolio a consistent and comprehensive set of mission and user requirements was established as a basis for designing, developing, building and implementing such a 5GSBI system. It encompasses all the general features, business aspects including use cases, a variety of service features, system performance, management and orchestration as well as radio access technologies together with the constraints (security, regulations, technical boundaries and limitations, business constraints …) that need to be considered for the realization of the system. Once entrepreneurs are convinced of the business viability, they can use such documented requirements to invest in procuring or building such a system in the hope of reaping a sizable profit.

An iterative approach was implemented to map the mission and user requirements onto a comprehensive set of system and service requirements together with the associated system architecture and implementation options that are able to serve the selected set of use cases.

For each of the Mission and User Requirements (MUR) scenarios:

- a self-standing set of consistent Services and System Requirements including internal and external interfaces for the 5GSBI MUR scenarios is derived. These contain top-level system functional and performance as well as system design requirements together with service exploitation models
- end-to-end (E2E) architecture and implementation options are described consisting of a space segment, ground segment, user segment, network segment and operational concept and including all critical components, characterization of technical solutions, preliminary performance values and suitable trade-offs.

4 Architecture

The 5GSBI shall provide satellite access services to ground-based 5G infrastructures improving the service quality offered to mobile users. For this purpose, its perimeter is defined as being composed of (i) space nodes, i.e., satellites with a radio frequency (RF) payload for communication with users on the ground and with the system ground nodes and gateways; (ii) ground nodes and gateways for communication with the space nodes and interconnection with the terrestrial network; and (iii) ground control segment for control, management and operation of the system. The related technology elements are assessed with respect to their technical feasibility, based on their current state of art, as well as their expected evolution.

For each of the major architecture elements (cf. Figure 3) the study identifies the possible options and assesses the associated trade-offs. A consistent and comprehensive set of mission and user as well as system and service requirements is derived for both a mid-term (2025 - 2030) and a long-term (beyond 2030) time frame. These results allow the elaboration and detailed description of an architecture concept suitable for implementation in the second half of this decade.

4.1 KPIs and architectural elements

The KPIs are derived from a large selection of use cases, which are not described further in this paper, but are representative for the set of use cases that form the basis for 5G and beyond 5G network design. The KPIs that are underlying this study are:

- System Bandwidth, which is the required overall system bandwidth for operation
- Link budget as defined in 3GPP TR 38.821 [11] for non-terrestrial networks (NTN)
- System Throughput corresponding to the estimation of number of users
- Doppler Robustness – the impact of the Doppler drift and its robustness is part of the communications standard (e.g., 5G New Radio (NR) for NTN) and is highly depending on the envisaged frequencies. As part of the frequency assessment, it will be assessed

whether the envisioned frequency already considered Doppler compensation within in the communication protocol.

- Latency assessment against requirements defined earlier in the study (not covered in this paper) for Vertical Market Segments Requirements, Use Cases and KPIs.
- System Cost in terms of initial capital investment cost as well as operational cost
- Quality of Service (QoS) in terms of packet loss and throughput (Bit/Hz/s)

The architecture elements and related aspects which are discussed are:

- Frequency spectrum – technical characteristics of the band (e.g., wavelength and implied antenna size, available bandwidth); Other potentially conflicting service assignments; Regulatory limitations and obligations of the administrations concerned; General usability of the band for "IMT over satellite" usage; Spectrum cost
- Orbit assessment – Constellation design; Orbit; Number of satellites; Infrastructure costs
- Satellite payload – Payload type (transparent / regenerative); Payload power, size, weight and costs; Inter-Satellite Link (ISL) capability
- Satellite platform and control – Satellite type; Antenna; Control ground segment
- Ground segment – Antenna type (target Effective Isotropic Radiated Power – EIRP); Cost of gNB (e.g., Bill of materials – BOM, Non-recurring engineering costs – NRE…)
- User segment – Antenna type (target EIRP); Modem chipset; Terminal cost (e.g., BOM, NRE…); Power supply
- Network segment – Network management; Caching and background bearers; Network performance; QoS; Security
- Network management – Software networks; Network management split; Continuous integration / continuous deployment.

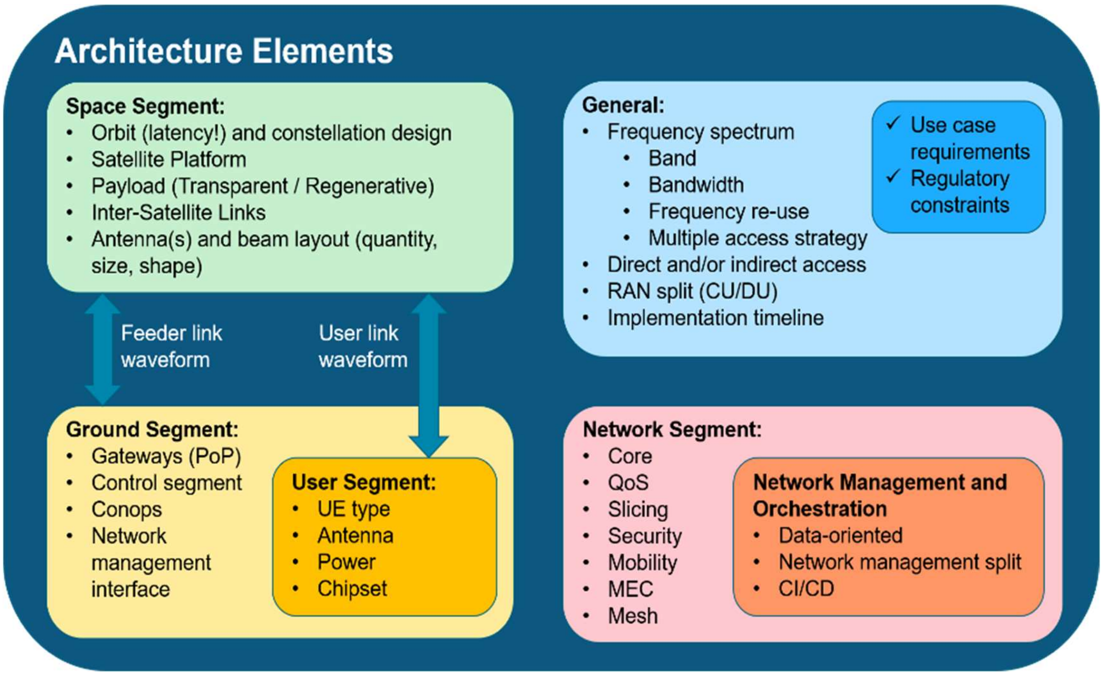


Figure 3: Architecture elements

4.2 From Use Case Requirements to System Architecture

A first iteration is carried out with rough link budget calculations, on the one hand, to get an initial assessment of how the use cases can be implemented with theoretical best-case assumptions and, on the other hand, to see how the use case implementation is restricted with realistic values. The following steps form the first iteration and are illustrated in Figure 4.

Step 1 – Based on the specified data rates for the uplink and downlink of the respective use cases, the required spectral efficiency is calculated. For this calculation, the bandwidth, which is frequency-dependent and limited from a regulatory point of view, must be determined. These frequency bands and the respective bandwidths are presented in section 4.3.

First assessments of which use cases can be implemented in which frequency bands can be made based on achievable spectral efficiencies, which are up to 8-bit/s/Hz. Spectral efficiency is briefly discussed in section 4.4. Options in which different frequency bands are to be used for uplink and downlink are not considered here.

Step 2 – A preselection of the orbits in combination with the UE types is prone to errors and does not provide the connection to the required data rates or the determined spectral efficiencies without link budget calculations. This results in the need to calculate link budgets for up- and down link. According to 3GPP, the Carrier to Interference plus Noise Ratio (CINR) is calculated for the link budgets, but no statement can be made about the interference in the first iteration, so that only the Carrier-to-noise ratio (CNR) can be calculated in the first iteration. In the second iteration, the Carrier-to-interference ratio (CIR) can be specified for a specific system architecture and use case and thus the Carrier-to interference and noise ration (CINR) can be calculated.

Step 3 – To determine the maximum theoretical spectral efficiency (SE) based on CNR, we derive it from the Shannon Capacity by removing the impact of the transmission bandwidth. This capacity represents the maximum data rate for a given bandwidth and SNR. By normalizing the capacity to the transmission bandwidth, we obtain the Shannon limit, representing the maximum achievable spectral efficiency.

Step 4 – After calculating the required spectral efficiency SE_{uc} for each use case, the maximum achievable spectral efficiency SE_{max} can be allocated to each use case and the assigned UE type.

Step 5 – The required E2E latency determines the maximum distance between the space and ground segments. If no latency requirement is defined for a use case, then all orbits are initially suitable for the implementation of that use case. This results in all options with which the system architecture for the respective use cases can be implemented. One option is the combination of (i) Frequency band; (ii) Max. Orbit; and (iii) Specific user terminal type.

Step 6 – In this step a filtering of the use cases takes place to determine the use cases that should be considered in the second iteration based on market and technology fit.

