5GAA Automotive Association

Defining measures for successful implementation of 3GPP-based automotive satellite connectivity

5GAA Automotive Association
Technical Report

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This document has been prepared by the 5G Automotive Association (5GAA) and is based on the information and technology available at the time of its publication. It reflects the most current and accurate version to the best of 5GAA's knowledge. As technologies and industry standards continue to evolve, 5GAA is committed to regularly reviewing and updating this document as necessary to ensure its continued relevance and accuracy.

VERSION:	1.0
DATE OF PUBLICATION:	29 September 2026
DOCUMENT TYPE:	Technical Report
EXTERNAL PUBLICATION:	Yes
DATE OF APPROVAL BY 5GAA BOARD:	27 July 2026

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Executive summary

Satellite communications are rapidly evolving from a niche technology into a strategic enabler of ubiquitous automotive connectivity. As vehicles become increasingly software-defined and dependent on continuous connectivity, terrestrial mobile networks alone cannot guarantee the required service availability. Large geographical regions remain outside cellular coverage, while natural disasters and infrastructure failures can temporarily disrupt terrestrial networks. For this reason, 5GAA has consistently advocated the integration of Non-Terrestrial Networks (NTN) into the mobile ecosystem based on global 3GPP standards rather than proprietary satellite solutions. The objective is to create a seamless extension of terrestrial networks that provides resilient, global connectivity for future connected vehicles.

This report analyses the technical, commercial and architectural challenges of automotive satellite connectivity and evaluates realistic deployment pathways. The study confirms that future automotive NTN demand will vary significantly by use case. Safety and resilience applications such as emergency calls, hazard warnings and disaster management generate relatively low traffic volumes and can already be supported by Narrowband Internet of Things (NB-IoT) satellite systems. In contrast, future services such as high-definition (HD) map distribution, cloud gaming, teleoperated driving, video communication, and advanced remote operations require orders of magnitude more bandwidth and will depend on wideband and broadband NTN solutions.

A key finding of the report is the substantial mismatch between future demand and the traffic capacity offered by current NB-IoT NTN solutions. While NB-IoT NTN provides a highly valuable extension of network coverage and enables globally available emergency messaging, the available system capacity is extremely limited. Traffic density calculations show that even moderate automotive service demand can quickly exceed narrowband capacity limits. As a result, NB-IoT NTN should be viewed primarily as an enabling technology for safety-critical messaging and emergency services, rather than a scalable platform for future connected-vehicle applications.

The market outlook confirms a phased adoption model for satellite connectivity. Industry feedback indicates that narrowband NTN services will enter mass deployment first, beginning in 2029. Wideband services are expected shortly thereafter in 2030. First 3GPP compliant broadband satellite can be expected in the same year but broadband services requiring higher-frequency terminals will likely become commercially relevant only in the early to mid-2030s. Across all original equipment manufacturers (OEM) responding to the survey, there is strong consensus that NTN will become part of future vehicle architectures. The key differentiator is not if satellite connectivity will be deployed, but which level of capability will be integrated, and when.

The report also demonstrates that future NTN business models will initially be driven by safety, resilience and coverage-extension use cases. OEMs expect narrowband and wideband satellite capabilities to become embedded vehicle functions, while broadband services are more likely to be introduced as premium or optional features. Survey results also show that emergency services, hazard warnings and vehicle safety functions consistently rank highest in perceived customer value and criticality.

From a technology perspective, the analysis of broadband satellite terminals confirms that compact automotive user equipment operating in high-frequency bands, Ku- and Ka-bands, is technically feasible and can comply with existing regulatory requirements. However, terminal complexity and cost remain significant challenges. Radio frequency (RF) front ends, beamforming architectures, PCBs, and antenna systems represent the dominant cost drivers. Continued innovation in antenna integration, RF integration, and semiconductor technology will therefore be essential to achieve automotive-scale deployment.

The architectural analysis further concludes that NTN should not be treated as a standalone communication system. The greatest value is achieved through deep integration between terrestrial and non-terrestrial networks, including roaming, common subscriber management, seamless mobility, and hybrid TN/NTN architectures. Future vehicles should be capable of dynamically selecting the most appropriate access technology while maintaining service continuity and consistent user experience.

Perhaps the most important evidence comes from the various live demonstrations conducted by 5GAA members. These demonstrations successfully validated emergency messaging, hazard warnings, NTN-based eCall concepts, NTN/TN switching, satellite-assisted voice services, and NR-NTN-based broadband applications. Collectively, they prove that 3GPP-based satellite communications have moved beyond theoretical feasibility and are now capable of delivering real automotive services. However, the demonstrations also confirmed current limitations, including uplink latencies of several seconds, strong dependence on GNSS availability, and the challenges associated with GEO-based narrowband systems.

Strategic recommendations

1. Treat NB-IoT NTN as a coverage and safety solution

NB-IoT NTN provides immediate value by enabling emergency messaging, hazard warnings, disaster notifications, remote vehicle access, and basic resilience functions. Today's capacity limitations recommend NB-IoT NTN as an enabling technology for safety-critical messaging and basic connected services rather than a scalable platform for future connected-vehicle applications.

2. 5G NR-NTN as enabler of the target architecture

The report shows that future automotive applications will require substantially greater capacity than NB-IoT NTN can deliver. 5G NR-NTN supports significantly higher data rates, lower latency, higher network capacity, mobility between TN and NTN, and seamless integration into the 5G advanced ecosystem. Therefore, 5G NR-NTN should become the primary focus of future deployments, standardisation efforts, and vehicle platform development. 5G NR-NTN offers the capability to support automotive services including safety and emerging data-intensive applications which are the base for software-defined vehicles.

The report shows that future automotive applications will require substantially greater capacity than NB-IoT NTN can deliver. Therefore, NR-NTN should become the primary focus of future deployments, standardisation efforts, and vehicle platform development. NR-NTN offers the capability to support both future safety services and emerging data-intensive applications.

3. Focus on direct-to-device for automotive

The automotive industry should actively support standardisation and regulatory initiatives that enable direct-to-device (D2D) satellite communications based on NR-NTN technology. 5G NR-NTN eliminates the need for proprietary satellite terminals, reduces vehicle integration complexity, accelerates market adoption, and leverages the global mobile ecosystem. Within NR-NTN, D2D represents the most scalable path towards mass-market automotive satellite connectivity and should be regarded as a strategic priority for future NTN evolution.

4. Integrate TN/NTN vehicle connectivity

Future telematics architectures should assume that NTN is an integrated extension of cellular networks rather than an isolated backup solution. Seamless mobility between terrestrial and satellite access should become a core vehicle requirement, ensuring continuous connectivity under all coverage conditions.

5. Continue engagement in broadband NTN technologies

Automotive stakeholders should continue driving technologies in frequencies above 10 GHz, like Ku- and Ka-band, to enable NTN developments supporting future broadband use cases.

1 Introduction

Since 2021, 5GAA has communicated how important connectivity is for the automotive sector. Ubiquitous and seamless connectivity is a key enabler for the rapid digitalisation of vehicular services. Satellite communication is seen by 5GAA as a complementary extension of terrestrial networks, helping to mitigate coverage gaps or as a stand in when terrestrial networks break down.

5GAA is also known for its position that non-terrestrial networks should be integrated into terrestrial networks on the basis of global mobile standards (3GPP). This was communicated first in our position paper published in October 2022. At this time, satellite communication was mostly proprietary, costly and involved special equipment to receive/send satellite signals. Since then, we have tried relentlessly to shape the ecosystem for connectivity with the extensive communication of automotive requirements. We have described NTN use cases including Service Level Requirements (SLR) and we compiled these use cases into the so-called 'NTN roadmap', which was published in September 2024 and has turned out to be a very powerful tool to align the various stakeholders in the ecosystem.

Another milestone of our work was the specification of antenna parameters for NTN. These have been infused into the standardisation process of 3GPP. In August 2025, 3GPP released specifications for the so-called High Power UE for FR1 Power Classes 1 and 2.

In 2026, most satellite operators are committing to 3GPP standards for future developments. There is also an ongoing concentration process with many mergers and acquisitions. Drastically reduced launch costs enable large low-earth orbit satellite constellations, operating in frequencies that can be received even by cell phones, enabling Narrowband and Wideband services.

But there are also many implementation challenges which need to be addressed before many of these developments fully materialise. This report will focus on some of these implementation challenges. The following key questions will be answered:

1. What are viable reference scenarios for calculating the amount of data traffic which is generated if vehicles are communicating via NTN? While it is probably not possible to calculate such data traffic accurately, these reference scenarios are aimed at estimating at least the dimension of data traffic depending on the coverage situation, the data rates required by various applications, the traffic situation, and the probability of usage.
2. What are the business considerations for establishing satellite communications for automotive? What do the customers value most? How much do the customers and the industry's perspective match? 5GAA has conducted a global customer survey and a new member survey in order to answer these questions.
3. Expensive high-frequency satellite terminals are considered as one of the largest hurdles for Broadband satellite services. How can the costs for high frequency satellite terminals be reduced? What are the drivers

and complexities? 5GAA has analysed the so-called 'complexity drivers' of satellite terminals to establish the extent to which costs can be reduced if satellite terminals are implemented at large scale.

4. What architectures are recommended for the integration of NTN into TN? What are the advantages and disadvantages of the various options. How do these architectures contribute to interoperability and scalability?

5. Finally, we answer the question if automotive satellite communication will work in real life. 5GAA has conducted various live demonstrations to show the technical viability of satellite communication.

This report contributes to the ongoing discussion regarding the evolvement of standards-based satellite communications and D2D in particular.

2 Definitions, symbols and abbreviations

2.1 Definitions and symbols

For the purposes of the present document, the following definitions and symbols apply.

A	Penetration coefficient
Bprop	Proportion of the global population located in coverage blind spots of terrestrial networks
Bland	Proportion of global land area not covered by terrestrial networks
N	Global vehicle parc in use (vehicles in operation)
S	Global land area
DensityNTN	Average density of NTN-dependent vehicles
DTrafficDemand	Area traffic demand for each use case
DDataRate	Data rate of the relevant use case
Factivity	Activity factor of the relevant use case
K	Scaling factor used to characterise the average density of vehicles using NTN for communication under different TN coverage categories and traffic demand scenarios

2.2 Abbreviations

For the purposes of the present document, the following symbols apply:

3GPP	Third-Generation Partnership Project
5GAA	5G Automotive Association
CINR	Carrier-to-Interference-plus-Noise Ratio
CNR	Carrier-to-Noise Ratio
DL	Downlink
EIRP	Equivalent Isotropically Radiated Power
ETSI	European Telecommunication Standards Institute
FR1	Frequency Range 1
FR2	Frequency Range 2
GEO	Geostationary Earth Orbit
GNSS	Global Navigation Satellite System
GSMA	Global System for Mobile Communications
GSO	Geosynchronous Orbit
HD	High Definition
HPLMN	Home Public Land Mobile Network
HR	Home Routing
IMS	IP Multimedia Subsystem

IoT	Internet of Things
IoT-NTN	Internet of Things Non-Terrestrial Network
ITS	Intelligent Transportation Systems
Kbps	Kilobit per second
KPI	Key Performance Indicator
LBO	Local Breakout
LEO	Low-Earth Orbiting
LTE	Long-Term Evolution
MEO	Medium Earth Orbit
MHz	Megahertz
MNO	Mobile Network Operator
MOCN	Multi-Operator Core Network
MORAN	Multi-Operator Radio Access Network
MSS	Mobile-Satellite Service
NB-IoT	Narrowband Internet of Things
NB-NTN	Narrowband Non-Terrestrial Network
NGSO	Non-GEO Stationary Orbit
NIDD	Non-IP Data Delivery
NR	5G New Radio
NR-NTN	New Radio Non-Terrestrial Network
NSA	Non-Standalone
NTN	Non-Terrestrial Networks
OEM	Original Equipment Manufacturer
PLMN	Public Land Mobile Network
PRB	Physical Resource Blocks
PSAP	Public Safety Answering Points
QoS	Quality of Services
RAN	Radio Access Network
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
SatComs	Satellite Communications
SINR	Signal-to-Interference-plus-Noise Ratio
SLRs	Service Level Requirements
SNR	Signal-to-Noise Ratio
TCU	Telematics Control Unit
TN	Terrestrial Network
TR	Technical Report
UE	User Equipment
UL	Uplink
VoLTE	Voice over LTE
VoNR	Voice over New Radio
VPLMN	Visited Public Land Mobile Network
VSAT	Very Small Aperture Terminal

3 Realistic reference scenarios for automotive satellite communication

3.1 Overview

To reach that point, however, it is important first to define these reference scenarios, including the geographical setting, coverage situation, density of settlement, road network, number of cars, and probability of various applications shown in the NTN roadmap being used. These references can be used later for system-level assessment to calculate the data transmission needs in a certain area over a given amount of time. In turn, this information can be used in cooperation with potential satellite operators to evaluate if future offerings will be able to meet the demand of mobile users (incl. automotive).

This TR adopts a demand-side perspective of the intelligent and connected vehicle industry, grounded in the global intelligent and connected upgrade trend observed across the automotive sector. Its core objective is to quantitatively calculate the total NTN communication data demand from intelligent vehicles (or vehicles equipped with satellite communication capabilities) across different application scenarios, for the current period and coming years.

On the one hand, through scenario-based modelling and systematic calculation, we clarify the magnitude of the total data demand for vehicle-to-satellite communication, as well as the demand structure characteristics across different scenarios. On the other hand, by benchmarking the calculation results against the existing capabilities of current satellite-terminal systems, it quantitatively identifies the gap between existing technical capabilities and actual business requirements.

The findings of this report can provide quantitative data support and directional guidance for satellite operators, automobile manufacturers, and relevant industrial chain stakeholders in terms of future industrial development and layout.

To accurately quantify the total data traffic demand of intelligent vehicles for communication via NTN, we adopt a layered and progressive calculation framework for quantitative analysis, with the specific implementation path as follows:

- Firstly, based on global geospatial data, terrestrial cellular network coverage distribution, and datasets of intelligent vehicle population and trip characteristics, we calculate the average distribution density of intelligent vehicles equipped with satellite communication capability in global areas outside terrestrial cellular network coverage, where communication can only be realised via NTN.
- Secondly, according to [1] we classify the NTN coverage conditions of target areas into three categories. Meanwhile, combined with the temporal distribution characteristics of in-vehicle communication services, the traffic load is divided into four gradients according to off-peak and peak traffic conditions.

- Finally, combined with the per-vehicle baseline data traffic demand of typical NTN application scenarios for intelligent vehicles, the total satellite communication data demand of intelligent vehicles under different coverage scenarios and traffic load conditions is derived in a layered manner.

It should be noted that this technical report aims to provide researchers and the industry with typical reference scenarios for vehicle-to-satellite communication and a demand-side and supply-side traffic density analysis methodology. The specific values of various parameters presented in this report are for reference purposes only and shall not be construed as industry target values or the only valid values. Industry researchers may make appropriate adjustments based on different scenario configurations and underlying assumptions. Consequently, the final results obtained under different scenario configurations and parameter values may differ from those presented in this report.