Step 7 – Finally, the use cases are grouped in clusters with similar requirements, which can be potentially met by the same architecture and link budget calculation.

The second iteration is a more detailed investigation and elaboration of the selected system architecture elements, consisting of space, user, ground and network segments. It cannot be detailed in this paper due to space constrains.

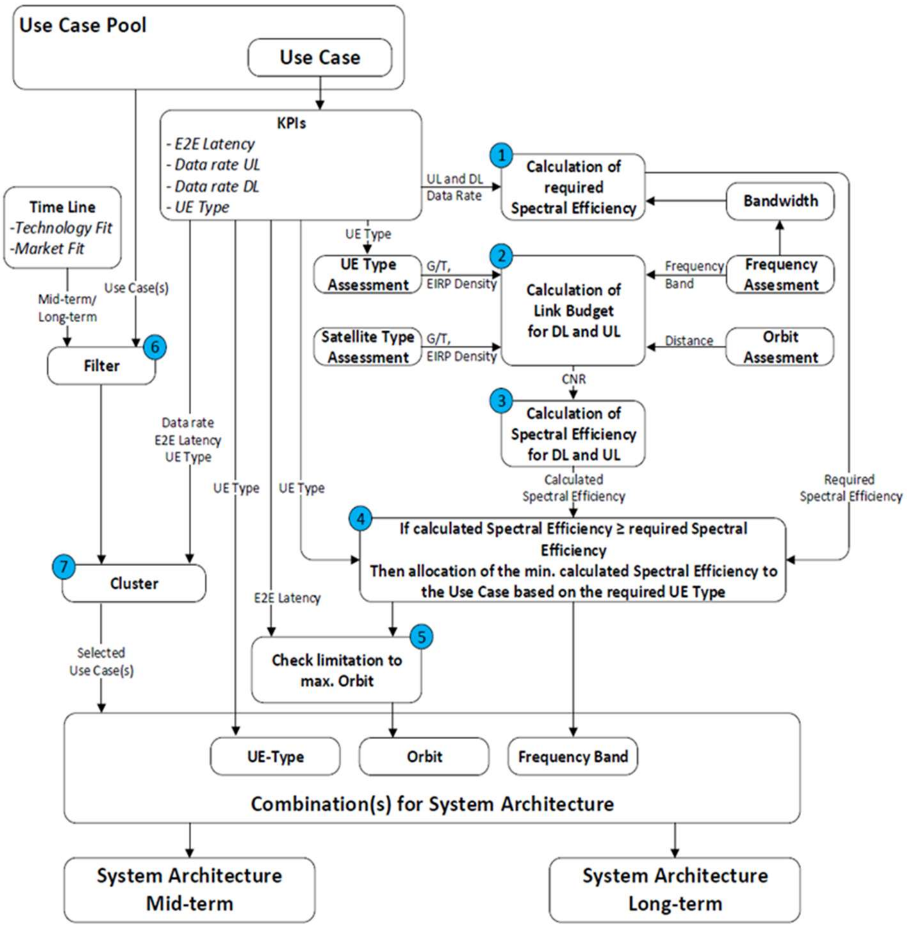


Figure 4: Approach from use case to system architecture options

4.3 Frequency Options and Trade-offs

The considered frequency spectrum plays a major role in the system architecture, because of the high impact on parameters such as – among others – antenna size, signal attenuation, signal distortion in the atmosphere, and last but not least the regulations for spectrum licenses. A full review and assessment of all ITU frequencies is out of scope, however we reviewed the 3GPP frequencies defined in 5G-NR and 5G-NR-NTN and concluded on certain options.

Taking into account the frequency options derived from the above-mentioned review a rather long list of frequencies has been identified. For further study a down-selection of frequency options is made – among others – to consider whether the frequency options are part of the FR1 or FR2 frequency range and also if this frequency is currently covered by the current 3GPP Rel-17 NTN work item. The resulting frequency options are listed in Table 2.

Table 2: Frequency options for technical assessment

Band	Fixed / Mobile	Frequency for further assessment	Available max. user bandwidth
< 1 GHz	Mobile	UL/DL: 1.0 GHz	DL/UL: 1 MHz
S band	Mobile	UL/DL: 2.0 GHz	DL: 30 MHz (2x15 MHz) UL: 30 MHz (2x15 MHz)
C band	Fixed	UL/DL: 4.8 GHz	DL: Typ. 36 MHz UL: Typ. 18 MHz (1/2*DL)
K/Ka band	Fixed	UL: 30 GHz DL: 20 GHz	DL: 400 MHz (Up to 2.4 GHz) UL: 400 MHz (Up to 2.5 MHz)
Q band	Fixed	UL: 49 GHz DL: 39 GHz	DL: 2 GHz UL: 2 GHz

It should be noted that 3GPP currently studies frequencies in the range 52.6 – 71 GHz, which may present an interesting option for future implementations of 5G-NR over satellite [12]. Furthermore, an ongoing discussion in ITU-R suggests the integration of satellite requirements for the use of IMT frequencies. This may lead to the ability to cooperatively use the same frequencies for terrestrial and satellite communications in beyond 5G networks.

4.4 Achievable spectral efficiency

The considered options for the 5GSBI architecture and the iterative down-selection process followed in the study can be found in [6]. As a main criterion for technical feasibility to support the previously assessed use-cases, the required spectral efficiency (SE) to achieve the desired data rates in up- and downlink are compared with the achievable SE. The latter is estimated from link budget calculations, which entails assumptions on the RF terminals, both on ground (i.e. the user equipment - UE) and at different orbits, as well as the frequency bands under consideration. In terms of orbit, geostationary (GEO), medium earth (MEO) at 8000 km and three low earth orbits (LEO) at 1200 km, 600 km and 300 km were considered. In terms of frequency bands, the following options were investigated: below 1 GHz, S-Band, C-Band, Ka-Band and Q/V-Band. For all different combinations, it was then investigated which use-cases each system architecture concept can support. By additionally weighting the use-cases according to their previously assessed technical and market fit, the most promising concept was identified for further detailing. For example, for the enhanced mid-term scenario, a constellation at 1200 km altitude and utilizing a combination of S- and Ka-Band was found to be the most promising architecture solution concept.

For that case, the SE values as listed in Table 3 can be achieved. This detailed link budget assessment considers a slant range of 1894 km derived from a satellite scan angle of 45° at the 1200 km orbit. Furthermore, carrier-to-interference ratio (CIR) from ref. [7] is taken into account. The resulting carrier-to-interference and noise ratio (CINR) is then translated into a spectral efficiency according to a 5G NR link level simulation tool.

Table 3 Achievable spectral efficiencies for the investigated architecture concept

UE type	Spectral efficiency in bit/s/Hz			
Direction	Uplink		Downlink	
Band	S	Ka	S	Ka
Handheld, low power	0.05	-	0.05	-
Handheld, high power	0.55	-	0.32	-
VSAT, low power	1.76	0.61	1.27	1.65
VSAT, high power	2.51	2.21	1.27	1.65
Large, high power	-	2.77	-	1.65

Note that the handheld UE types are not considered feasible for Ka-Band usage and the large, high power UE type is not considered useful for S-Band. Hence there are no SE values for these cases. In general, the achievable SE increases with size and power of the UE, however, on the downlink side this scaling is limited as here the interference dominates the link budget.

Following the link budget analysis, a preliminary power budget for the satellite is approximated in order to determine a rough order of magnitude (ROM) estimate of the platform size and weight and thus also provide an input for the ROM cost estimate. First, power consumptions for the user link and the feeder link are approximated. For the user link in the enhanced mid-term scenario with regenerative payload, the on-board processor must be able to process the air interface 5G NR. For this, a complete gNB on-board the satellite is assumed, because the delay requirements on the F1 interface between a Central Unit (CU) and a Distributed Unit (DU) are considered to be too demanding for an NTN link, but some more detailed trade-offs need to be conducted to decide upon suitable options of splitting the NTN gNB between the satellite and the gateway. Generally, the latency requirements are relaxing towards the higher layers of the radio access network (RAN) protocol stack from the physical layer to the Packet Data Convergence Protocol (PDCP) layer. As an example, the O-RAN overview in [8] states latency requirements between 250 µs for the lower 7.2 split (DU to Radio Unit, RU) up to 10 ms between PDCP and IP layers. As a consequence, the link between the upper layer of a gNB and the core network is possible via NTN link and can be implemented either with 3GPP native radio access technologies stacks or with non-3GPP radio access technologies such as DVB-S2X. Due to good efficiency and availability of space-grade components, DVB-S2X is assumed for the feeder link with 500 MHz bandwidth and a SE of 5.6 bit/s/Hz [9] resulting in a capacity of 2.8 Gbps per feeder link. Power consumption of the user link is estimated as 78.6 W and the feeder link is estimated as 55.9 W.

Secondly, power consumption for inter-satellite links as well as additional elements as the power amplifiers for the RF links and the payload controller are estimated. A total of four ISL is assumed with 60 W power consumption each. For the power amplifiers, the value from the Ka-Band link budget calculation is used, which corresponds to 55.1 W and represents the worst-case power consumption in the enhanced mid-term scenario. For the payload controller 20 W are allocated in the power budget. In order to evaluate the total power consumption, eight user links are assumed per feeder link, in which case the maximum aggregate user link capacity is roughly equal to the feeder link capacity. For one and two feeder links, the estimated total power consumption then sums up to 1.4 kW and 2.6 kW respectively.

For obtaining an estimate of the minimum number of satellites required, single-fold global coverage is assumed as minimum requirement. Furthermore, only polar orbits are assumed. Following the approach in [10] and considering the orbit at 1200 km and a satellite scan angle of 45°, which corresponds to a minimum elevation angle of 33° for the ground terminals, the minimum number of satellites is estimated at 180. Note that this is just a lower limit. Other constraints as for example overall system capacity may drive the need for additional satellites and potentially different orbit configurations.

As a quantitative metric for system capacity for the enhanced mid-term scenario, the maximum sellable capacity is estimated. For this, it is considered that each satellite has 16 user beams that each can support a maximum data rate that depends on the allocated band, the UE and the direction of transmission as summarized in Table 4. This table considers the SE of Table 3 multiplied by the maximum bandwidth, which is assumed as 10 MHz for S-Band and 200 MHz for Ka-Band. Depending on the geographic distribution of users and use cases, the 16 beams of each satellite could be split between Ka-Band and S-Band based on actual demand.

Table 4 Maximum sellable capacity per beam

UE type	Max. sellable capacity per beam in Mbit/s			
Direction	Uplink		Downlink	
Band	S	Ka	S	Ka
Handheld, low power	0.5	-	0.5	-
Handheld, high power	5.5	-	3.2	-
VSAT, low power	17.6	122	12.7	330
VSAT, high power	25.1	442	12.7	330
Large, high power	-	554	-	330

4.5 Orbit Options and Trade-offs

Considering our vision for a 5GSBI for the mid- and long-term evolution of the 5G NTN systems, it is clear that the resulting system would consist of different space segment assets, including geo-stationary earth orbit (GEO) as well as low earth orbit (LEO) satellites in the mid-term. Substantial surge of commercial interest in LEO settings, increased the technical maturity and lowered the cost of SmallSat and IoT technologies, thereby facilitating the inclusion of LEO constellations into the 5G NTN ecosystem.

The following space assets can potentially be used for a 5GSBI. These are mainly classified based on the height of operation. *HAPS* (High altitude Platform Systems) operate at 8-50 km but have strong limitations concerning payload mass. *VLEO* (Very-Low Earth Orbit) operated at 250-350 km and have advantages in terms of link budget and low latency, however, a large number of satellites is needed to achieve the desired coverage. *LEO* satellites are operating at 350-1500 km and represent the emerging state-of-the-art with a good link budget and latency. Emerging technical maturity enables flexible constellations with a varying degree of complexity. MEO (Medium-Earth Orbit) satellites are operating at 7000-25000 km, and one constellation is operational today. MEO satellites would provide a good link budget but are a challenge for small and simple UEs. GEO (Geo-stationary Earth Orbit) satellites operate at 35786 km and are the state-of-the-art today. For ground users they appear at a fixed position in the sky and have due their antenna sizes and power budgts a good link budget but very high latency. Other special cases such as Geosynchronous or High-Elliptical Orbit satellites are not further considered. A detailed analysis of the orbit options under investigation is presented in [6]. Beyond the orbit itself, further parameters influencing the architecture have been identified and studied, such as inclination, constellation geometry, topology and inter-satellite links. The detailed analysis of these parameters is beyond the scope of this paper.

4.6 Payload Options and Trade-offs

3GPP TR 38.821 [11] defines two NTN-based NG-RAN architectures; (i) transparent satellite-based NG-RAN architecture and (ii) regenerative satellite-based NG-RAN architectures. Thus, depending on the requirements derived from the use cases, either transparent or regenerative payloads can be used. In the transparent architecture, analogue transparent and digital transparent payloads can be differentiated.

The advantages of analogue transparent payloads compared to digital transparent payloads are the low complexity and simple implementation. The disadvantages are the low flexibility with regard to the filter bandwidths and routing capabilities. In addition, the number of UL and DL channels has a high influence on the size weight and power (SWaP) of the payload.

The digital transparent payloads are often based on customized Application-Specific Integrated Circuits (ASICs) or one-time programmable Field-Programmable-Gate-Arrays (FPGAs) and offer flexibility in terms of variable physical layer filtering of the UL traffic channels, gain control and physical layer routing/switching to different DL that enables flexible management of RF spectrum.

A general disadvantage of the transparent payloads compared to the regenerative payloads is that physical layer processing such as re-modulation or re-encoding is usually not implemented due to the fact that these algorithms can't be updated in-orbit and so the system is not flexible for future applications. Since the signals are untouched inside the satellite, all higher layer functions have to be addressed by more complex gateways, which provide the necessary connectivity to the ground system and provide less re-configurability. However, by adding additional switches for routing purposes some flexibility can be introduced in these systems.

Regenerative payloads allow the signal conversion from one air interface to another, de-/modulation and de-/coding [13]. Transmission errors of the uplink can be corrected in the satellite and the communication standard can be adapted to environmental influences, e.g., another modulation could be chosen to achieve a better CINR or spectral efficiency. A further advantage of regenerative payloads is the flexible way to route user data by setting up or "spanning" a communication network in space that allows to implement a high speed, low latency and ultra-secure data network in space. The communication path from one to another UE can be realized with a gateway-independent meshed network data connectivity from transmitter to receiver with inter satellite links (ISL). Regenerative payloads are often based on FPGAs so that possible adaptations or changes of the processed air-interface standards could be carried out with in-orbit reconfiguration over the mission lifetime of a satellite. However, the flexibility of FPGAs has high costs in terms of high-power consumption.

For the mid-term, an architecture based on transparent payloads is the most likely solution, however, under certain circumstances and assuming usage of FPGAs, a regenerative payload is also feasible in the mid-term. The regenerative processing of higher data rates leads to higher payload power, size, weight and costs (SWaP-C), which need to be traded against the provided flexibility. For the long-term, ASIC implementations are realistic, which may provide a better ratio of processing capacity and power consumption.

4.7 Ground Segment Options and Trade-offs

The ground segment elements for non-terrestrial networks play a central role in the convergence with terrestrial networks. There five basic ground segment elements are:

- User Equipment – device with which the user connects to the 5G/6G non-terrestrial network ideally through 3GPP radio access technology. Non-3GPP access technology could be used but requires the use of the non-3GPP interworking functionality at the interface to the 5G Core network.

- Ground Control Segment – monitors, manages and controls all elements of the 5GSBI, i.e., the entire space segment and all gateways and internal and external interfaces.
- Gateway(s) – connects the satellite payload with the core network, i.e., it provides the feeder links between the satellite and the ground as well the interface of the user/data plane of the NTN to the core network.
- Core Network – connects all central telecommunications and data processing nodes and servers with the base stations.
- Data Centres and Central Servers – are application and use case dependent and are the final destination of the transmitted data beyond the pure peer-to-peer employed for storing, processing and acting upon the data.

4.7.1 Ground Control Segment

The main functionalities of the Ground Control Segment (CGS) are:

- Customer and Order management, i.e., the entire interface with the customer for reception and cancelation of requests, complaints and customer relations, usage logging and invoicing, etc.
- Network management, i.e., (i) managing nodes (adding, modifying, dropping), interconnects, carrier utilization, etc. (ii) managing the interfaces to the 5G system to which satellite access services are provided and the respective core network(s), (iii) directing and possibly re-directing the data streams, i.e., activate the respective nodes and notifying the customers, (iv) network monitoring and provisioning of relevant data and KPIs also to the 5G system, (v) dynamic network optimization.
- System management, i.e., securing necessary supplies (power, water…) and maintenance services to keep the system running as well as administration of all service contracts.
- Management of the 5GSBI nodes, i.e., (i) TM reception and processing as well as TC processing and maintenance of the availability for each space node, (ii) consolidating the space node availability and providing the network management with the respective availabilities for planning, (iii) receiving the data stream directives from the network management and issuing TCs to the respective space nodes according to the space node assignment schedule, (iv) receiving information that could affect space node availability such as collision or space weather warnings through external providers
- Management of the gateway nodes, i.e., TM reception and processing as well as TC processing and maintenance of the availability for each gateway, (ii) consolidating the gateway availability table and providing the network management with the respective availabilities for planning, (iii) receiving the data stream directives from the network management and issuing TCs to the respective optical ground stations according to their respective assignment schedule, (iv) receiving auxiliary information, like weather information, maintenance needs…, affecting the availability of the individual gateways.