3.2 Vehicle density

According to official statistical reports published by the GSMA [2], 350 million people worldwide currently reside in remote areas with no coverage from terrestrial mobile communication networks, meaning 4% of the global population falls within the coverage blind spots of terrestrial mobile networks. Meanwhile, the global population distribution analysis in GSMA's thematic report *Non-Terrestrial Networks: Opportunities and Challenges* [3] demonstrates that the global population is mainly concentrated within less than 20% of earth's total land area. While the coverage of existing terrestrial mobile communication networks is also primarily focused on this population agglomeration zone, the remaining 80% of the global land area is not effectively covered by terrestrial mobile networks.

According to official statistics released by Hedges & Company [4], the global vehicle parc in use reached 1.645 billion units by the end of 2025. Considering that not all in-service vehicles are currently equipped with satellite communication access capability, the market penetration of intelligent vehicles will increase significantly in the future along with the rapid development of the global intelligent connected vehicle industry, and the penetration rate of in-vehicle terminals with NTN communication capability will grow correspondingly. To quantitatively characterise the scale of vehicles with NTN communication capability, we introduce a penetration coefficient α, which is defined as the ratio of the number of in-service vehicles with NTN communication capability to the total global vehicle parc in use.

This report quantitatively derives the average vehicle density in areas not covered by terrestrial networks, based on two core parameters: the proportion of the global population located in coverage blind spots of terrestrial networks β_{prop}, and the proportion of global land area not covered by terrestrial networks β_{land}.

The core derivation formula is presented as follows:

$$\mathrm{Density}_{\mathrm{NTN}} = \frac{N \times \beta_{\mathrm{prop}} \times \alpha}{S \times \beta_{\mathrm{land}}}, \quad (3\text{-}1)$$

where N is the global vehicle parc in use, S is the global land area.

In this TR, the value of parameter α is set to 20%, which corresponds to the baseline assumption that 20% of vehicles are equipped with NTN communication capabilities. Given the significant variations in automotive functional requirements across different countries and regions, as well as the rapid iteration and development of the automotive industry, automotive-satellite communications are expected to achieve broader adoption in the coming years. Accordingly, the value of α may be adjusted appropriately, either increased or decreased, to reflect different market conditions and technology penetration scenarios.

By substituting the aforementioned parameter values into the corresponding formula, the global average density of NTN-dependent vehicles is derived as 0.1 vehicle/km2 as follow,

$$\text{Density}_{\text{NTN}} = \frac{N \times \beta_{\text{prop}} \times \alpha}{S \times \beta_{\text{land}}} = \frac{1.645 \times 10^9 \times 4\% \times 20\%}{1.49 \times 10^8 \times 80\%} = 0.1 \text{ vehicle/km}^2. \quad (3\text{-}2)$$

With the continuous evolution of technology and the large-scale deployment of terrestrial networks, the values of β_{prop} and β_{land} may be dynamically adjusted. Meanwhile, the parameter α can also adopt differentiated values according to application scenarios or technology evolution stages. Equipment vendors and researchers can conduct targeted simulation analysis and performance evaluation based on different value combinations of the above parameters.

3.3 Requirement of use cases

We screened the top six typical use cases with the most concentrated traffic demand in vehicle-to-satellite communication scenarios over the next five to 10 years through an industry-wide expert questionnaire survey. The full list of these use cases is as follows:

1. Voice Call (including third-party emergency calls)
2. Remote Access
3. Traffic Management in Disaster Situations
4. Entertainment (Wideband): Video call (720p), Video stream (720p), Live broadcast in real time, Cloud gaming
5. Hazard Information, Data Collection and Sharing for HD Maps
6. Teleoperated Driving Support

On this basis, quantitative analysis and modelling were carried out for the key parameters of each use case, including data rate, activation ratio, and vehicle density. Among them, the values of data rate are mainly set with reference to the relevant content in *Use Cases and Service Level Requirements* published by 5GAA [5]. The detailed parameters are listed in the table below. The area traffic demand $D_{TrafficDemand}$ for each use case can be calculated by the following equation,

$$D_{\text{Traffic-Demand}} = D_{\text{Dare-Rate}} \times F_{\text{activity}} \times \text{Density}_{\text{NTN}} \quad (3\text{-}2)$$

Table 1 KPI for top six use cases

Use cases		Data rate of use case	Activity factor	Vehicle density	Area traffic demand for each use case
Voice Call (including third-party e-call)		DL: 4.75 kbps UL: 4.75 kbps	10%	0.1 /km^2	DL: 0.0475 kbps/km^2 UL: 0.0475 kbps/km^2
Remote Access		DL: 8 kbps UL: 8 kbps	5%	0.1 /km^2	DL: 0.04 kbps/km^2 UL: 0.04 kbps/km^2
Entertainment	Video call (720p)	DL: 1 Mbps UL: 1 Mbps	2%	0.1 /km^2	DL: 2 kbps/km^2 UL: 2 kbps/km^2
	Video stream (720p)	DL: 5 Mbps UL: /	5%	0.1 /km^2	DL: 25 kbps/km^2 UL: /
	Live broadcast in real time	DL: / UL: 3 Mbps	2%	0.1 /km^2	DL: / UL: 6 kbps/km^2
	Cloud gaming	DL: 20 Mbps UL: 1 Mbps	2%	0.1 /km^2	DL: 40 kbps/km^2 UL: 2 kbps/km^2
Hazard Information Data Collection and Sharing for HD Maps		DL: 4 Mbps UL: 40 kbps	5%	0.1 /km^2	DL: 20 kbps/km^2 UL: 0.2 kbps/km^2
Teleoperated Driving Support		DL: 0.4 Mbps UL: 32 Mbps	1%	0.1 /km^2	DL: 0.4 kbps/km^2 UL: 32 kbps/km^2
Traffic Management in Disaster Situation		DL: 24 kbps UL: 48kbps	50%	10 /km^2	DL: 120 kbps/km^2 UL: 240 kbps/km^2

Note:

1. Activity factor: defined as the ratio of in-vehicle terminal users adopting the corresponding use case to the total number of users with NTN communication capability in the target scenario within the same statistical period.
2. For the use case *Traffic Management in Disaster Situation*, considering that satellite communication services need to cover not only users in the normal coverage blind spots of the TN, but also users who cannot access TN services due to terrestrial network paralysis caused by disasters and thus switch to NTN for communication, the vehicle density value for this use case is set to 100 times that of other conventional use cases.

Equipment vendors and researchers may adopt assumption values different from those in this report for use case data rate, activity factor and vehicle density, and derive the corresponding area traffic demand for each use case based on the formulas and analysis methodology proposed in this report.

3.4 Data demand under different scenarios

Affected by multiple factors including geographical setting, economic development level and population distribution characteristics, there are significant regional differences in the coverage level of the global terrestrial network. Based on the classification method specified in [1], coverage situations have been clustered into three categories, as follow:

1. Small countries typically densely populated and well covered by TN networks (examples are FR, DE, etc.).
2. Small countries typically sparsely populated and only well covered by TN networks in certain regions like capitals, coastline (examples are some African countries).
3. Large countries typically densely populated in some areas (coasts) but sparsely populated and not well covered by TN networks in certain other regions (examples are Australia, Canada, USA, Brazil, etc.).

Other factors affecting coverage include application scenario attributes, seasonal cycle fluctuations, and diurnal time distribution characteristics. There are also dynamic factors such as the different scale of communication users, as well as the type and frequency of service usage in areas covered by NTN, resulting in a non-uniform and spatiotemporally volatile situation in satellite communication data traffic demand. This makes it very difficult to ascertain a single fixed traffic baseline to fully cover the real service requirements under different boundary conditions. To accurately quantify the scale of NTN traffic demand in different scenarios, and ensure the comprehensiveness and scenario adaptability of subsequent system capacity calculation and resource planning, we divide the NTN communication traffic demand into **four gradient levels** in combination with the service characteristics of in-vehicle satellite communication and extreme scenario requirements as follow

1. Light Traffic Demand
2. Medium Traffic Demand
3. Heavy Traffic Demand
4. Disaster Situation Traffic Demand

Taking the in-vehicle NTN communication scenario of remote natural scenic spots as an example, during the peak tourist season, the number of self-driving vehicles and tourists entering the area without TN coverage increases exponentially, and the usage frequency of services such as in-vehicle high-definition map update, video backhaul, online entertainment and emergency communication is greatly increased, which will directly lead to a sharp surge in NTN traffic demand in this area during this period. In the off-season, the scale of vehicles and users in this area is greatly reduced, only generating a low scale of basic communication traffic. This validates the spatiotemporal fluctuation characteristics of traffic demand and further confirms the necessity and rationality of multi-level traffic demand classification.

Accordingly, a scaling factor k is introduced to characterise the average density of vehicles using NTN for communication under different TN coverage categories and traffic demand scenarios. The calculation baseline is derived from the vehicle density in TN non-coverage areas calculated in Section 4.2 of this document. Detailed values of the scaling factor and vehicle density for each coverage category and traffic scenario are presented in Table 2. For different categories and corresponding traffic demand scenarios, the values of the scaling factor may be adjusted according to actual deployment scenarios. Correspondingly, all related results in subsequent calculations and analyses shall be adjusted accordingly.

Table 2 Scaling factor k and vehicle density

		Light Traffic	Medium Traffic	Heavy Traffic	Disaster Situation
Category 1	Scaling factor *k*	1	2	5	100
	Vehicle density	0.1	0.2	0.5	10
Category 2	Scaling factor *k*	2	5	10	100
	Vehicle density	0.2	0.5	1	10
Category 3	Scaling factor *k*	0.5	1	2	100
	Vehicle density	0.05	0.1	0.2	10

Note: For disaster situation traffic demand, along with the use case *Traffic Management in Disaster Situation* in Table 1, the scaling factor $k = 100$.

Based on the parameters in Table 1 and Table 2, we calculate the area traffic demand of each use case under different traffic demand scenarios and TN coverage categories. The overall global area traffic demand is further aggregated and calculated on this basis, with the final calculation results detailed in Table 3.

It should be specially noted that for the use case *Traffic Management in Disaster Situation*, since this use case is only triggered in disaster scenarios and has no service demand in conventional communication scenarios, its traffic demand is not included in the three conventional scenarios: *Light Traffic Demand, Medium Traffic Demand, and Heavy Traffic Demand*, and is only calculated in the *Disaster Scenario Traffic Demand* scenario in this report. Furthermore, considering that the coverage area of a single beam in satellite communication can reach 2000 km^2, when a local area within the beam coverage suffers from a disaster, the remaining non-disaster areas covered by the beam still have traffic demand from other conventional use cases. To simulate the upper limit of traffic demand under extreme working conditions, in the calculation of the total traffic demand for the disaster scenario, we take the conventional service traffic of the *Heavy Traffic Demand* scenario as the baseline, superimpose the traffic demand of the *Traffic Management in Disaster Situation* use case, and finally obtain the total area traffic demand result under this scenario.

Table 3 Calculation of total data demand under different scenarios

Traffic mode	Use case		Category 1		Category 2		Category 3	
			DL	UL	DL	UL	DL	UL
Light Traffic	Voice Call		0.0475	0.0475	0.095	0.095	0.0238	0.0238
	Remote Access		0.04	0.04	0.08	0.08	0.02	0.02
	Entertainment	Video call	2	2	4	4	1	1
		Video stream	25	/	50	/	12.5	/
		Live broadcast	/	6	/	12	/	3
		Cloud gaming	40	2	80	4	20	1
	Hazard Info. and HD Map		20	0.2	40	0.4	10	0.1
	Teleoperated Driving		0.4	32	0.8	64	0.2	16
	Traffic Management in Disaster Situation		/	/	/	/	/	/
	Total (kbps/km²)		87.5	42.3	175	84.6	43.7	21.2
Medium Traffic	Voice Call		0.095	0.095	0.2375	0.2375	0.0475	0.0475
	Remote Access		0.08	0.08	0.2	0.2	0.04	0.04
	Entertainment	Video call	4	4	10	10	2	2
		Video stream	50	/	125	/	25	/
		Live broadcast	/	12	/	30	/	6
		Cloud gaming	80	4	200	10	40	2
	Hazard Info. and HD Map		40	0.4	100	1	20	0.2
	Teleoperated Driving		0.8	64	2	160	0.4	32
	Traffic Management in Disaster Situation		/	/	/	/	/	/
	Total (kbps/km²)		175	84.6	437.5	211.5	87.5	42.3
Heavy Traffic	Voice Call		0.2375	0.2375	0.475	0.475	0.095	0.095
	Remote Access		0.2	0.2	0.4	0.4	0.08	0.08
	Entertainment	Video call	10	10	20	20	4	4
		Video stream	125	/	250	/	50	/
		Live broadcast	/	30	/	60	/	12
		Cloud gaming	200	10	400	20	80	4
	Hazard Info. and HD Map		100	1	200	2	40	0.4
	Teleoperated Driving		2	160	4	320	0.8	64
	Traffic Management in Disaster Situation		/	/	/	/	/	/
	Total (kbps/km²)		437.5	211.5	875	423	175	84.6
Disaster situation	Voice Call		0.2375	0.2375	0.475	0.475	0.095	0.095
	Remote Access		0.2	0.2	0.4	0.4	0.08	0.08
	Entertainment	Video call	10	10	20	20	4	4
		Video stream	125	/	250	/	50	/
		Live broadcast	/	30	/	60	/	12
		Cloud gaming	200	10	400	20	80	4
	Hazard Info. and HD Map		100	1	200	2	40	0.4
	Teleoperated Driving		2	160	4	320	0.8	64
	Traffic Management in Disaster Situation		120	240	120	240	120	240
	Total (kbps/km²)		557.5	451.5	995	663	295	324.6

3.5 Gap between the demand side and the supply side

After completing the calculation of regional traffic density on the demand side, this report further conducts a quantitative analysis of the supportable area traffic capacity on the supply side in order to clarify the gap between communication supply capacity and service demand under the current capability boundary of satellites and terminals, and provide quantitative reference and theoretical support for satellite equipment manufacturers and terminal manufacturers in subsequent product planning and technical research.

The core calculation steps for supply-side capacity density are as follows:

Step 1: Define the core satellite-side technical parameters based on the 3GPP TR 38.821 specification and the typical system design of mainstream satellite enterprises;

Step 2: Define the core terminal-side technical parameters based on the 3GPP TR 38.821 specification and the typical design of commercial products from mainstream terminal manufacturers;

Step 3: Calculate the link budget results under the three technical modes: Narrowband, Wideband and Broadband;

Step 4: Derive the regional bearing capacity under the corresponding modes based on the link budget results and spectrum efficiency;

Step 5: Complete the quantitative comparison between the demand side and the supply side, analyse the traffic demand-supply gap, and propose targeted performance enhancement methods.

3.5.1 Reference scenario parameters

The scenarios are considered in Table 4.