Despite the importance of the CGS for system operation, it is not a driving factor for the definition of the system architecture of the 5GSBI, but is rather adapted to its needs. For the management of the satellites and gateways there exists significant heritage. For constellations with a large number of satellites, autonomy of the CGS is desirable, in order to keep operating costs under control.

4.7.2 Gateways

The satellite uses either a transparent payload, or in future 3GPP releases a regenerative payload and can be placed into GEO, MEO, or LEO altitude. A transparent satellite works as a relay between the UEs and the base station (gNB – next generation NodeB), implemented on the gateway side on the ground. In contrast, a regenerative payload acts as an orbiting gNB, with a backhaul link to the core network on the ground. Accordingly, the ground segment comprises different functional elements of the 5G NTN system. The following options are considered:

- Backhaul scenario – similar to conventional satellite communications ground segments. Traditional VSAT (Very-small-aperture terminal) hub station equipment can be used for backhaul purposes without the need for a 5G NR waveform.
- Transparent payload – the satellite-enabled gNB is on at the gateway station. Depending on the constellation and beam configuration, multiple gNBs are required in the ground segment to support multiple GEO or LEO satellites, and/or multiple beams, each representing a gNB. In this case, a single gNB-CU and multiple gNB-DUs can be implemented in the ground segment.
- Processed (regenerative) payload – in this case, the ground station is used to backhaul at least one gNB on board of a satellite and connect the N2/N3 interfaces of the gNB(s) to the core network on the ground. The modem in the ground segment in this case is similar to the backhaul scenario, and a satellite specific RAT can be used. A special case is a higher layer split, where the gNB-CU is part of the ground segment, and the gNB-DU is on the satellite. In this case, a satellite specific RAT and modems for the communication link could be used as well.

4.7.3 User Segment

3GPP TR 38.821 describes two representative UE terminal types for use with 5G NTN, one is the smartphone type with omnidirectional antenna and +23 dBm transmission power for 2 GHz, and the other is a VSAT terminal for above 10 GHz, 2W power and directional antenna.

However, in real deployments, we anticipate at least three more UE types as we summarise the possibilities below:

- UE type 1: as defined in [11] this is a smartphone type terminal for lower frequencies, low transmit power and omnidirectional antenna.
- UE type 2: a UE with low transmit power as for type 1, to be compatible with smartphone type RF components. The difference is that another antenna is used for the terminal instead of the omni antenna, leading to improved link budgets through antenna gain and less antenna noise temperature. The 10 dBi are achieved e.g., by a small dish (<< 60 cm) or a patch antenna.
- UE type 3: a VSAT terminal with reduced transmit power, to enable lower cost 5G-NTN enabled devices. Especially the RF equipment is a cost driver for modems and so we assume reduced power at 200 mW.
- UE type 4: as defined in [11], for operation mainly above 10 GHz, increased transmit power of 2 W and a 60 cm dish antenna.
- UE type 5: a stationary UE for fixed installations with a bigger dish (1.5 m diameter) for higher throughput.

However, none of these UE types are sufficiently representative of vehicle mounted terminals when taking into account typical passenger cars or commercial vehicles. Therefore, two modified UE types accounting for the specific installation constraints on vehicles are proposed by the 5GAA for automotive use cases:

- Modified UE type 1 for FR1 with increased transmit power (400 mW even up to 800 mW) and increased antenna gain (3 dBi even up to 6 dBi).
- Modified UE type 3 for FR2 with increased transmit power (5 – 7 W) but reduced antenna gain (25 to 33 dBi) to account for smaller antenna installations on passenger cars

These characteristics are derived from current estimates of suitable vehicular terminals and may be adapted during the design process.

4.7.4 Network Segment and Interfaces

In 3GPP System Architecture (SA2) a set of network functions and interfaces are defined which enable the functioning of the end-to-end 5G system. Several additional advances, as described in the following, are the basis to trigger the new network segment flexibility options each with its own set of trade-offs.

- NTN RAN Advancements – Regarding the access related functionality, the system is fully defined for cellular type of networks stemming from GSM wide area wireless communication. From this perspective additional modifications should be brought to the network segment to optimally consider the additional specific items of 5G NTN upper layers (beyond PHY) such as the native capacity of broadcasting, always available downlink, and the cost of the establishment of the uplink. From this perspective, the

network functions should be adapted beyond the study item [14] of Rel. 17 towards next generations. Especially with the development of the new multicast and broadcast functionality as well as with respect to the support of Machine Type Communication (MTC) within 5G, beyond Release 16, there are several additional optimizations in the network segment which could be adapted towards scheduled communication and uplink optimizations.

- Transport integration - Regarding the core network functionality, 3GPP did not yet start the integration of the transport network characteristics with the network itself. The only integration was proposed at the 3GPP Network Management Level (SA5) where the management components of the core network could potentially communicate with the management components of the transport network. As such, there is an urgent need to be able to convey the information from the transport network towards the core network, because at the moment, the communication resources bottleneck is not anymore in the access with a well dimensioned transport in the back to support it, but in the backhaul itself. For example, a current 5G radio head can handle 1 – 1.5 Gbps, resulting in potentially 100 Gbps per Base-Band Unit, not being matched by any current backhaul technology available today. Careful attention should be given on how to allocate the end-to-end network resources while concentrating on the potential congestion point which at the moment is shifting from the access to the transport.
- Ultra-flat, high-distributed deployments – A new perspective on the network function placement and their management should be given. Starting with the 5G system an ultra-flat, highly-distributed network architecture with functionality at the edge is proposed while having only specific functionality to connect to central entities. The result is that the current split inherited from 4G with RAN at the location and the core centralized is transforming into a new split with RAN and part of the core at the location and the rest of the core centralized. Because of this extensive edge functionality, a most promising technology is the collapse of the edge core network and of the RAN central unit (CU) within a single set of functions handling local mobility management and resources optimisation as well as local data path offload.
- Redesign of core network – With the "softwarization" of the network, new opportunities to optimize the resource usage have emerged. In the current 5G architecture a first step was made into this direction, although with still highly limited capabilities. The architecture is still tributary to the network functions instead of the specific services and subscriber state information is still split for the different network functions. A new radical services approach towards the network would be highly beneficial.
- Space node – With the redesign of the core network, there is the possibility to deploy smaller functionalities which do not require extensive processing and provide a significant advantage for the end-to-end communication such as forwarding data path elements able to change the end-to-end data path according to available routes.

- RAN “Softwarization” – is now the main focus of the RAN technologies. With new architectures such as O-RAN the direction of RAN development advances also towards new split of the RAN functionality itself into multiple network functions distributed along a processing data path. This has opened the door towards a more split version of the RAN functionality which gives the option for 5G and beyond-5G NTN to consider some minimal functionality with large benefits to be deployed as part of satellite payload and thus to split the RAN functionality between space and the hub part of the ground segment.
- UE Centric – The increase of the computing capacity of the UE, provides the opportunity to move some of the functionality towards the user equipment where some decisions can be taken easier based on the local sensing information e.g., handover decisions. To be able to steer the decisions of the UE towards what the network can offer, the network requires new mechanisms for transmitting indications to the UE (such as the 3GPP Rel. 17 conditional handover).

5 Critical technology elements

The study investigates technologies that are critical for the implementation and deployment of a 5GSBI in the mid- and long-term. The identified technologies are classified into categories that reflect the importance of each technology element, as well as their expected maturity in the mid- and long-term. The following list highlights the most critical technology elements that should be considered for rapid further development:

- Space segment: (i) Software defined flexible satellites, (ii) Payload energy efficiency, (iii) 5G TN/NTN routers in satellite, (iv) 5G regenerative payloads, (v) Q-/V-Band Broadband transponders and (vi) LEO Direct Radiating Array (DRA) payload antennas
- Ground segment: (i) Ground segment diversity, (ii) Dynamic frequency management, (iii) "Best" access selection, (iv) 5G TN/NTN network management layer, (v) Autonomous network demand-driven ground control centre, (vi) Software Defined Gateways, (vii) 5G TN/NTN routers, (viii) UE integration in aeronautical, maritime, passenger cars, trains, trucks and busses combined with Flat panel antenna technologies, (ix) Modems and 5G NTN chipsets, (x) Battery energy consumption.
- Network segment: (i) Seamless (Over-the-air) Updates with remote attestation, (ii) Mesh Network, (iii) Distributed and federated network management, (iv) E2E integrated data-driven network control, management and orchestration with deterministic communication, (v) 5G security by design and secure processor architectures, (vi) NTN-Terrestrial convergent core network as well as (vii) Asynchronous data exchange, (viii) Delay compensation, (iv) Subscriber profiling, (v) Semantic routing

Given the most promising system concepts, the technologies were identified that need to be employed in the 5GSBI to maximize interoperability with terrestrial 5G networks and how to achieve the QoS levels that are necessary to become a viable complement to terrestrial services for widespread adoption.

A comprehensive and complete Technology Roadmap was derived that identifies and describes the key enablers and the critical technology elements including technology pre-developments, validation plans and demonstrations to raise the technology readiness level and enable the realisation of the proposed system architectures and implementation scenarios.