Table 4 Reference scenario parameters

Constellations	LEO 600	GEO
Orbit type	Circular orbiting around the earth	Notional station keeping position fixed in terms of elevation/azimuth with respect to a given earth point
Altitude	600 km	35,786 km
Spectrum (service link)	Existing MSS spectrum, including ▸ S/L band in Wideband (e.g. 2 GHz), ▸ Ka band in Broadband (e.g. DL 20 GHz/UL 30 GHz)	<6 GHz (e.g. 2 GHz) >10 GHz (e.g. DL 20 GHz, UL 30 GHz)
Min./Max. channel bandwidth capability (service link)	5/20/30 MHz in wideband, 50/100/200/400 MHz in broadband	180 kHz (narrowband)
Payload	Transparent (including radio frequency function only) Regenerative (including all of RAN functions)	

Earth-fixed beams	Yes	
Max. beam foot print size (edge to edge) regardless of the elevation angle	50 km in Wideband, 20 km in Broadband	3,500 km
Min. elevation angle for both sat-gateway and user equipment	30° for service link and 10° for feeder link in Wideband	10° for service link and 10° for feeder link
Max. distance between satellite and user equipment at min elevation angle	1075.6 km	40,581 km
Max. round trip delay (propagation delay only)	Transparent payload: 20.05 ms Regenerative payload: 7.17 ms	Transparent payload: 541.46 ms Regenerative payload: 270.73 ms
Max differential delay within a beam	144 us in Wideband and 57.8 us in Broadband at 30° elevation angle	10.3 ms
Max Doppler shift (earth fixed user equipment)	20 ppm in Wideband, 20 ppm in Broadband	0.93 ppm/s
Max Doppler shift variation (earth fixed user equipment)	0.27 ppm/s in Wideband, 0.27 ppm/s in Broadband	0.000 045 ppm/s

3.5.2 Parameter assumptions

Table 5 and Table 6 representing satellite parameters and UE characteristics are considered as the baseline.

Table 5 Satellite parameters for system level simulator calibration

	S/L band	**Ka band**
Satellite antenna parameters		
Antenna element pattern	Table 7.3-1 in TR 38.901	Table 7.3-1 in TR 38.901
Horizontal/vertical 3 dB beam width of single element (degree)	90 for H 90 for V	90 for H 90 for V
Antenna element spacing	0.667 lambda	0.667 lambda
Antenna polarisation	Circular (RHCP or LHCP)	Circular (RHCP or LHCP)
Equivalent satellite antenna aperture	2 m	0.5 m
Element maximum gain	4 dBi	4 dBi
Antenna maximum gain	30 dBi	38.5 dBi
Payload characteristics for DL transmissions		
Satellite EIRP density/beam (dBW/MHz)	34	4
Payload total DL power level (dBW)	23 (200 W)	23 (200 W)
Aggregated EIRP (Total) (dBW)	53	61.5
Maximum EIRP per Satellite beam (dBW)	16 beam: 41	128 beam: 40.5
Total number of beam footprints	1,058	8,803
Payload characteristics for UL transmissions		
G/T	1.1 dB K^{-1}	13 dB K^{-1}

Table 6 UE characteristics for system-level simulations

UE Characteristics	Handheld	Vehicle-mounted (Wideband)	NB-IoT (Narrowband)	Vehicle-mounted (Broadband)	Vehicle-mounted (Broadband)
Frequency band	S/L band	S/L band	S/L band	Ka band	Ka band
Antenna type and configuration	(1, 1, 2) with omni-directional antenna element: 1T2R	(1, 1, 2) with omni-directional antenna element: 1T2R	(1, 1, 1) with omni-directional antenna element: 1T1R	Directional with 60 cm	Directional with 400 in a 20x20 equivalent aperture diameter
Polarisation	Linear: +/-45°X-pol	Linear: +/-45°X-pol	N/A	circular	circular
Rx Antenna gain	-5.5/0 dBi per element	0dBi per element	-5.5/0 dBi per element	39.7 dBi	30.8 dBi
Noise figure	7 dB/4 dB	7 dB/4 dB	7 dB/4dB	1.2 dB	2 dB
Tx transmit power	23 dBm, 26 dBm, 31 dBm	23 dBm, 26 dBm, 31 dBm	23 dBm, 26 dBm, 31 dBm	33 dBm	39 dBm
Tx antenna gain	-5.5/0 dBi per element	0dBi per element	-5.5/0 dBi per element	43.2 dBi	34.5 dBi

3.5.3 Link budget

This report aims to calculate the upper limit of supply-side capacity based on the capabilities of current satellite and terminals. For this purpose, the link budget results in Table 7 are all calculated using terminal characteristic parameters under near-ideal operating conditions. For example, for Narrowband and vehicle mounted terminals of Wideband, the UE power is set to 31 dBm (this value is the formal agreement reached by the 3GPP RAN4 in Release 19), the UE antenna gain is set to 0 dBi, and the Noise figure is set to 4 dB. The above parameters are optimistic assumptions adapted to upper-limit calculation. Table 7 presents the detailed calculation results of the CNR for different terminal types, including Narrowband, Wideband and Broadband vehicle-mounted terminals.

Table 7 Link budget calculation

Parameters	Value		
UE type	Vehicle-mounted (Wideband)	NB-IoT (Narrowband)	Vehicle-mounted (Broadband)
Target elevation angle	30°	12.5	30°
Freq. band /GHz	2	2	20/30
Channel BW /MHz	20	0.18	400
UE Power /dBm	31	31	39
NF /dB	4	4	2
UE Antenna Gain /dBi	0	0	30.8(DL)/34.5(UL)
Antenna configuration	1Tx, 2Rx	1Tx, 1Rx	Directional D = 20cm
EIRP /dBW	47(DL)/1(UL)	51.6(DL)/1(UL)	30(DL)/43.5(UL)
G/T / dB/K	-28.62(DL)/1.1(UL)	-28.62(DL)/19(UL)	15.9(DL)/13(UL)

PL_{FS} /dB	159.1		190.58		179.1/182.6	
PL_{A} /dB	0		0.2		0.5	
PL_{SM} /dB (shadowing margin)	0		3		0	
PL_{SL} /dB (scintillation loss)	0		2.2		0.3	
PL_{AD} /dB	3		0		0	
PL_{POL} /dB	0		3		0	
B (dBHZ)	73(20M DL) /55.6(2RB UL)		52.6(180kHz DL) /41.8(15kHz UL)		86	
K (dBW/K/Hz)	-228.6					
CNR /dB	DL	UL	DL	UL	DL	UL
	11.9	**13**	**0**	**7.9**	**-1.6**	**14.7**

3.5.4 Gap between demand side and supply side

The following equations are used to calculate the CINR and Data rate:

$$CINR = -10\log_{10}\left(10^{-0.1CNR[dB]} + 10^{-0.1CIR[dB]}\right) \tag{3-3}$$

$$Data\ rate = (1 - overhead) * PRBnumber * BW_{PRB} * \log_2\left(1+10^{0.1CINR[dB]}\right) \tag{3-4}$$

Table 8 shows the area traffic capacity of different types of terminals, where the beam diameter of Wideband is 50 km, Broadband is 20 km, and GEO Narrowband is 250 km.

Table 8 Area traffic capacity calculation

	Vehicle-mounted (Wideband)		**NB-IoT (Narrowband)**		**Vehicle-mounted (Broadband)**	
CNR /dB	DL	UL	DL	UL	DL	UL
	11.9	13	0	7.9	-1.6	14.7
CINR /dB	7.84	10	-0.4	6.73	-1.72	11.33
Data Rate / Mbps	46.3/20 MHz	1.15/2 RB 60.9/20 MHz	0.14/180 kHz	0.035/15 kHz 0.42/180 kHz	243.4/400 MHz	1390/400 MHz
Area traffic capacity	23.6 kbps/ km²	31 kbps/ km²	0.0028 kbps/ km²	0.0086 kbps/ km²	775 kbps/km2	4426.7 kbps/ km2

We conduct a traffic demand-supply gap analysis between the supply side and the demand side by comparing the total area traffic demand density of each scenario in Table 3 with the calculated area traffic capacity results in Table 8.

Table 9 presents the traffic density requirements of each use case for Category 1 under different traffic load scenarios, as well as the traffic density capabilities that can be provided by the supply side in Narrowband, Wideband and Broadband. Figure 1 to Figure 4 visually illustrate the traffic density gap between the demand side and the supply side for each use case. In these figures, bars of different colours represent the traffic density requirements of the corresponding use cases, and circular markers represent the upper bound of traffic density that can be provided by the supply side in different frequency bands. If the height of a bar exceeds the circular marker of the corresponding colour, it indicates that the traffic density supply capability of that frequency band cannot meet the requirements of the corresponding use case, and a demand-supply gap exists, which needs to be addressed by adopting other frequency bands or implementing additional technical enhancement/optimisation measures.

Narrowband has limited bandwidth in NB-IoT, so it cannot meet the concurrent traffic demand of a large number of vehicles. In Wideband, the requirements of use cases such as *Voice Call*, *Remote Access*, *Video call* and *Live broadcast* are largely satisfied. However, for use cases including *Video stream*, *Cloud gaming*, *Hazard Info. and HD Map*, *Teleoperated Driving*, and *Traffic Management in Disaster Situation*, the Broadband mode with larger bandwidth is required to meet their demands.

Table 9 Gap between demand side and supply side in Category 1

(kbps/km^2)		Light Traffic		Medium Traffic		Heavy Traffic		Disaster Situation	
		DL	UL	DL	UL	DL	UL	DL	UL
Voice Call		0.0475	0.0475	0.095	0.095	0.2375	0.2375	0.2375	0.2375
Remote Access		0.04	0.04	0.08	0.08	0.2	0.2	0.2	0.2
Entertainment	Video call	2	2	4	4	10	10	10	10
	Video stream	25	/	50	/	125	/	125	/
	Live broadcast	/	6	/	12	/	30	/	30
	Cloud gaming	40	2	80	4	200	10	200	10
Hazard Info. And HD Map		20	0.2	40	0.4	100	1	100	1
Teleoperated Driving		0.4	32	0.8	64	2	160	2	160
Traffic Management in Disaster Situation		/	/	/	/	/	/	120	240
Total demand		87.5	42.3	175	84.6	437.5	211.5	557.5	451.5
Narrowband		0.0028	0.0086	0.0028	0.0086	0.0028	0.0086	0.0028	0.0086
Wideband		23.6	31	23.6	31	23.6	31	23.6	31
Broadband		775	4426.7	775	4426.7	775	4426.7	775	4426.7

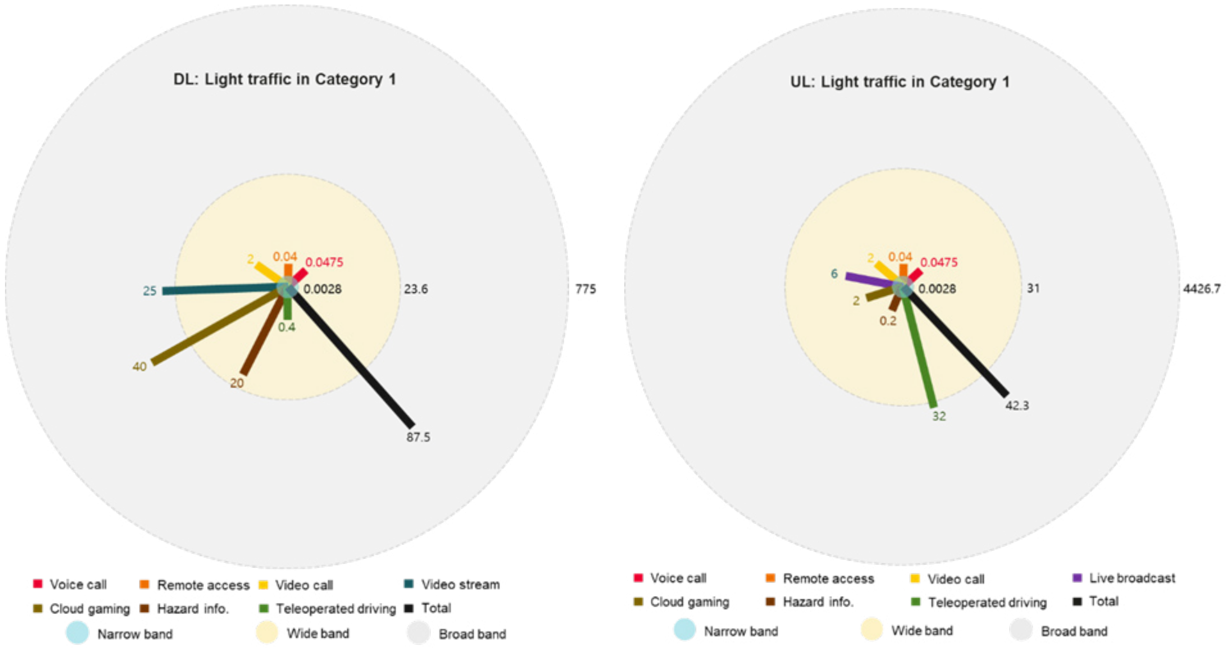


Figure 1 Area traffic for demand side and supply side in light traffic in Category 1

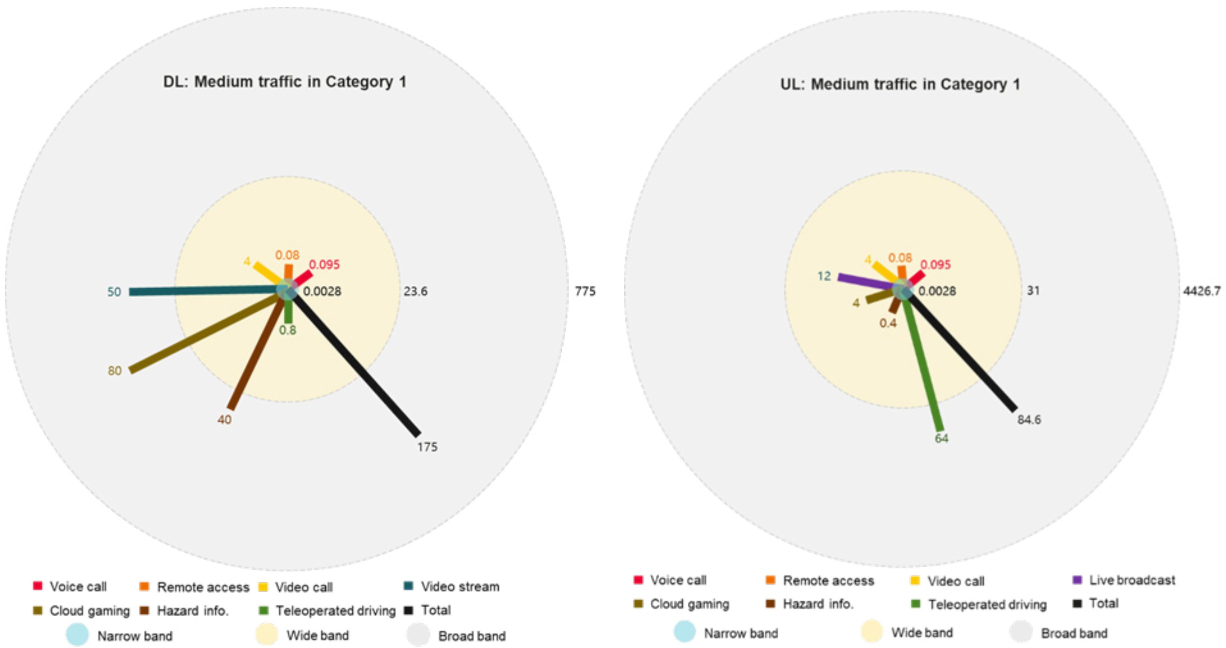


Figure 2 Area traffic for demand side and supply side in medium traffic in Category 1