Focussing again on the above-described enhanced mid-term scenario, the following technology elements were deemed critical:

- Payload energy efficiency: To obtain a more detailed understanding of correlation between energy consumption and processing power of a regenerative payload. This is a pre-condition for design of high-performance regenerative payloads for future 5G space ASIC or FPGA.
- Direct radiating array (DRA) payload antennas: To enable flexibility for reacting on changing usage demands, i.e. matching instantaneous traffic requirements and/or mitigate rain attenuation.
- "Best" Access Selection: For a continuous communication across the integrated 5G satellite-terrestrial system.
- 5G TN/NTN network management layer: Convergence between the currently separated systems.
- 5G TN/NTN routers: Dynamic forwarding of traffic across the different paths and optimizing the network utilization according to the momentary congestion and use cases.
- User Equipment integration and flat panel antenna technologies for respective verticals and use-cases, e.g., aeronautical, maritime, passenger car, trucks, busses and trains
- Modems 5G NTN with chipsets: Analogue to chipsets for terrestrial applications or preferably integrating TN and NTN capabilities.
- Battery Energy Consumption: Reducing the energy consumption of user terminals is key for many use cases.
- Mesh Network: Provide an increased network robustness for distributed networks.
- End-to-end deterministic communication: Deterministic delay is required by several new use-cases such as collaborative robots, VR, XR, etc.
- Distributed network management: Distributed networks require an adapted network management.
- Infrastructure and radio and network resources slicing: Customized functionality from the terrestrial 5G system can be immediately adopted by 5G NTN with similar benefits related URLLC and mMTC.
- End-to-end integrated data driven network control and management and orchestration: To improve the control and optimization of networks. Enable scalability, adaptability and real-time responding to error or fault conditions.

- 5G security by design including new secure processor architectures: Should be added for software on third party hardware as well as for distributed systems in order to provide the expected trust for the distributed satellite system.
- NTN-Terrestrial convergent core network (transparent NTN to the complete system): Usage of the same interfaces eases the adoption of NTN as the onboarding and network management processes do not have to be specifically adapted.
- Asynchronous Data Exchange: De-congest the network by delaying communication (for permitting use cases) to when the network conditions are good.
- Delay Compensation: Related to determinism of communication, relevant for use cases, where the time differences introduced by the network communication need to be compensated, e.g. remote surgery, remote machine operation or VR.
- Dealing with PQRS (Performance Quality Resilience Security): Equivalent to runtime network management.

The Critical Technology Elements identified in the 5G-IS study are key enablers that are needed for an initial mid-term implementation as well as longer term technological advances that are indispensable to build upon the strengths of satellites to fully deliver all the benefits that NTN is capable of. This requires a vigorous R&D effort for which the study has identified the prioritized technology development steps and a comprehensive demonstration roadmap to accelerate technology maturation and demonstration as well as achieve sufficient technology readiness to be available when needed by the customers.

Many of these Critical Technology Elements are also relevant for specifically addressing automotive use cases. Of utmost importance needed to be addressed immediately for a timely implementation are the following two key enablers:

- The automotive user terminals and associated performance assumptions are currently lively debated within 5GAA with the main directions of having a slightly more performant terminal compared to a handheld device for below 6 GHz bands and a less performant terminal compared to a “VSAT” device for above 6 GHz bands.
- On the network segment, different options for NTN-TN integration considering different number of operators and carriers have been analysed. It is expected that multiple of these options will be used in future deployments depending on the respective cooperation between satellite operators and mobile network operators and additionally it may vary from country to country due to related national spectrum regulations.

Overall, the technical assessment in the automotive extension clearly indicates the feasibility of a 5GSBI serving the automotive industry already in the mid-term timeframe (2025-2030). Of course, there is still a lot of technical work to be completed for the implementation of such a system, but there are no showstoppers visible. Part of the work has already been initiated:

- cooperatively within 5GAA aligning towards the use case roadmap as well as standardization and regulatory topics [17],

- within the work programme of the ESA Strategic Programme Line "Space for 5G/6G" and
- dedicated development efforts at the relevant industrial players (automotive OEMs, MNOs, SNOs and satellite large system integrators)

Further acceleration of the individual and cooperative efforts is necessary to grow and mature the ecosystem, but the need for action has clearly been recognized by all stakeholders to advance 5G NTN satellite communications as an enabler of optimized connectivity for the car of the future.

6 Services and system exploitation models

While the standardisation of non-terrestrial networks in 3GPP is currently evolving, several principal implementation options for 5G satellite access are identified. Release 17 completed in early 2022 for the first time specifies direct access, i.e. the connection of user equipment (UE) directly to a satellite via 5G new radio or narrowband IoT. The standard also specifies non-3GPP direct access via proprietary radio protocols and waveforms to the satellites, but which requires the use of the interworking functionality to connect to the 5G core network. Finally, it specifies indirect access where the satellite provides backhauling services between relay nodes or base stations and is thus part of the transport network.

Suitable service exploitation models are derived from the actor role model defined by 3GPP for the 5G ecosystem, and which is further elaborated by work of the 5G PPP. The models consider emerging concepts for 5G NTN services provision and exploitation for terrestrial networks and verticals markets. These concepts are departing from a mere extrapolation of current business models for 4G. In the context of 5G, and increasingly in the context of beyond 5G and 6G the main involved stakeholders are concerned about the emergence of 5G ecosystems as an effective instrument that facilitates creating value for the customer. This approach follows the recognition that few stakeholders alone cannot cover the full breadth of the possible benefits for the vertical markets. The possible deployment and exploitation scenarios range from clearly business and market-oriented models, public private partnerships, and models with a high public engagement. The evolution shall consider the potential strategic importance for Europe of a 5G (extending to beyond 5G and 6G) space-based infrastructure, going as far as declaring the creation of such an infrastructure an Important Project of Common European Interest.

6.1 Role models in the 5G provisioning ecosystem

The starting point for the elaboration of service exploitation models is the high-level model of roles defined in 3GPP TR 28.801, which includes the business roles of (i) Communication Service Customer (CSC), (ii) Communication Service Provider (CSP), (iii) Network Operator (NOP), (iv) Virtualization Infrastructure Service Provider (VISP), (v) Data Centre Service Provider (DCSP), (vi) Network Equipment Provider (NEP), (vii) NFVI Supplier and (viii) Hardware Supplier. Based on the 3GPP high-level model of roles, the 5G PPP architecture WG has extended the model and proposes the roles in 5G provisioning systems as illustrated in Figure 5.

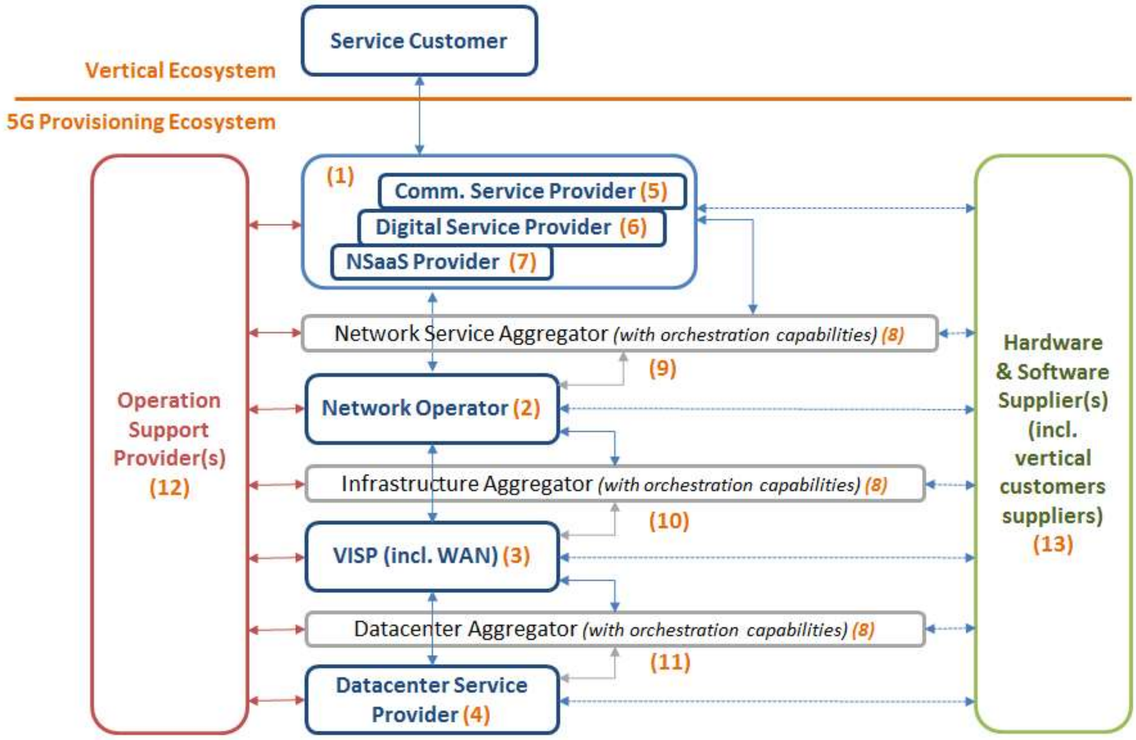


Figure 5 Roles in 5G provisioning systems (5G PPP [15])