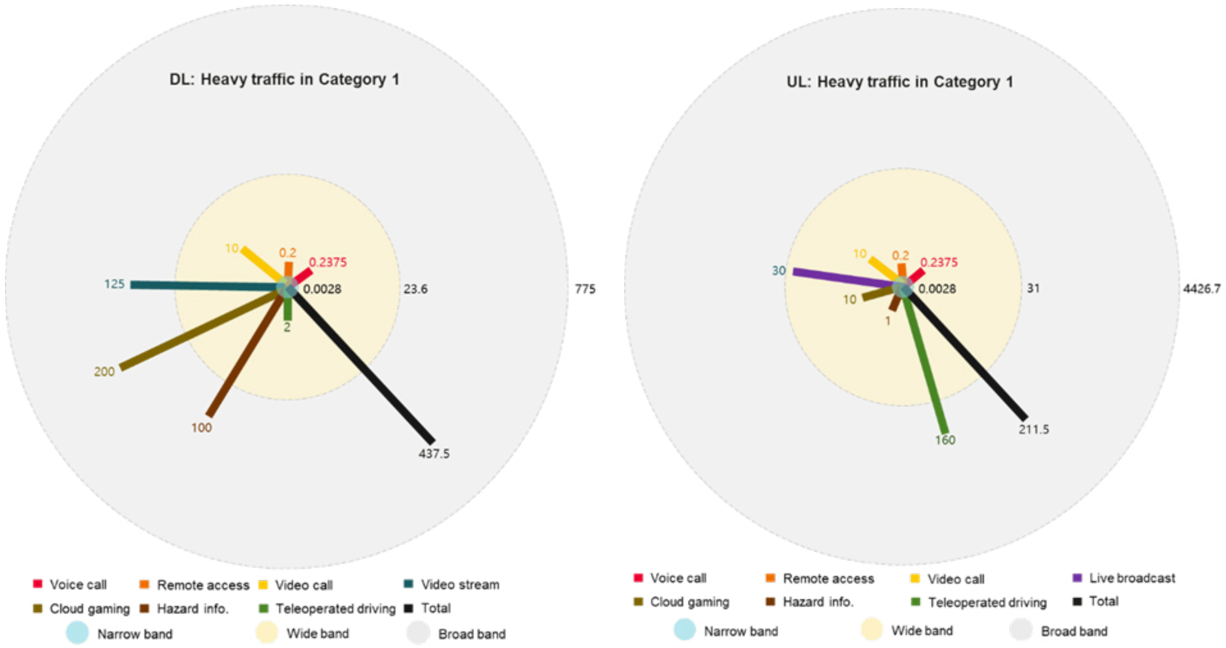


Figure 3 Area traffic for demand side and supply side in heavy traffic in Category 1

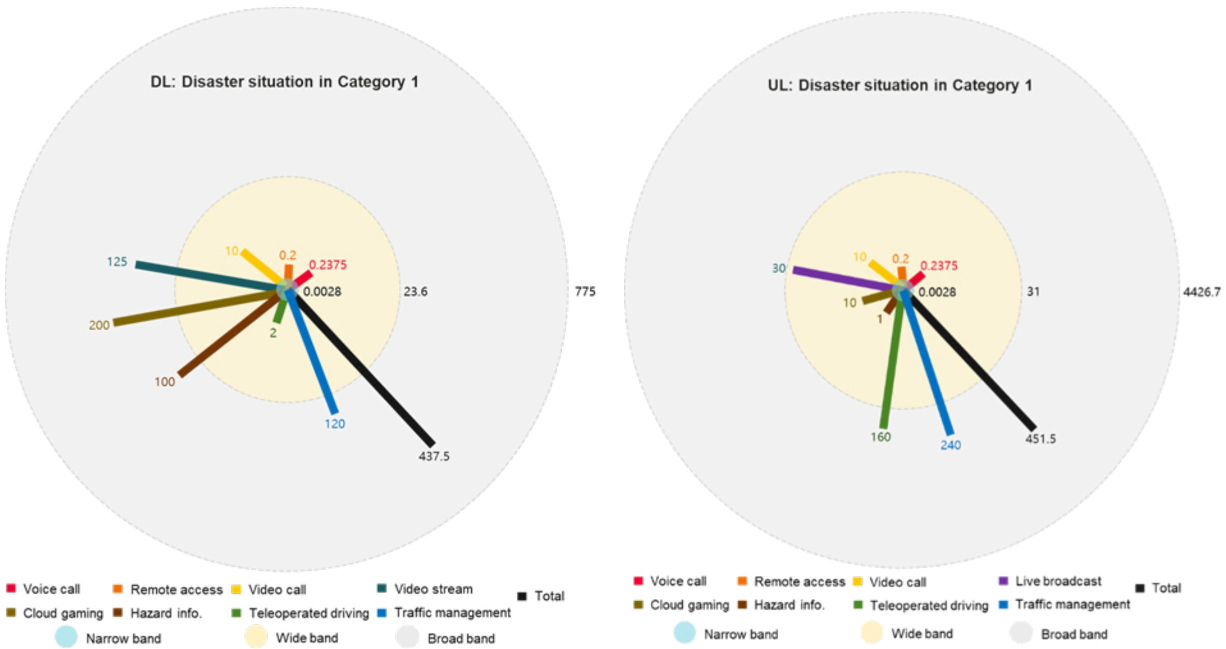


Figure 4 Area traffic for demand side and supply side in disaster situation in Category 1

Table 10 and Figures 5 to 8 present the traffic density requirements of each use case for Category 2 under different traffic load scenarios, as well as the traffic density capabilities that can be provided by the supply side in Narrowband, Wideband and Broadband. In contrast to Category 1, due to the higher vehicle density corresponding to Category 2, the traffic density requirements of each use case are correspondingly increased. In scenarios such as Heavy Traffic, use cases including *Live broadcast* can no longer be satisfied by the Wideband and need to be carried by the Broadband.

Table 10 Gap between demand side and supply side in Category 2

Use Case (kbps/km^2)		Light Traffic		Medium Traffic		Heavy Traffic		Disaster Situation	
		DL	UL	DL	UL	DL	UL	DL	UL
Voice Call		0.095	0.095	0.2375	0.2375	0.475	0.475	0.475	0.475
Remote Access		0.08	0.08	0.2	0.2	0.4	0.4	0.4	0.4
Entertainment	Video call	4	4	10	10	20	20	20	20
	Video stream	50	/	125	/	250	/	250	/
	Live broadcast	/	12	/	30	/	60	/	60
	Cloud gaming	80	4	200	10	400	20	400	20
Hazard Info. and HD Map		40	0.4	100	1	200	2	200	2
Teleoperated Driving		0.8	64	2	160	4	320	4	320
Traffic Management in Disaster Situation		/	/	/	/	/	/	120	240
Total demand		175	84.6	437.5	211.5	875	423	995	663
Narrowband		0.0028	0.0086	0.0028	0.0086	0.0028	0.0086	0.0028	0.0086
Wideband		23.6	31	23.6	31	23.6	31	23.6	31
Broadband		775	4426.7	775	4426.7	775	4426.7	775	4426.7

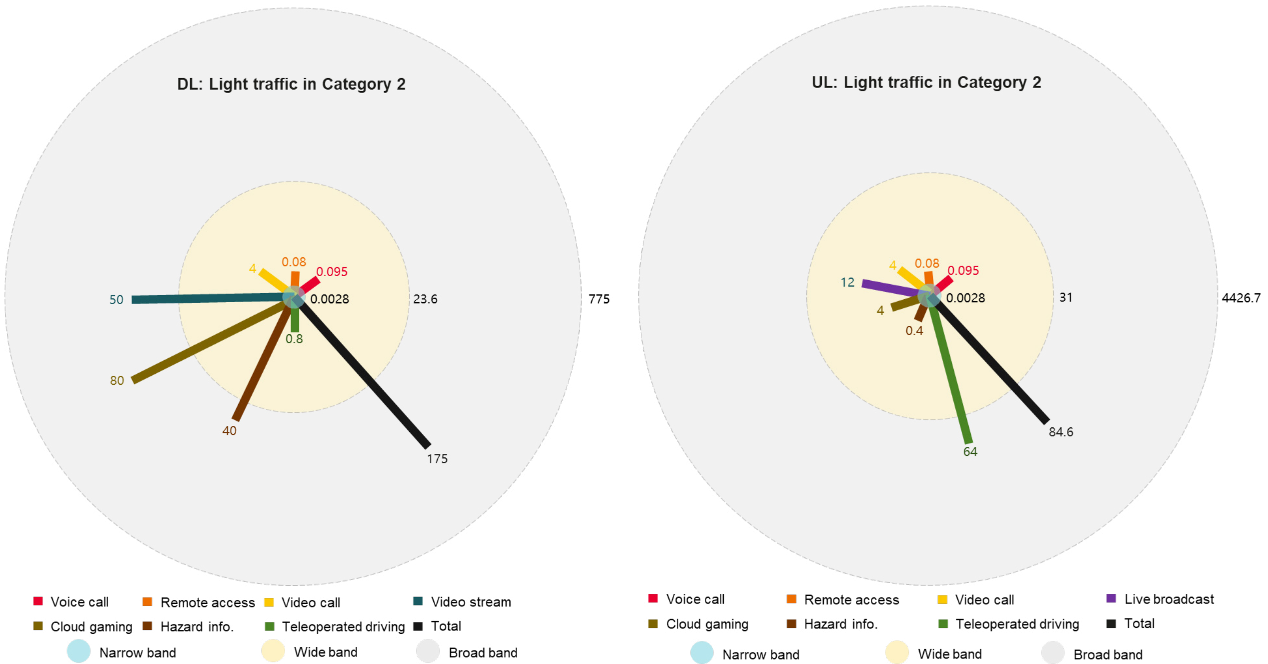


Figure 5 Area traffic for demand side and supply side in light traffic in Category 2

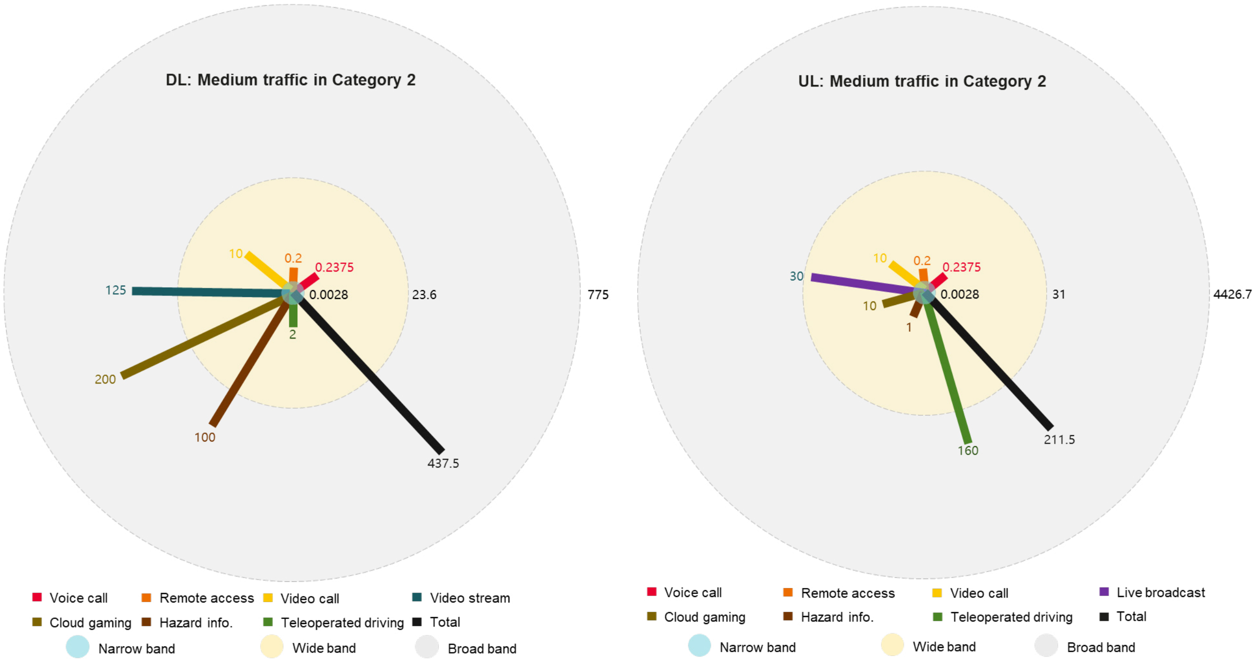


Figure 6 Area traffic for demand side and supply side in medium traffic in Category 2

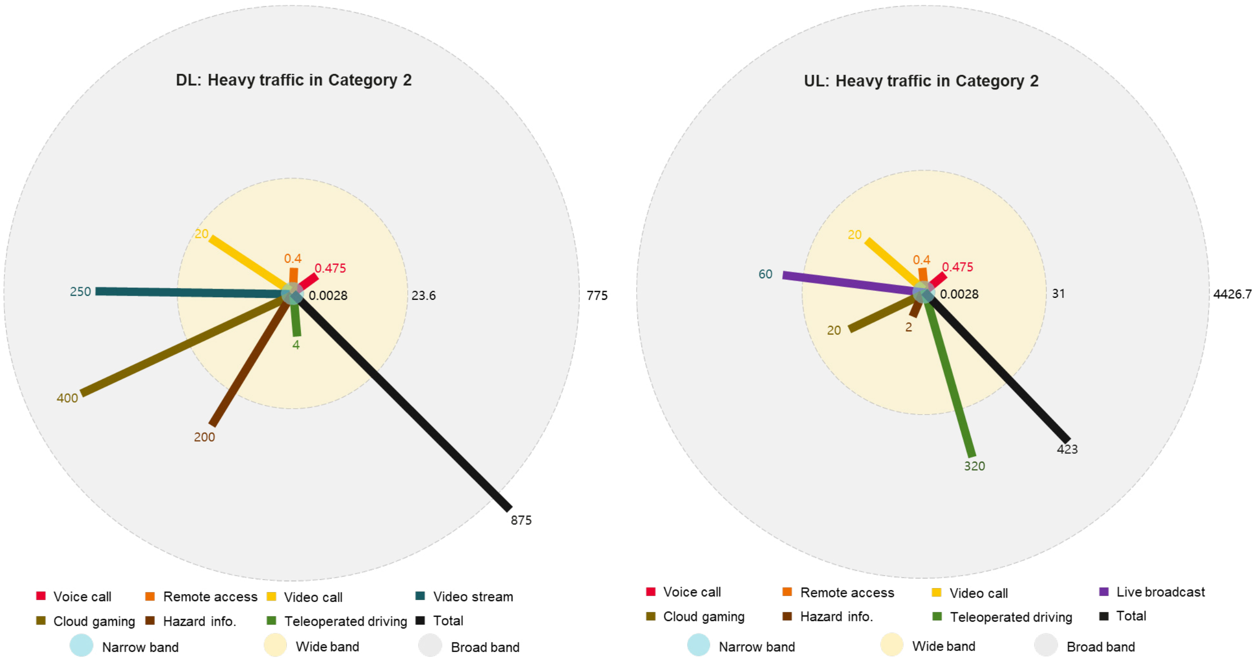


Figure 7 Area traffic for demand side and supply side in heavy traffic in Category 2

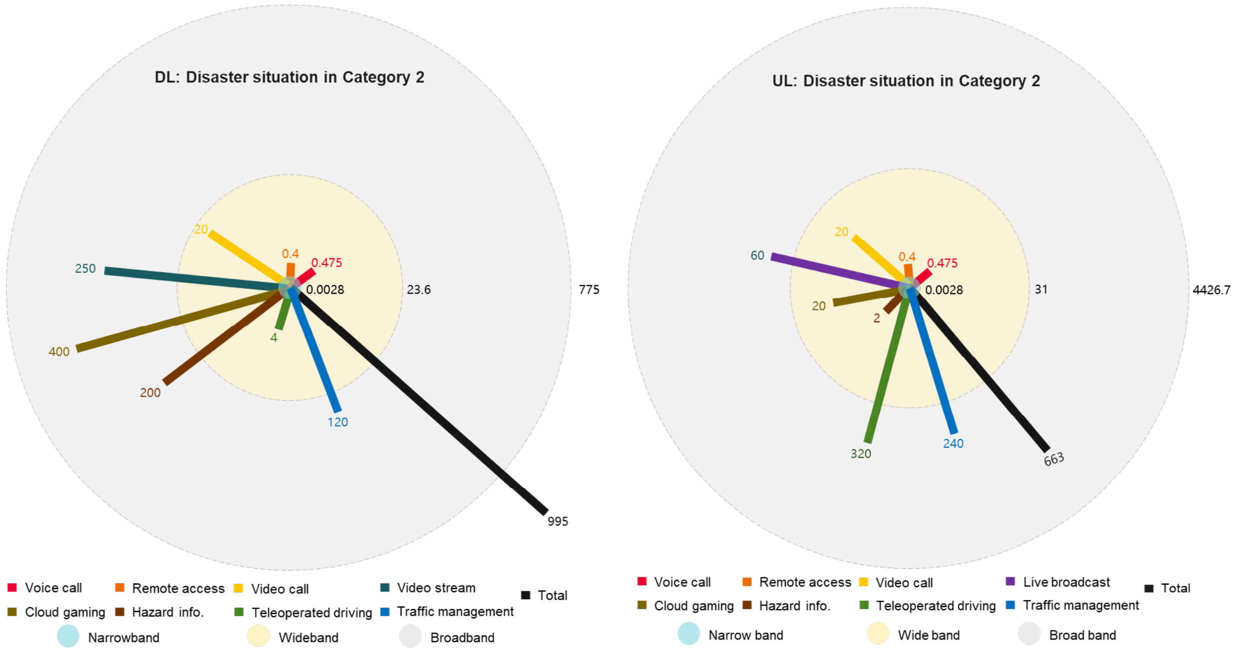


Figure 8 Area traffic for demand side and supply side in disaster situation in Category 2

Table 11 and Figures 9 to 12 present the traffic density requirements of each use case for Category 3 under different traffic load scenarios, as well as the traffic density capabilities that can be provided by the supply side in Narrowband, Wideband and Broadband modes. In contrast to Category 1, due to the lower vehicle density corresponding to Category 3, the traffic density requirements of each use case are correspondingly reduced. In the Light Traffic scenario, most of the use cases can be satisfied by the Wideband mode, but the total traffic demand when all use cases are transmitted concurrently will still exceed the maximum traffic density upper bound that this mode can provide. In the Medium Traffic and Heavy Traffic scenarios, high-traffic use cases including *Video stream*, *Cloud gaming*, *Hazard Info. and HD Map*, *Teleoperated Driving,* and *Traffic Management in Disaster Situation* still need to be carried by the Broadband mode with larger bandwidth to meet their requirements.

Table 11 Gap between demand side and supply side in Category 3

(kbps/km²)		Light Traffic		Medium Traffic		Heavy Traffic		Disaster Situation	
		DL	UL	DL	UL	DL	UL	DL	UL
Voice Call		0.0238	0.0238	0.0475	0.0475	0.095	0.095	0.095	0.095
Remote Access		0.02	0.02	0.04	0.04	0.08	0.08	0.08	0.08
Entertainment	Video call	1	1	2	2	4	4	4	4
	Video stream	12.5	/	25	/	50	/	50	/
	Live broadcast	/	3	/	6	/	12	/	12
	Cloud gaming	20	1	40	2	80	4	80	4
Hazard Info. and HD Map		10	0.1	20	0.2	40	0.4	40	0.4
Teleoperated Driving		0.2	16	0.4	32	0.8	64	0.8	64
Traffic Management in Disaster Situation		/	/	/	/	/	/	120	240
Total demand		43.7	21.2	87.5	42.3	175	84.6	295	324.6
Narrowband		0.0028	0.0086	0.0028	0.0086	0.0028	0.0086	0.0028	0.0086
Wideband		23.6	31	23.6	31	23.6	31	23.6	31
Broadband		775	4426.7	775	4426.7	775	4426.7	775	4426.7

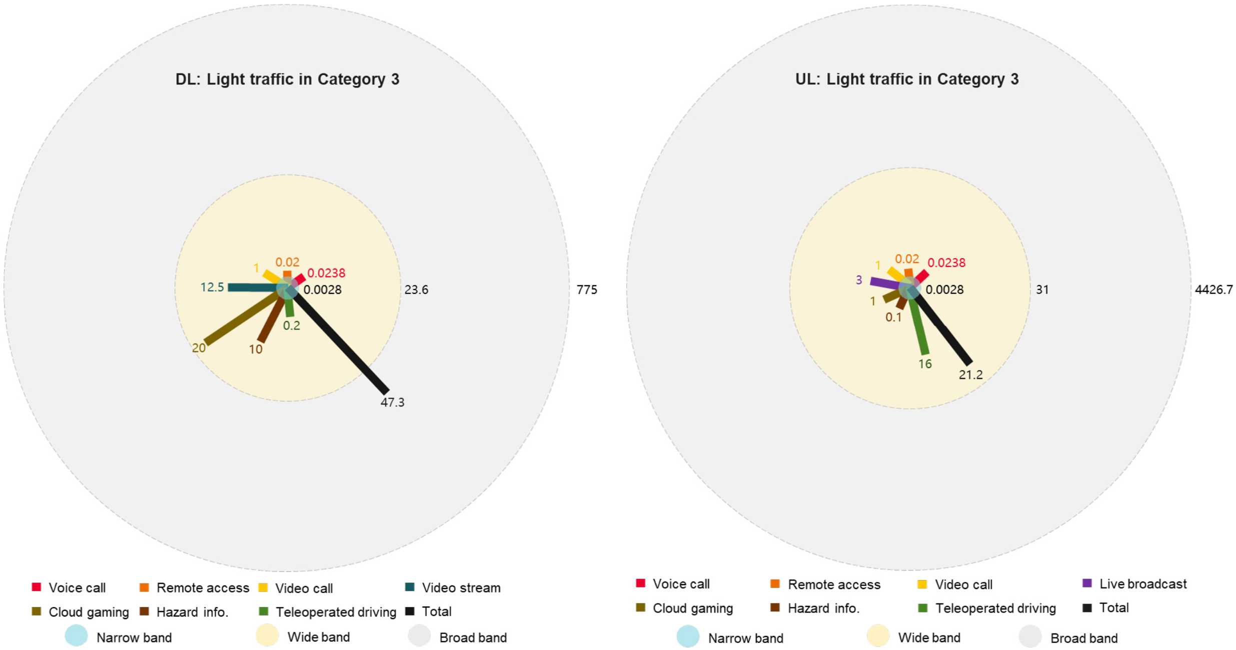


Figure 9 Area traffic for demand side and supply side in light traffic in Category 3

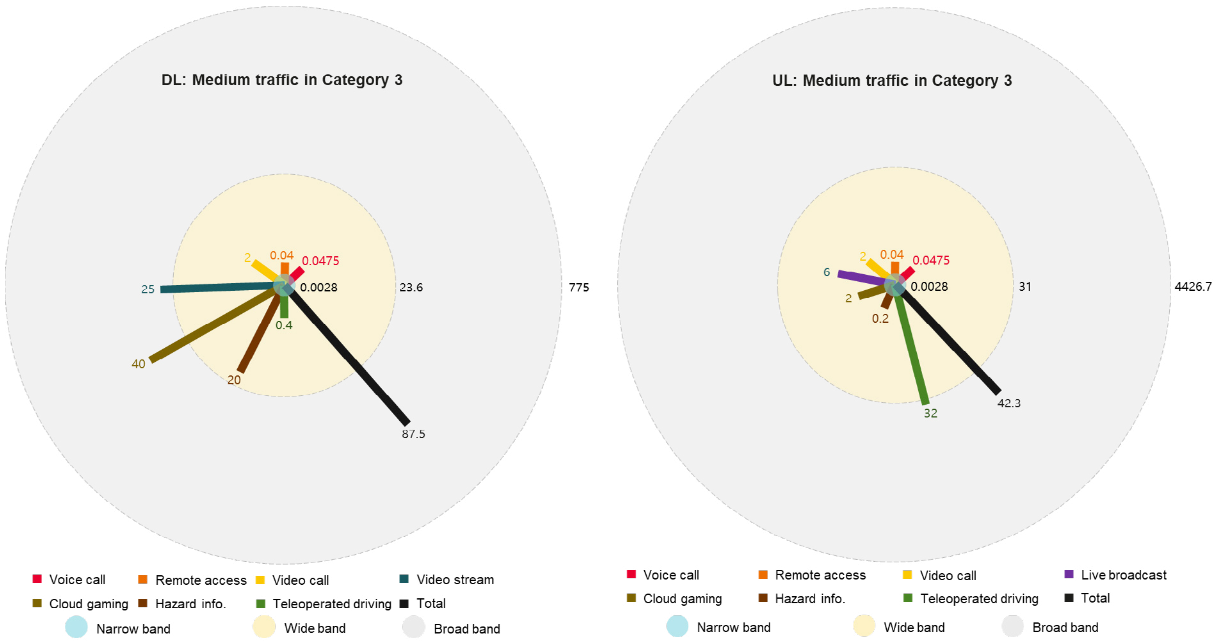


Figure 10 Area traffic for demand side and supply side in medium traffic in Category 3

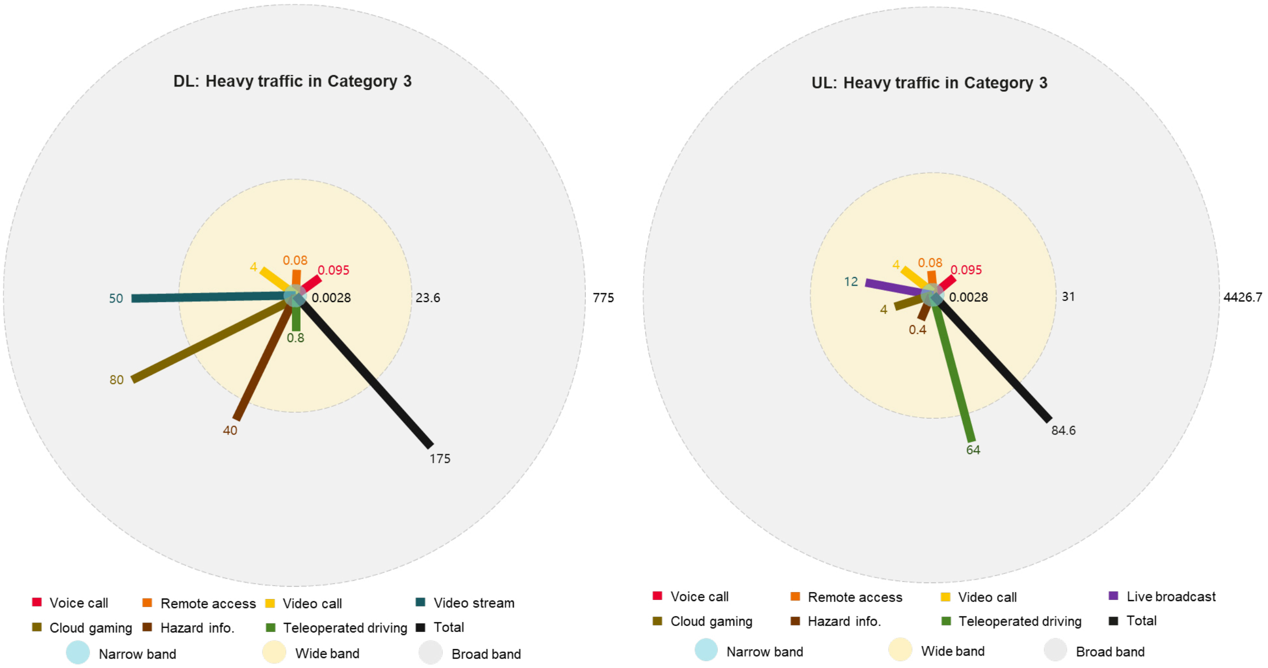


Figure 11 Area traffic for demand side and supply side in heavy traffic in Category 3

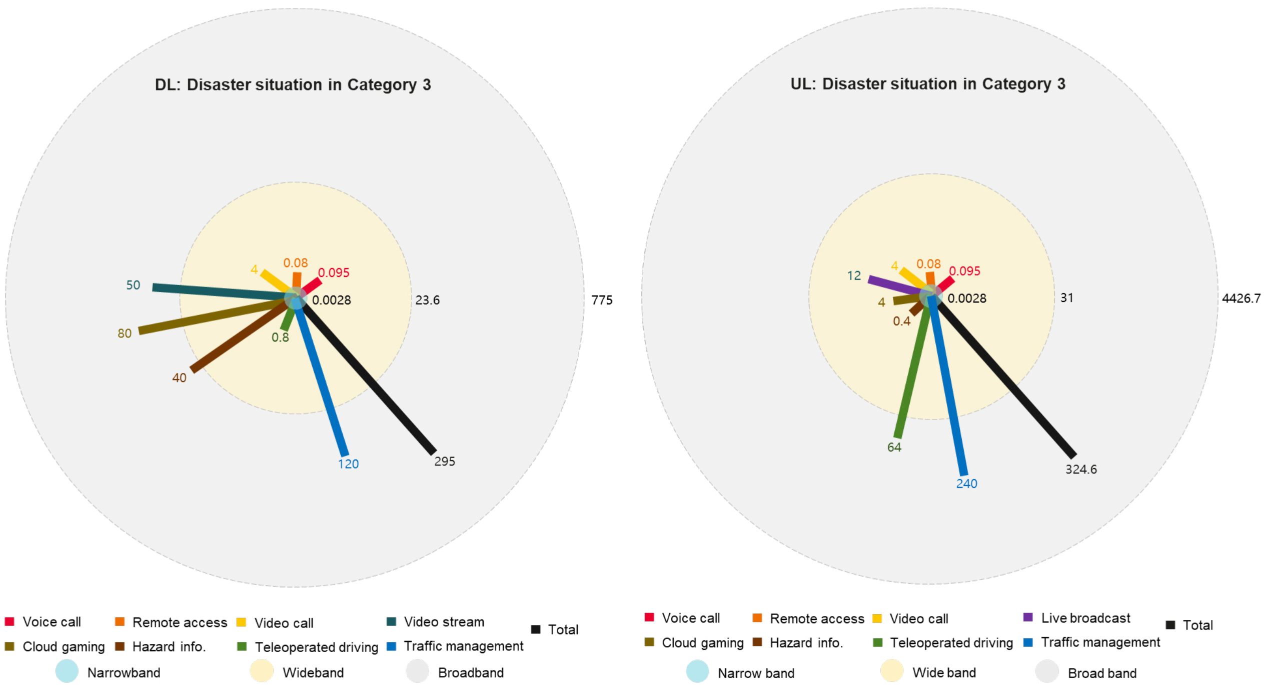


Figure 12 Area traffic for demand side and supply side in disaster situation in Category 3

3.6 Conclusion and recommendation

This Technical Report starts from the most representative and urgently demanded use cases. Through quantitative assumptions on key parameters including the density of NTN-dependent vehicles, different geographical coverage categories, and scaling factors under different traffic demand scenarios, the traffic density demand of in-vehicle communication for NTN networks under various scenarios is systematically calculated. Meanwhile, based on the mature technical capabilities of current satellite and terminal equipment, this report quantitatively analyses the maximum supportable traffic density upper bound from the supply side. Through the comparative analysis of traffic density between the demand side and the supply side, the gap between the current in-vehicle NTN communication traffic demand and supply capability is identified.