The identified roles can be shared between one or more stakeholders, which will assume the management of relevant interfaces at business and technical level. A principal role in 5G service provisioning is that of the Service Provider (SP), depicted as (1) in Figure 5, which directly interfaces the Service Customers and obtains and orchestrates resources from Network Operators (2), Virtualisation Infrastructure Service Providers (VISP) (3) and Data Centre Service Providers (DCSP) (4) (collectively referred to as Infrastructure Providers). The role of the SP comprises the roles of Communication Service Provider (CSP) (5), entailing the activities for offering traditional telecom services, Digital Service Provider (DSP) (6), entailing the activities for offering digital services such as enhanced mobile broadband and IoT to various vertical industries, and Network Slice as a Service (NSaaS) Provider (7) entailing the activities for offering a network slice along with the services that it may support and configure. Additional roles can be identified, such as the Service Aggregators at various layers, i.e., the Network Service Aggregator, the Infrastructure Aggregator and the Datacentre Aggregator (8), or the Spectrum Aggregator, having business relationships with several spectrum license owners in order to share spectrum more cost efficiently and in a flexible way. The role of Network Service Aggregator can undertake the activities of service provisioning across multiple network operators required, e.g., in cross border, or in multiple private and public network environments.

6.2 Instantiation of role model for 5G-IS use cases

Different use cases identified in 5G-IS have different provisioning requirements and will be based on different assumptions on the potential business benefits of stakeholders in the ecosystem. It will be up to the stakeholders to make a choice of how a service should be delivered to the market.

Herein we present two instantiations of the above models for two basic assumptions. The first instantiation puts the solution provider in the centre (see Figure 6), which implies that the solution provider is the single point of contact with the VSP (Vertical Service Provider). We consider this instantiation a more “conservative” scenario, in which the main actors largely retain their established role in a telecommunications ecosystem.

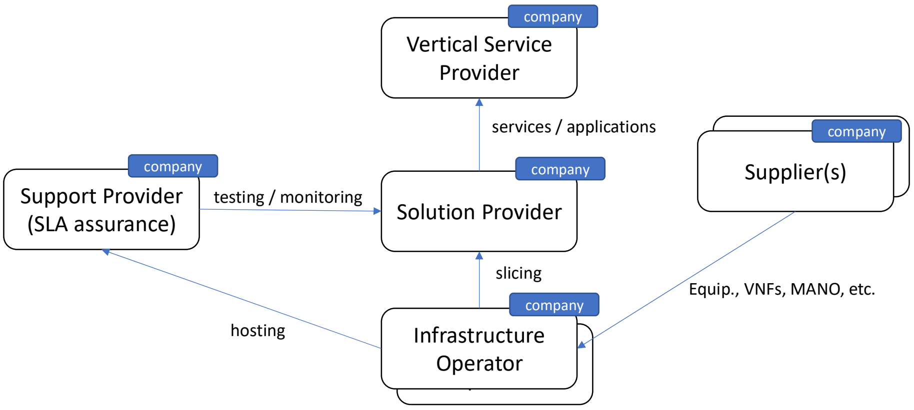


Figure 6 "Conservative" instantiation of role model

In the “conservative” case the infrastructure operator (SatCom company), adopts roles only up to Network layer of the value network, offering network services to the solution provider (SP). The SP handles the service layer and is an actor that offers solutions in a certain vertical sector (e.g. automotive). The SP interacts with the vertical service provider (VSP) alone. The VSP is the customer of the solution (e.g., automotive application provider) that in turn does business in the respective vertical sector. The support provider provides services, possibly hosted on the infrastructure, and supports the solution provider during operation, e.g., by providing testing and monitoring services. Finally, different suppliers provide hardware and software 5G system components to the infrastructure, as well as applications.

The second instantiation puts the infrastructure operator in the centre (Figure 7), implying that this role becomes the single point of contact towards the VSP. This obviously works only if the infrastructure operators assume aggregation tasks, whereby bundling all necessary functions towards the customer including the provision of the solution. This form of instantiation could be called an “aggressive” scenario, in which at least one actor (in this case the infrastructure provider) tries to increase its share of the overall business in the provisioning ecosystem.

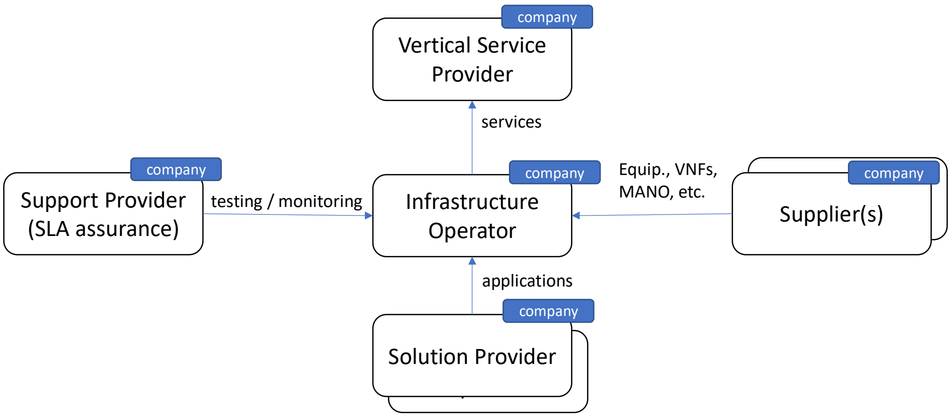
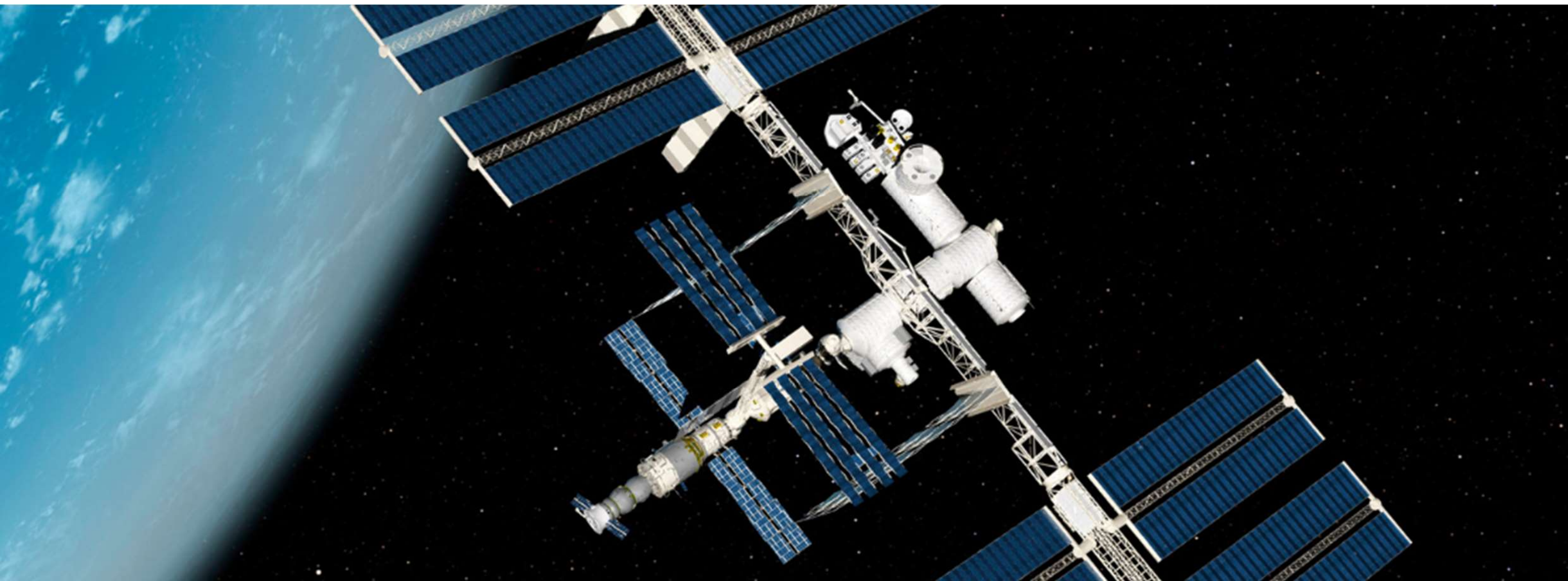


Figure 7 "Aggressive" instantiation of role model

In this case the infrastructure operator (SatCom company) follows a more "aggressive" strategy, i.e., it adopts roles at the Service layer and becomes the contact point for the customer, the vertical service provider in a certain vertical sector (e.g., automotive). This means that beyond operating the infrastructure, the infrastructure operator now acts as an integrator and combines services from multiple sources for offering a complete service solution to vertical service provider (VSP). On the other hand, the solution provider (SP) now adopts only the digital service provider (DSP) role, thus it just provides the vertical application(s) to the infrastructure of the infrastructure operator to enable the service offerings, without having direct contact with the VSPs.