According to the analysis results in Section 3.5 of this report, there are significant differences in the traffic density distribution and identified gap between the demand side and the supply side under different Categories and traffic demand scenarios. In Categories with lower vehicle density and Light Traffic scenarios, the Wideband can largely meet the traffic requirements of most use cases. As the vehicle density increases or a heavy load period occurs, the Wideband mode can still support the requirements of use cases such as *Voice call*, *Remote Access*, SD *Video call* and *Live broadcast*. However, in High Traffic situations, use cases including HD *Video stream*, *Cloud gaming*, *Hazard Info. And HD Map*, *Teleoperated Driving* and *Traffic Management in Disaster Situation* may not be effectively supported. Therefore, Broadband with wider available bandwidth, stronger radio frequency capability, and more focused beam coverage is required to provide services.

The parameter values adopted in this report can be used as a reference baseline. Researchers may adjust the assumed parameters such as the global density of NTN-dependent vehicles, use case data rate, use case activity factor and scaling factor under different scenarios according to actual deployment requirements, and conduct corresponding area traffic analysis on the demand side and the supply side based on the methodology proposed in this report.

Based on the above analysis, the following conclusions and recommendations are drawn in this report:

1. Continuously deepen the research on frequency ranges > 10 GHz (FR2-based NTN) for in-vehicle communication technologies, and rely on the High Traffic density support capability of FR2 to meet the growing in-vehicle communication traffic demand;
2. Conduct hierarchical classification based on the traffic demand characteristics of different use cases, and rationally select the Wideband or Broadband mode to carry NTN communication services;
3. Continuously enhance satellite-side capabilities, including increasing antenna aperture, improving antenna gain, and optimising satellite constellation deployment to achieve more precise beam coverage;
4. Simultaneously improve terminal-side capabilities, and comprehensively

enhance communication quality by optimising in-vehicle terminal antenna design and enhancing radio frequency performance.

Currently, the large-scale commercialisation of satellite communication based on NTN still faces many systematic challenges. In addition to the aforementioned continuous improvement requirements for satellite-side and terminal-side hardware capabilities, the international coordination mechanisms and national legal and regulatory systems related to spectrum resources also urgently need to be re-examined and optimised.

Satellite communication spectrum is a globally shared asset, and there are significant differences in allocation policies, usage rules and regulatory requirements among different countries and regions. Furthermore, the spectrum-sharing mechanism between terrestrial mobile communication and satellite communication has not been fully established. These factors have become one of the core bottlenecks restricting the global large-scale deployment of NTN in-vehicle communication. To this end, the industry needs to continuously track the global satellite communication technology evolution, industrial chain maturity and national regulatory policies, establish a multi-dimensional evaluation system, and more accurately and comprehensively quantify and evaluate the actual service capabilities and performance boundaries that satellite communication can provide under different communication frequency bands (such as FR1 and FR2), different geographical regions, and different application scenarios.

4 Predicting how the market will evolve

4.1 Introduction

In the last Technical Report ‘Maximising the benefits of satellite communications for automotive’ we published the 5GAA NTN Roadmap the first time in 2024.

Original NTN-roadmap from 2024.

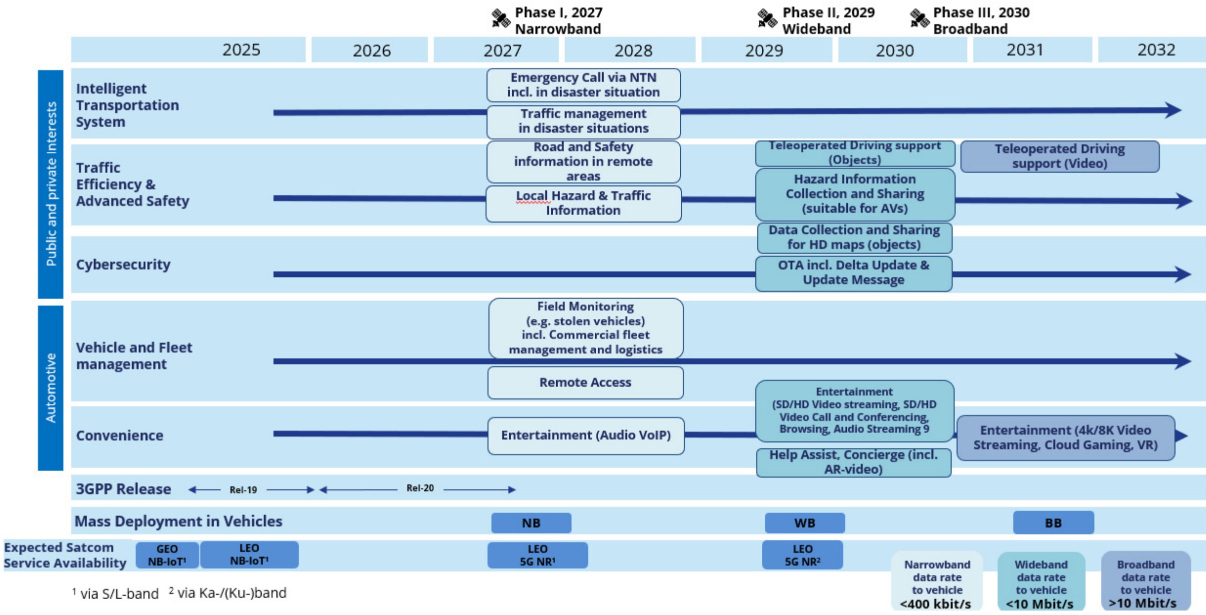


Figure 13 NTN Roadmap 2024

This roadmap was aimed at creating a joint vision for the deployment of the various clusters of NTN use cases. We could identify three clear steps for mass market deployment. The assumption was that NB-IoT services could be offered based on 3GPP Release 17 and the use of existing geostationary NB-IoT satellites. NB-IoT NTN would be deployed first in 2027, followed by wideband use cases, based on NR-NTN under 3GPP Release 18, and then low-earth orbit satellite constellations in 2029. In combination with higher frequencies (e.g., Ka/Ku band) and more sophisticated ground terminals, broadband data rate services were scheduled for 2031 onwards.

4.2 Update of the NTN roadmap

Now, two years later, we wanted to know to what extend our predictions have changed. Additionally, the business perspective comes more and more into focus. Will there be a market for automotive satellite connectivity? What use cases are most critical from the customer perspective?

Therefore, 5GAA has conducted a global customer survey in cooperation with Viasat in autumn 2025. The results of the customer survey are discussed separately in a joint 5GAA/Viasat White Paper. Additionally, 5GAA has conducted a new member survey in spring 2026 to update the NTN roadmap, and to ask our members similar questions as in the customer survey. This will allow us to compare the industry perspective regarding priorities and willingness to pay with the customer perspective.

The survey comprises 31 responses from 5GAA organisations active in the connected-vehicle and telecommunications ecosystem. The findings are descriptive and should be interpreted as an indication of current industry expectations rather than as statistically generalisable estimates. Percentages cited below refer to the aggregate responses and, where specified, to the OEM subset shown in the survey material.

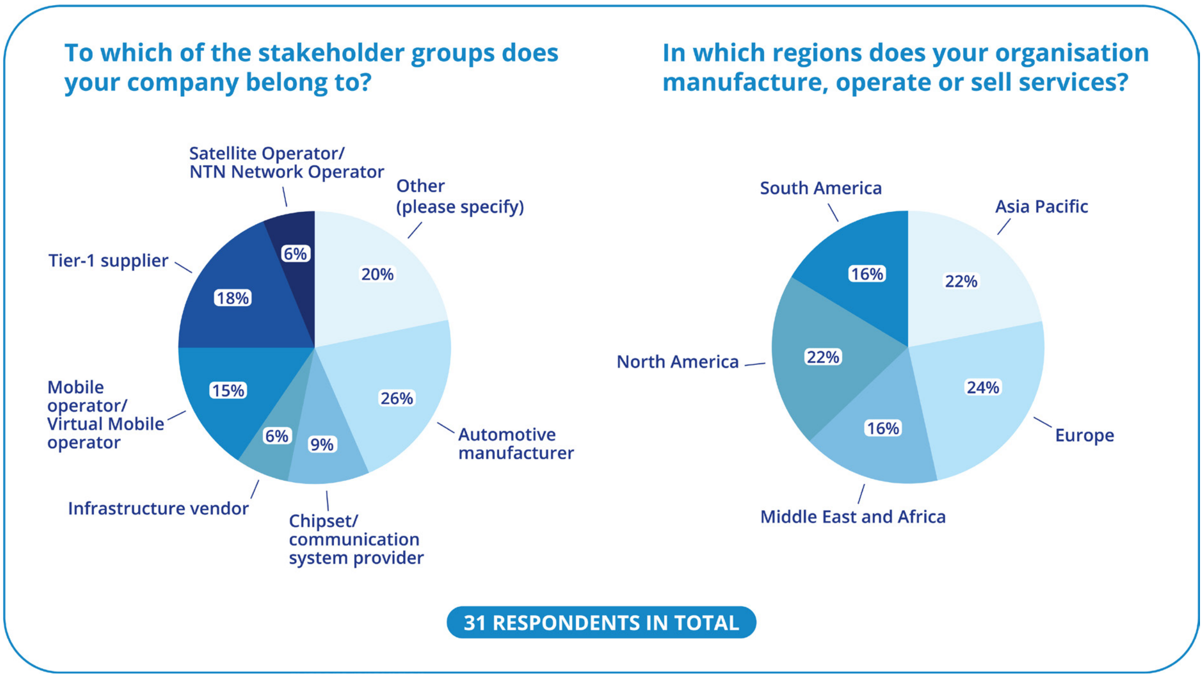


Figure 14 Overview of respondents

The evidence shows a similar phased, bandwidth-dependent adoption pathway for non-terrestrial-network connectivity in vehicles as in the 2024 survey. Respondents do not describe NTN as a single, simultaneous market introduction. Instead, the expected trajectory begins with Narrowband, safety- and resilience-oriented services, proceeds to Wideband services around the turn of the decade, and reaches Broadband applications only later and with materially higher uncertainty.

The NTN roadmap, as it was designed originally, does not give ranges or distributions of deployment times but refers only to the first deployment of the first OEM. From the 10 OEMs in the 5GAA, seven have taken part in the survey. We will take their answers, because they are the only ones who know when they will deploy.

Following this logic, the NTN roadmap can be updated in the following way:

The good news is, all seven (5GAA) OEMs responded that they will deploy! This is a very strong signal to the market. We will now discuss the study results according to the various classes of use cases.

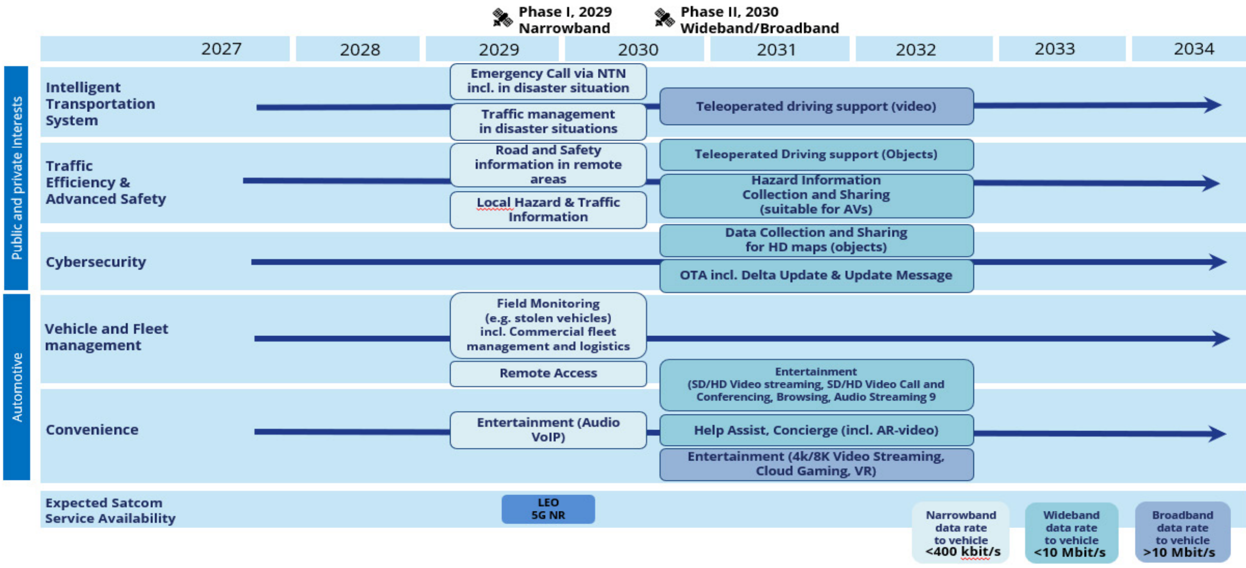


Figure 15 Updated NTN roadmap based on 5GAA member survey

Compared to the last NTN roadmap, narrowband data rate use cases are expected to be mass deployed two years later, starting in 2029. From 2030, wideband and broadband data rate use cases will be mass deployed. This can be explained with the introduction of the much more capable NR-NTN based technology which is forecasted to materialise around the same time.

- If applied with radio equipment, operating in the so called FR1 frequencies (600 MHz and 6 GHz), narrowband use cases can be supported.
- Additionally, if the satellites are operating in low-earth orbits, even wideband data rate use cases of up to 10 Mbit/s can be supported with the same equipment.
- If NR-NTN is operated in frequency ranges above 10 GHz even broadband data rate use cases are possible.

The vehicle integration strategy follows the same bandwidth gradient. Narrowband hardware is primarily expected to be built into vehicles as base equipment. Some 80% of the OEM respondents are following this strategy. This is consistent with the role of Narrowband NTN as an enabling layer for safety-relevant or reliability-critical use cases that benefit from being universally available across vehicle lines.

Wideband integration appears more segment- and configuration-dependent. In the OEM sample the answers are evenly split between base equipment and variant configurations (40% each), with 20% uncertainty. Wideband NTN therefore appears likely to be introduced selectively by model line, trim level, region, or connectivity package rather than as a standard feature.

Broadband hardware is most often treated as optional or commercially differentiated. OEM responses show a pattern, with broadband divided between variant and optional-extra approaches (33.3% each), 16.7% base equipment, and 16.7% uncertainty. This suggests that broadband NTN is associated with premium, high-bandwidth, discretionary services for which willingness to pay and hardware cost recovery are not yet established.

Who will pay for NTN services? This is one of the central questions in discussions regarding the market potential of satellite communications. In the end, someone has to pay for the extra effort invested in better connectivity. In the survey, we tried to identify who will likely pay for NTN-based services and who will potentially gain extra revenues along the value chain.

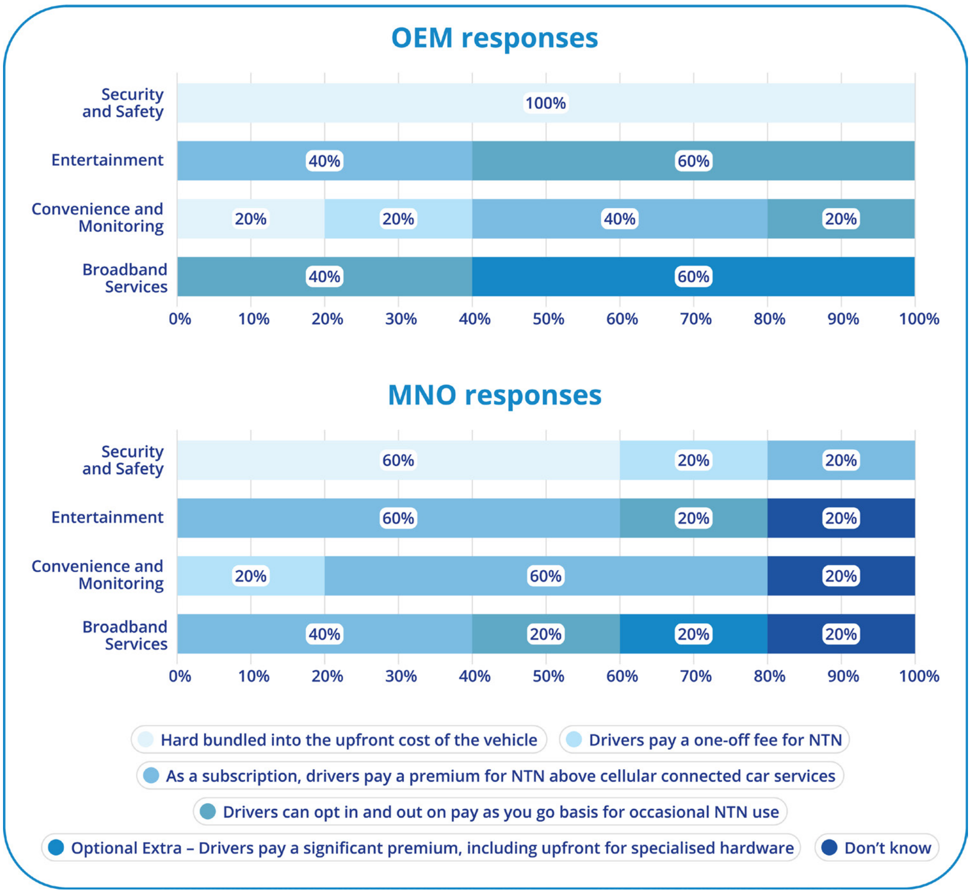


Figure 16 Which NTN-based use case clusters will be paid for directly by drivers?

Corresponding to the outcome of the customer survey [6], the willingness to pay for safety seems to be the lowest. All OEMs have answered that these services need to be bundled into the upfront (hardware) costs of the vehicle. Entertainment services, in contrast, can be sold as a subscription or drivers can opt in or -out. Broadband services will be paid by the drivers through various payment models.

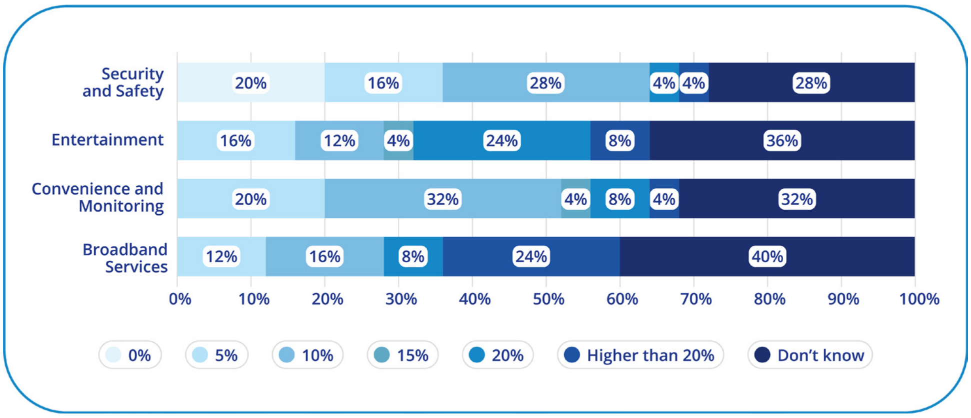


Figure 17 How much of premium would you expect drivers or OEMs to pay for services with ubiquitous connectivity on top of base cellular subs?

Here again, the expectations regarding the willingness to pay is the lowest for security and safety use cases with even 20% of respondents not willing to pay any premium. In contrast, the willingness to pay for broadband services is the highest with 24% expected to pay more than 20% premium on top of cellular subscriptions Additionally it has to be stated that the rate of answers with 'Don't know' is rather high for this question.

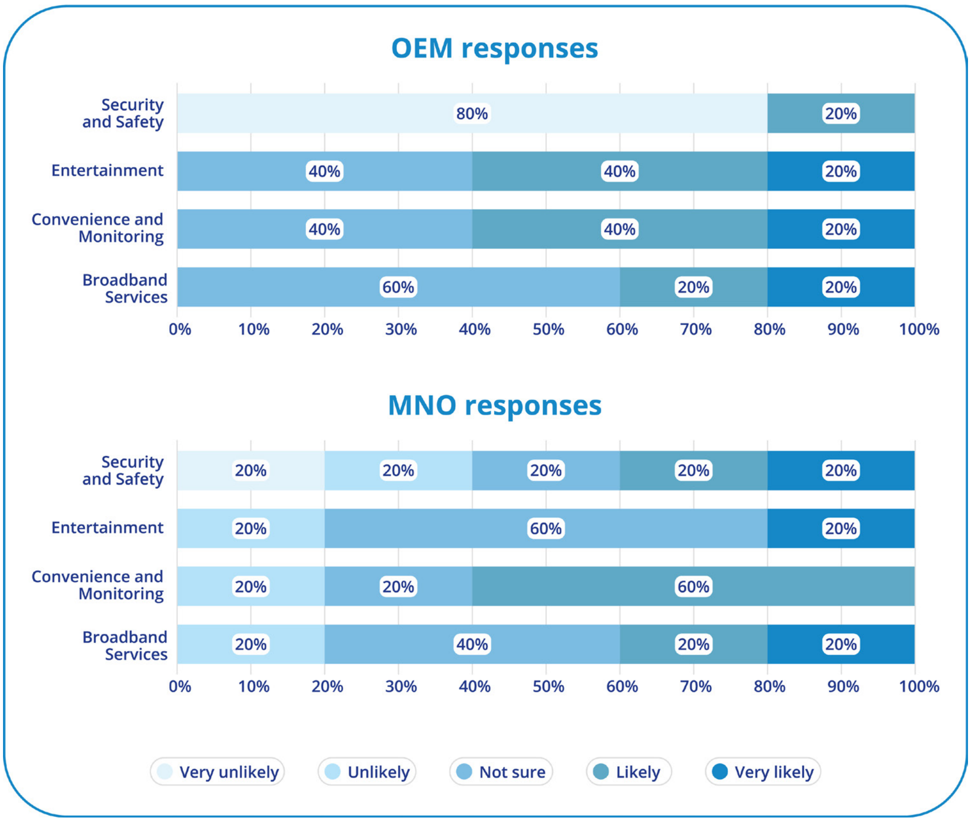


Figure 18 What is the likelihood of earning revenues for the various types of services for your type of organisation?

It is obvious that the expectations to earn revenues are varying very much depending on the type of organisation. The OEMs do not believe that they can earn any extra revenue with security and safety applications. Among the MNOs the believe to what degree they can earn money the answers are evenly distributed.

For entertainment services, OEMs are slightly more optimistic to earn money than the MNOs. Some 60% believe that it is either likely or very likely that OEMs can earn money. Only 20% of the MNOs state that it is very likely that they can earn extra revenue. The rest is either not sure or believes that extra revenue is unlikely. In general, responses to this question showed the highest degree of uncertainty compared to the other questions in the survey.

Another topic of interest is the priorities reported by various NTN-based services. We asked our 5GAA members the same questions as in the customer survey (conducted in Autumn 2025)

Rank	Use Case
1	**Emergency call**
2	Local hazard and traffic information
3	Road safety information
4	Traffic management in disaster situation
5	Field monitoring – remote car status check
6	Hazard information collecting and sharing
7	Remote access
8	Entertainment – audio and video calls
9	Help assist concierge
10	Updating and sharing of HD maps
11	Automatic software updates
12	**Entertainment – SD/HD**
13	Teleoperated driving support - objects
14	Entertainment - 4k
15	Teleoperated driving support – video

Figure 19 Rank the following NTN-based use cases: Based on criticality, how significant would be the impact of customers losing access to the application?

Emergency call is identified as the most critical use case, with a strong share of respondents ranking it as top priority. Safety-related use cases (e.g. hazard and traffic information, disaster management) consistently rank high, confirming their importance for reliability. Mid-ranking services (e.g. remote access, vehicle monitoring) show moderate criticality, suggesting relevance but not urgency. Convenience and infotainment services receive lower priority, indicating limited impact if unavailable. Advanced services (e.g. teleoperated driving, high-definition entertainment) are perceived as least critical, according to the ranking. The conclusion to be reached from this is that safety-driven use cases dominate perceived criticality.

These results largely align with the results from our customer survey [6] (conducted in autumn 2025). Customers expressed similar priorities, putting emergency call and hazard warnings at the top, and convenience and entertainment services further down.

In conclusion, the survey supports a sequential diffusion model for automotive satellite connectivity: embedded narrowband capability is expected first, wideband services follow as configurable vehicle variants, and broadband NTN remains a longer-term, optional or premium feature. The high share of 'don't know' responses, especially for wideband and broadband timing, indicates that industry planning is still fluid. Nevertheless, the convergence between timing expectations and integration strategies is analytically clear: the closer a service is to safety, resilience and basic connectivity, the earlier and more deeply it is expected to be integrated into the vehicle. The more it depends on high bandwidth and uncertain monetisation, the later and more optional the expected deployment model becomes.

5 Complexity drivers of terminals supporting higher frequencies

5.1 Introduction

The satellite user terminal integrates key components to ensure reliable communication, including the modem, modem interface, PNT system, and antenna unit. The modem is responsible for encoding, modulating, and demodulating data, often with 5G NTN functionalities for integrating satellite communications. The modem connects to the antenna unit via interfaces such as Digital DiFi, L-Band Analogue, and/or the Open AMIP Protocol, enabling effective communication across various system configurations. The positioning, navigation and timing (PNT) system is essential for determining the antenna's geographic location and orientation, ensuring real-time alignment with the satellite to maintain optimal signal quality and timing information.

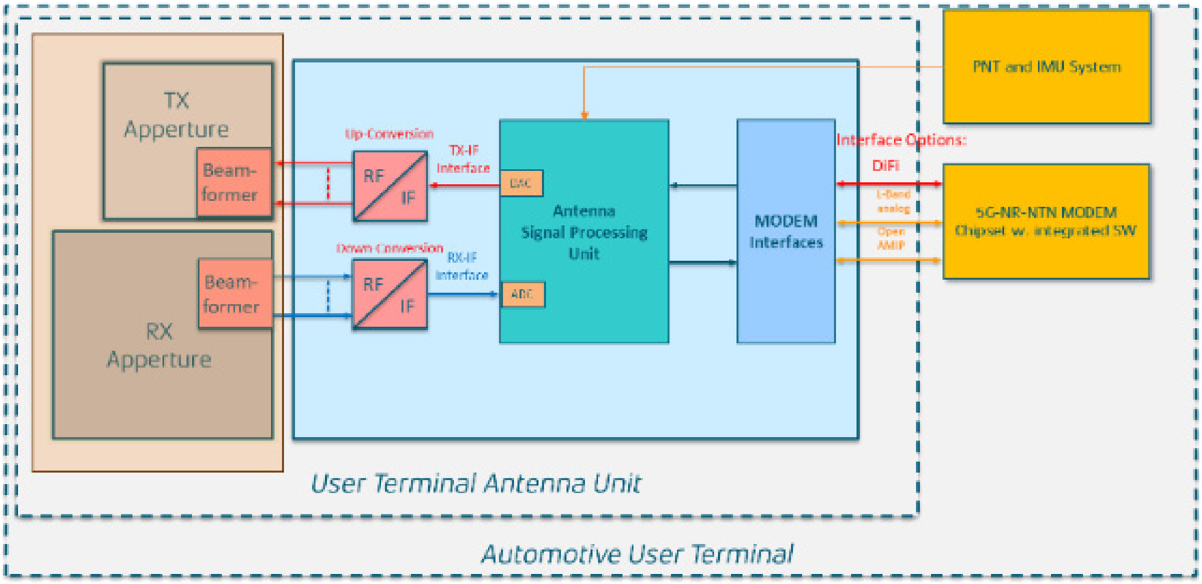


Figure 20 Main building blocks of a SATCOM FR2 user terminal

The antenna unit performs signal processing functions, including up-conversion and down-conversion, which convert intermediate frequency (IF) signals to radio frequency (RF) signals for transmission, and vice versa for reception. Beamforming techniques focus the signal precisely to the communicating satellite, enhancing communication efficiency, while high-power amplifiers (HPAs) and low-noise amplifiers (LNAs) ensure signal strength and integrity in both transmission and reception paths. The antenna aperture is the physical interface that transmits or receives the RF signal, playing a pivotal role in maintaining a stable and high-quality satellite communication link.

Antenna aperture architectures vary based on integration and product requirements. Shared apertures allow a single aperture for both Tx and Rx, whereas common apertures enable simultaneous Tx/Rx through multiplexing techniques. These configurations must balance size, isolation and performance based on application constraints.

In automotive environments, large satellite dish antennas are impractical due to their size and the thickness of the overall terminal. Phased arrays, particularly flat-panel designs, integrate more easily into vehicle bodies. Their principle of work is explained in Figure 21. The passive antenna elements are set in fixed spacing *d* between each other. Usually, *d* is set smaller than or equal than half wavelength of the operational frequency. Then, in order to create a wave front (i.e. the beam at a specified direction angle theta), the signal for each antenna element is delayed – the phase of the signal of each antenna element is shifted by a fixed value delta phi. In this way a far-field wavefront is created. The same principle applies for both transmission as well as for on reception side of a phased array system.