A special case of the second (aggressive) scenario, can be constructed for a multi-operator setup (see Figure 8). When two infrastructure operators in the 5G ecosystem collaborate to jointly offer services across multiple infrastructures, three alternatives can be derived, based on the strategy (conservative or aggressive) each of the infrastructure operators follows, i.e.:

- One of them (e.g., infrastructure operator A) follows a more aggressive strategy and adopts roles at the service layer of the value network, while the other (e.g., infrastructure operator B) follows a more conservative approach and adopts roles only up to the network and virtual infrastructure layer of the value network.
- Both of them follow the aggressive strategy
- Both of them follow the conservative strategy



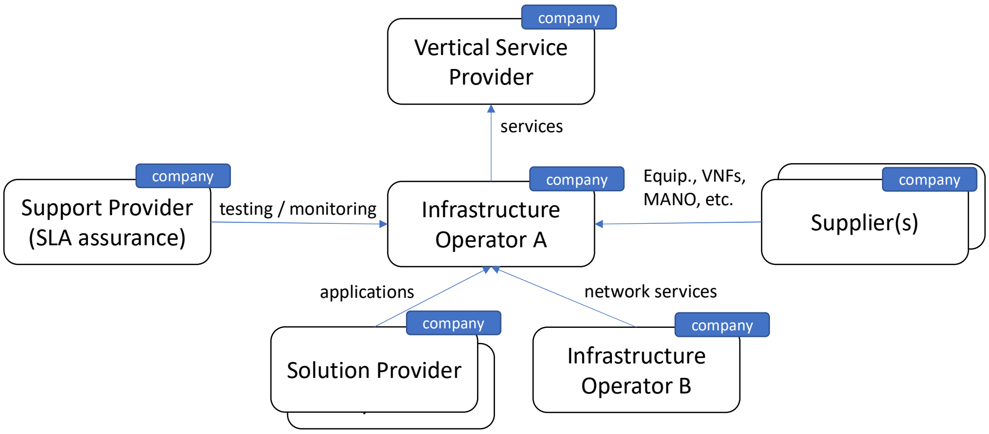


Figure 8 Multi-operator instantiation of role model with one "aggressive" operator

The second and third alternatives are trivial, in the sense that none of them can have a competitive advantage against the other. In the third alternative, each of them will provide network services to each other in order to build network services that expand their reach, potentially following a pay-as-you-go pricing scheme. In the second alternative, they will both take advantage of the network service offering of the other to gain benefits from providing solutions in an extended geographic region. In the first alternative, only the aggressive infrastructure operator (operator A) can take advantage of the other's network service offerings. Figure 8 above presents the case where only infrastructure operator A follows the aggressive strategy.

6.3 Procurement, business and deployment models

The starting point in evaluating the economic viability is the aggregation of all its relevant cost elements of the 5GSBI E2E system for the calculation of the Total Cost of Ownership (TCO), which encompasses Capital Expenditures (CAPEX) and Operating Expenses (OPEX) from the system's inception to its decommissioning. Since data on detailed cost figures in such a newly formed competitive market is integral to keep disclosed, publicly available data is scarce. Nevertheless, a simplified adaption of the standardized cost framework could be utilized to provide preliminary guidance and estimation on the overall Rough Order of Magnitude (ROM) cost structure for the system and all its major components of a typical 5GSBI. In addition, a high-level Concept of Operations was provided to support the estimation of the Operating Costs of an 5GSBI system. All these cost elements were aggregated to give a ROM estimation for the exemplary enhanced mid-term constellation that was presented above.

However, as there are still a lot of unknowns concerning the actual configuration, and consequently also the actual costs the cost estimate has to be taken with a lot of caution and cannot directly be used for the derivation of a valid business model that detailed cost and revenue models. The situation is mirrored on the revenue side, where the addressable markets have been well identified, but detailed market analyses – identifying who will pay how much for what service level – are not yet possible. While it should be noted that in the deep dive on the automotive/road transportation sector a first assessment of the economic value of different automotive use cases has been conducted, even this is not sufficient for reliable revenue estimates – especially as there no customer commitments at all.

Therefore, a simplified cost amortization model was devised that relied on the previously discussed cost models for a rough estimate of the total cost of ownership and deduced the relationship between monthly subscription fees and number of subscribers necessary for breakeven. As further variables the amortization time, the profit margin and the terminal costs where included.

Using this amortization model a number of dependencies were explored and two general business scenarios were analysed in more detail with some promising results concerning business viability as follows:

- Low End – Direct 2 Handheld
- High End – Governmental and Business Performance Connectivity

In addition, within the automotive extension two specific automotive business scenarios were analysed further:

- A narrowband service with low subscription costs @lower performance but accessible to and attracting many subscribers and
- A broadband service with high performance (e.g. data rate) but with significantly higher subscription fees, which may be attractive only for a select few subscribers

Preliminary values for achievable Average Revenue Per User (ARPU) were estimated for both scenarios based on

- coarse initial valuation of selected use cases and
- an (admittedly non-representative but nevertheless indicative) survey among the experts in the project team as well as
- on available (i.e. published) assessments of various market analysts.

The results show that for reasonable monthly subscription fees – of 5 – 20 € the for narrowband portfolio and 20 – 50 € for the broadband offering – the number of subscriber necessary to amortize the total system costs seem clearly achievable given the size of the global automotive market with close to 100 million cars being newly registered worldwide every year. They clearly indicate the potential for viable business models to support the implementation of a 5GSBI system in the medium term.

The employed methodology presents a powerful tool to assess 5GSBI business models, but further steps are necessary to generate and construct a unified framework on costs and revenues to guide in architectural decisions and implementation strategies involving market scope, performance and deployment. In particular, urgent work need to be conducted as follows:

- A thorough evaluation of vertical markets and use cases based on business risks and

- a further analysis into CAPEX, OPEX and total cost of ownership factoring in the performance that the system should achieve and the technical development that are necessary to achieve it including associated risks and timelines

While these results are preliminary, they give a clear indication of the viability of business models for a 5GSBI already in the mid-term. Still even for this scenario the unknowns – mainly regarding accessible markets and use cases, but also concerning the maturity, availability and especially also the cost of the necessary technologies – are so significant that reliable business modelling cannot be conducted yet. Of course, for the long-term scenario the uncertainties are even more prevalent:

- New, innovative markets, use cases, applications scenarios and services are expected to emerge, but it is difficult to predict today whether they will resonate with the users and will be widely adopted
- The technologies needed to implement them are still in very early research and development phases – consequently cost estimates are all but impossible and reliable schedules for their availability are hard to come by
- Standards and regulations that long term 5GSBI systems will be subject to are not at all apparent and therefore the environment in which a long-term 5GSBI – or better 6GSBI – is not predictable
- The market success of the mid-term scenario, that could provide some basis for extrapolation to the long-term has not been operationally demonstrated so far in the commercial world. While a satisfactory return on investments for the mid-term scenario is not absolutely essential for demonstrating business viability in the long-term (as long-term outlook could be much more promising) it certainly would help a lot to have it available.
- … and quite some more

Therefore, discussing the long-term business viability is not possible at this point as significant changes are anticipated – likely for the better but possibly also for the worse.

Overall, it can be concluded, that 5GSBI systems show significant promise of clear business viability and of associated return of investment to warrant further and much more detailed analysis and the timely initiation of suitable technology development programmes as urgent next steps.

Of course, once the evidence for feasibility, maturity, viability and customer demand of such a 5GSBI system has been convincingly established the question is who shall/should procure it. The level of its integration with the 5G system(s) for which it will provide satellite access and on how the system in its interplay between the various stakeholders is utilized and provides economic benefits is one of the determining factors. The service exploitation models form the basis for determining who benefits from the system (and how) and would consequently have a strong interest in procuring and owning the 5GSBI system. A first analysis indicates that the following procurement models seem at the moment most favourable and should be preferred:

- MNO – SNO joint venture – this configuration should have all the knowhow and capabilities (including hopefully spectrum licenses) to own and efficiently operate a 5GSBI
- Value Chain Vertical joint venture – this configuration contains all the necessary knowhow to make 5GSBI a success, but coordination among the different entities involved is a challenge and may degrade efficiency
- MNO or SNO single owner – either of these entities has sufficient knowhow (and hopefully also spectrum) to establish and manage a successful 5GSBI venture
- MNO-MNO or SNO-SNO joint venture– two operators joining forces or working with an entrepreneur could also be quite viable provided efficient coordination can be achieved.
- In addition, a Private-Public-Partnership with significant public investment (European or multi-national) and with either MNO or SNO (or both) could be mandated for supporting specific key industries such as the automotive sector, advance European sovereignty and independence, and pursue higher societal goals such as "connecting the unconnected" and "advancement of rural areas". The planned European Secure Constellation IRIS² could provide a much-needed spark to further advance cross-industry cooperation and reduce the risks for all partners involved.

Of course, the details of the most promising procurement models and possibly ensuing cooperations have to be explored in more depth. Especially in cooperative ventures compatibility between partners and their strategic orientation plays a major role.

The discourse between all relevant stakeholders of future 5GSBI systems needs to be accelerated in order to come to a joint understanding and a common way forward in implementing such a system in a timely and cost-efficient manner with a clear focus on the needs of the most important vertical markets and their users.

Critical technologies, functioning supply chains (in particular including launch services) and sufficient capital are the three elements that need to be ready for a successful implementation of a viable 5GSBI. Initial efforts have already been triggered some early technology developments have started and the workplans in the ESA strategic programme line "Space for 5G/6G" have been and are initiating further maturation projects. Significant experience in setting up and executing the mass production of satellites is now available at LSIs and suppliers. Still, designing the satellites and establishing the supply chain in the timeframe of 2 to 3 years is highly ambitious. But the most significant challenges for a timely deployment of a 5GSBI system in the mid-term (i.e., by mid-2028 at latest) are to secure the necessary capital for developing and building the system and the launches to bring the satellites into low earth orbit.

7 Recommendations

Analysts predict significant market potential for space-based infrastructures to provide 5G satellite access to 5G systems. There are still some obstacles, but the results of the 5G Infrastructure study give some clear indications on the necessary next steps to overcome them:

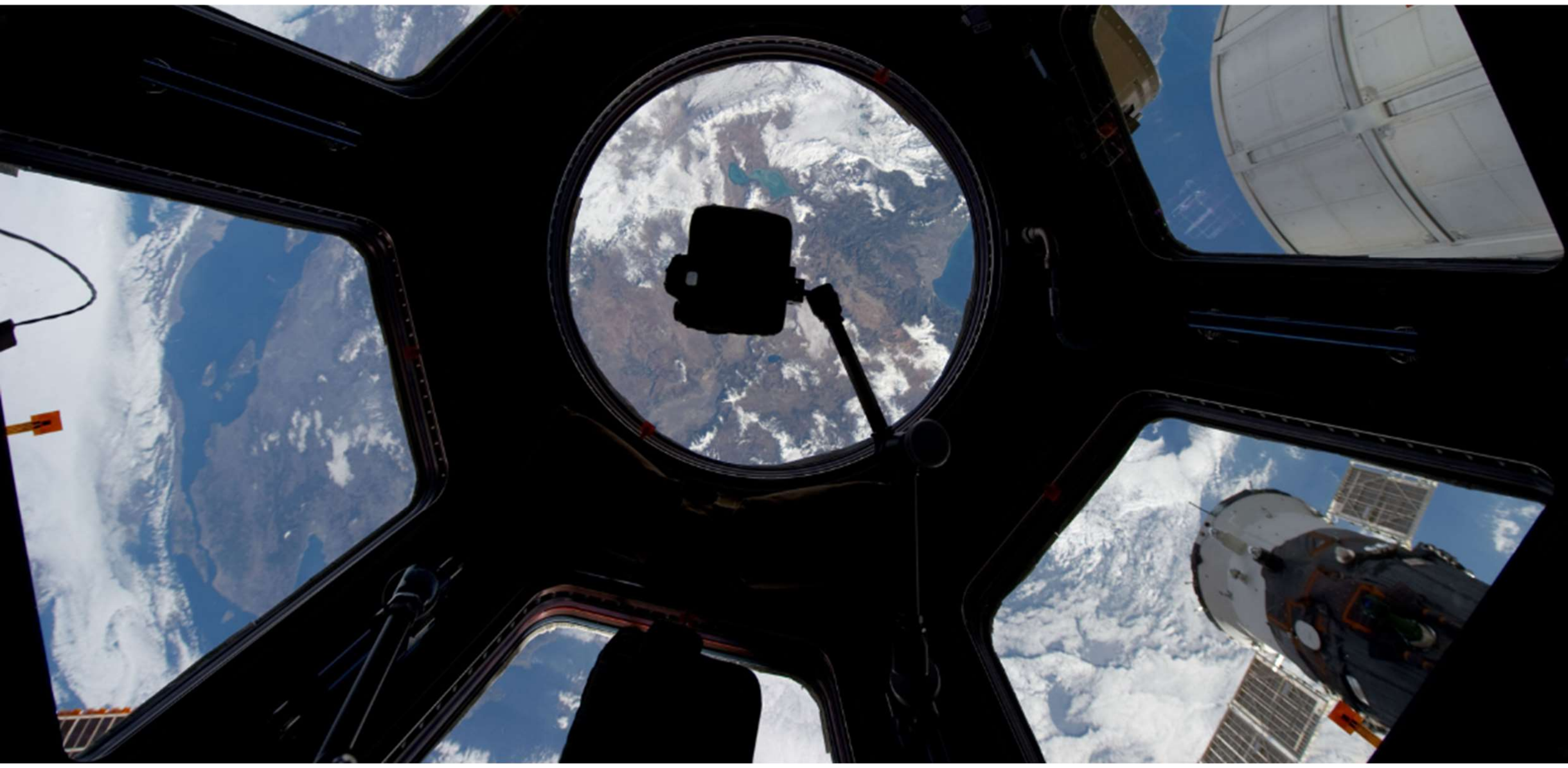
- For the multitude of use cases that require additional technical or market development a close co-operation between the space industry and the respective vertical market stakeholders is indispensable. Therefore, co-innovation and co-creation activities leading to viable demonstrations need to be quickly initiated to shape the ecosystem
- The most promising mid-term architecture concepts of 5G NTN need to be quickly matured to attract the interest of potential investors and operators. In a pilot implementation of a 5G NTN space segment, an open, expandable and as far as possible reconfigurable architecture shall be realized in co-operation with terrestrial mobile network and satellite network operators.
- A vigorous R&D effort to accelerate technology maturation and demonstration for the key enablers that are needed for an initial mid-term implementation has to be triggered immediately to achieve sufficient technology readiness for a timely realization.

Right now, there is a window of opportunity for satellite communications to become via 5G/6G NTN an integral part of the global telecommunications ecosystem. To seize this opportunity, the space industry and community needs to engage rapidly to have the required solutions available when they are needed. Considering the strategic importance for Europe of a 5G (extending to beyond 5G and even 6G) space-based infrastructure, this could go as far as declaring the creation of such an infrastructure an Important Project of Common European Interest. The current plans of the European Community for a constellation providing secure connectivity offer a unique time window for implementing innovative 5G NTN space-based solutions as a complement to terrestrial networks for the benefit of citizens and its core industry.

8 Current developments and outlook

Currently developments are underway that explore the concept of 5G repurposable payload as a service. These efforts entail developing a flexible and adaptable payload that can be repurposed to meet requirements of different use cases and missions. Among other the convergence of earth observation and telecommunications is in focus, aiming to enhance the functionalities and efficiencies of space missions by integrating communication and earth observation technologies. Two approaches are considered, namely Joint Processing and Communication (JPAC), and Integrated Sensing and Communication (ISAC). JPAC handles simultaneously data processing and communication tasks to improve efficiency and performance of Earth Observation missions. ISAC aims at optimising the use of resources and enhancing the overall functionality of space missions by integrating RF sensing functionalities into the communications payload. Both approaches envision multi-purpose processing capabilities onboard the satellite payload. The 5GEOSiS project, funded by ESA, is making first steps in this direction, with the ambition to support this evolution through the provision of a suitable hardware test-bed and initial trade-off studies.

On the standardisation front, progress is being made towards 3GPP Rel. 19 with further enhancements and capabilities being introduced for optimizing satellite access performance. Standardisation includes system aspects defining networking models, frequencies and hand-over to and from terrestrial networks. An excellent elaboration of the technical contributions of the NTN community to 3GPP is available on the 3GPP site at (https://www.3gpp.org/technologies/ntn-overview). Evidence of the very active NTN community contributions to 3GPP is the prestigious "Satellite technology of the year" award announced during the SATELLITE 2024 conference (https://www.3gpp.org/news-events/3gpp-news/ntn-award-2024).



List of contributors

- Helmut Zaglauer, Airbus Defence & Space
- Jörg Pfeifle, Airbus Defence & Space
- Anastasius Gavras, Eurescom GmbH
- Ádam Kapovits, Eurescom GmbH
- Marius-Iulian Corici, Fraunhofer FOKUS
- Thomas Heyn, Fraunhofer IIS
- Alexander Hofmann, Fraunhofer IIS
- Thi Uyen Ly Dang, Fraunhofer IIS
- Leo Frank, Fraunhofer IIS
- Florian, Völk, University of the Bundeswehr Munich
- Kevin Li, University of the Bundeswehr Munich
- Daniel Weinzierl, University of the Bundeswehr Munich

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