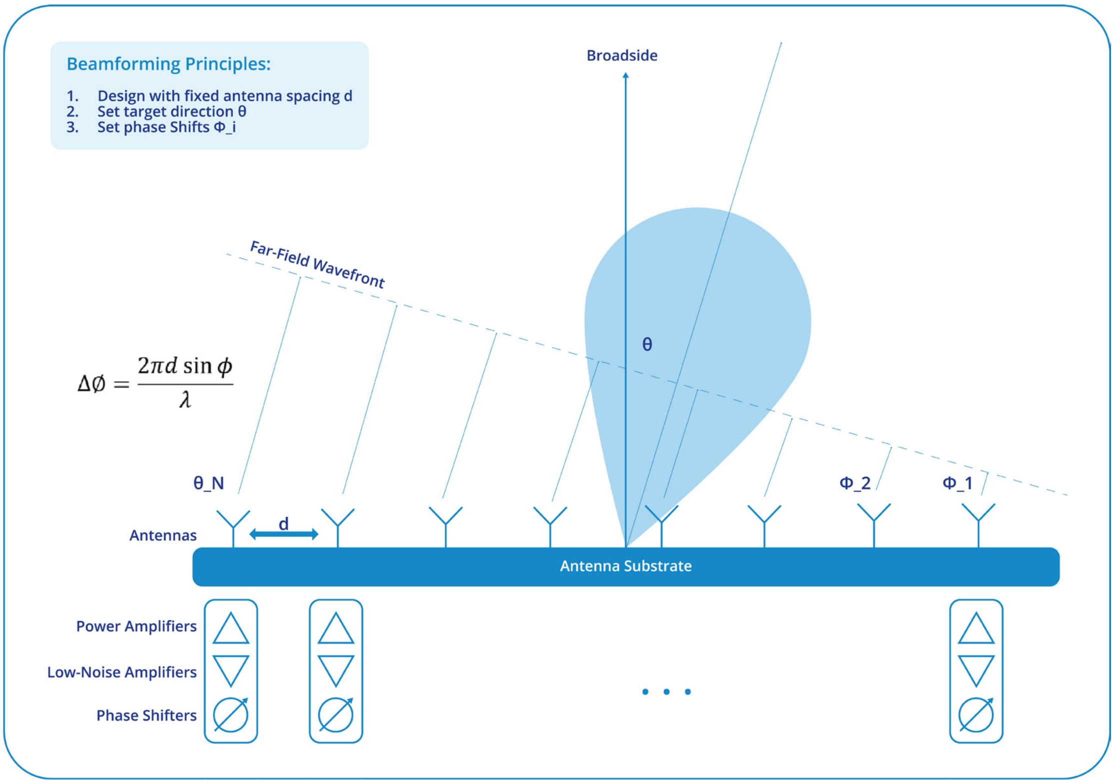


Figure 21 Principle of work in phased array antennas

The signal from each antenna element is then combined in a beamforming network, with up/down-conversion to an intermediate frequency and then filtered as shown below.

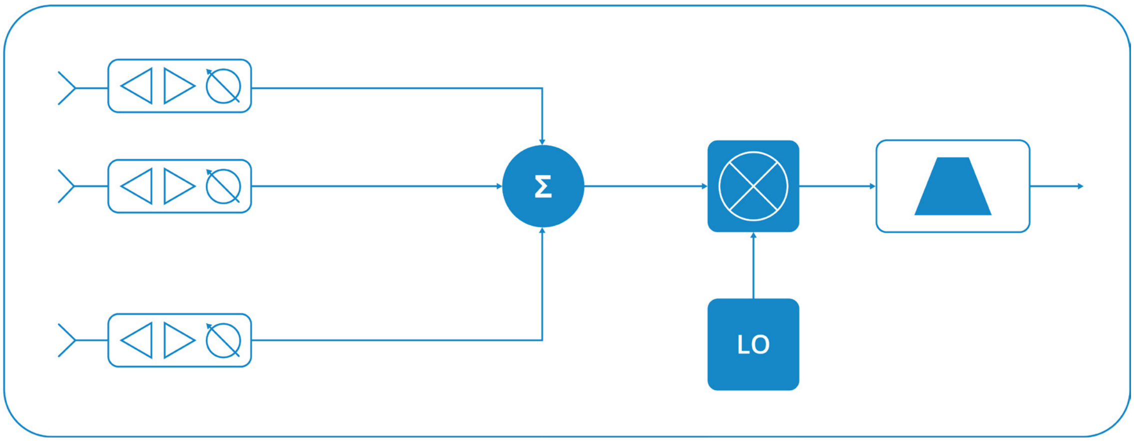


Figure 22 Signal combination in phased array antennas

There are three main architectures for combining the SATCOM radio signal:

- Analogue architecture
- Digital architecture
- Hybrid architecture

Their schematic is shown below.

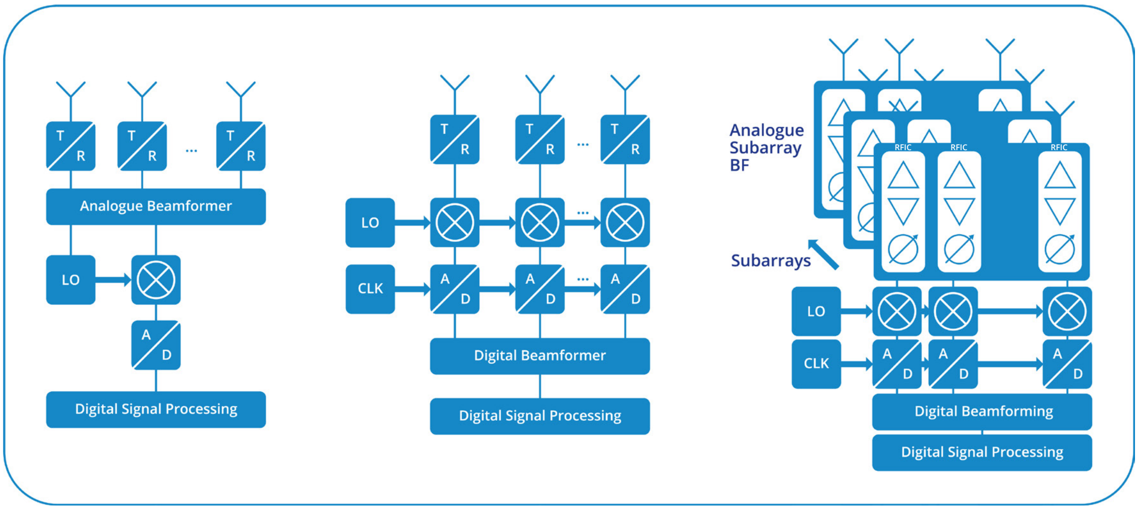


Figure 23 Signal combining architectures: a) Analogue, b) Digital, c) Hybrid architecture

In analogue beamforming the signal is combined in the analogue domain, i.e. combining networks like Wilkinson dividers. Afterwards, in receiver mode, the combined signal is down converted and then digitised for further signal processing. Analogue beamforming requires fewer high-power digital components like ADCs and DSPs. This is especially important in power-sensitive systems like satellites or mobile platforms. Analogue systems do, however, need careful calibration to account for non-ideal situations like phase shift tolerances and component mismatches. This can degrade performance if not maintained regularly.

In digital beamforming, the signal for each antenna element is directly up/down-converted to an IF, digitised and then combined in the digital domain. This requires analogue-to-digital converters and vice versa for each antenna element, followed by digital signal processing. This offers very high flexibility; multiple beams can be formed simultaneously and the beam patterns can be adapted dynamically. However, it requires digital processing hardware and algorithms, making the complexity of such solutions quite high. Finally, digital processing can introduce latency due to computation and data transfer.

Hybrid beamforming is a combination of analogue and digital beamforming. It tries to balance the advantages and limitations of both by doing some beamforming in the analogue domain (usually at the RF front end) and some in the digital domain after digitisation. In this way it reduces the number of ADCs and digital processors needed. Hence, saving power and cost compared to fully digital beamforming. It also scales better for large arrays by reducing digital hardware requirements, making large, phased arrays more practical. Such a scheme also requires careful design of both analogue and digital parts. Calibration is more complex because of the mixed domains. Nevertheless, hybrid beamforming is often the best and most practical choice for large arrays needing good performance without the full cost and power demands of digital beamforming.

5.2 Operational mode

We will adopt the approach of a full-duplex mode of operation, where both the transmitter and receiver transmit simultaneously.

One of the biggest challenges in full-duplex communication for phased-array antennas is self-interference: the received signal can be disrupted by the simultaneously transmitted signal.

To minimise these interferences, various techniques are employed, such as spatial filtering (separate apertures for transmit and receive antennas), temporal separation (e.g. time-division multiplexing in half-duplex systems), or selective decoupling of the transmit and receive units. Using self-interference cancellation (SIC) algorithms is a practical way to suppress this problem. The basic idea of SIC is that the system knows the transmitted signal and subtracts it in real time from the received signal to eliminate the interference.

However, the SIC method presents a practical challenge because the receiver is blocked by the simultaneously transmitted signal (i.e. interference from the transmitter). This prevents the receiver from properly detecting very weak signals, such as those from satellites. Therefore, for frequency division duplexing (FDD) the market often favours using separate apertures.

Considering integration aspects, full-duplex communication requires two separate arrays for integration. Additionally, no specifications for half-duplex mode are included in Release 18 and 19. It means that an area of, say, 20x20 cm2 would need to be split in half; one for the Tx and one for the Rx aperture. Given the state-of-the art devices now on the market, this design would result in insufficient EIRP and G/T for the link budget.

As a standard, we therefore need to propose broadband for half-duplex mode due to the small size of the terminal. The smaller form factor is also more suitable for integration into vehicles.

5.3 Complexity drivers

In our complexity discussions we must also consider the hybrid beamforming architecture. The functionality of signal amplification and phase shifting is integrated in the RF front end IC (RFIC). The RFIC controls four antenna elements and these are controlled by a digital beamformer. All these elements constitute a tile of the antenna aperture. Such tiles are then combined into one large array of elements as shown in the figure below.

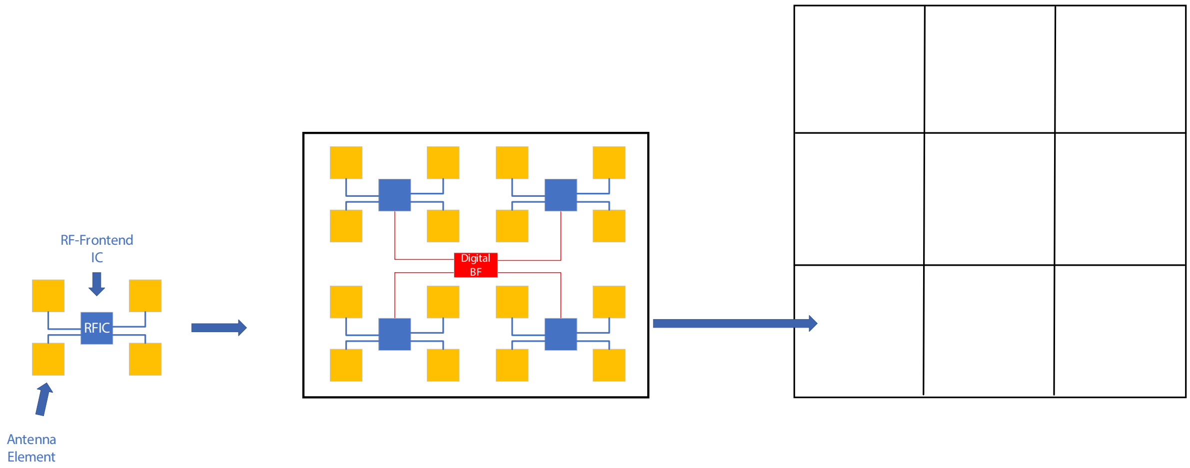


Figure 24 Reference architecture based on hybrid beamforming

The reference system assumes an aperture of 20x20 cm^2 in size. In Ka-band, it corresponds to a combination of 400 antenna elements arranged in a 20x20 array. The Tx and Rx antennas are sharing the same aperture. Hence, based on the architecture given above, we would have 100 RF-ICs with integrated up/down-converters, LNAs and PAs. This results in 25 beamforming ICs. Other building blocks in this scheme include PCB, DC/DC converters, clocking devices (i.e. PLLs and TCXOs), passive devices and connectors, interfacing devices, enclosure including radome, microcontroller system and the signal combining application-specific integrated circuit (ASIC).

In the system components, besides the conventional printed circuit boards (PCBs), the use of glass circuit boards (GCBs) can also be considered as an alternative. GCB antenna arrays offer an optical transmittance of approximately 30-40% and provide superior thermal conductivity (TC~1.1 W/(m·K)).

PCBs benefit from mature manufacturing processes and cost efficiency, making them highly suitable for mass production, with reliable performance and well-established fabrication techniques. Conversely, GCBs are characterised by lightweight, reduced thickness, optical transparency and enhanced thermal conduction properties, which facilitate improved integration and aesthetic considerations when installed on vehicle bodies or sunroofs. However, because of their transparency properties, GCB-based systems require specialised thermal management solutions, such as heat sink-less cooling or transparent cooling methods. To achieve sufficient link budget performance, the antenna array will employ low-power design topology and be slightly larger (recommended size is less than 25×25 cm) to compensate for differences in transmit power.

Both options have specific application scenarios, advantages and disadvantages. System design can be tailored to select the most appropriate material based on performance requirements, cost constraints and integration considerations.

For each of these devices, we calculated the relative cost (in terms of the overall system) when the number of pieces changes from 1,000 systems per year, to 100,000 – 1 million and 10 million systems per year. We also factor in the on-time or non-recurring engineering (NRE) costs associated with such development, including its product qualification, assembly and the corresponding testing. The relative costs and drivers are shown in the figure and table below.

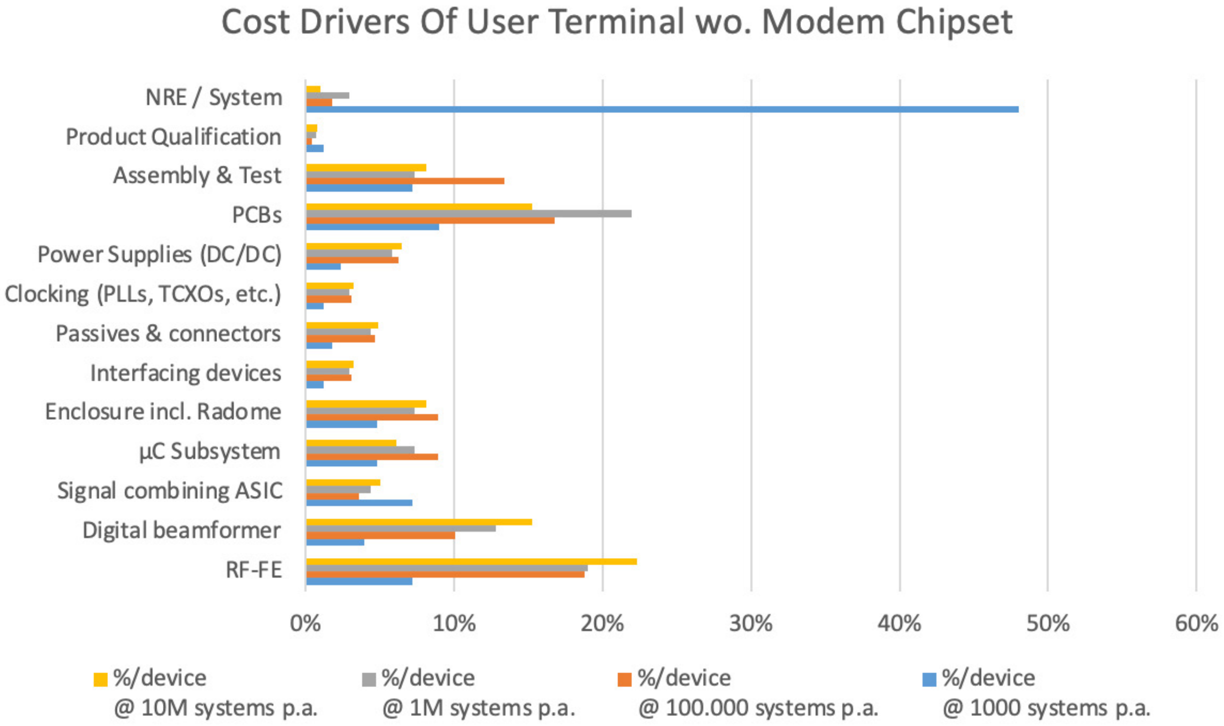


Figure 25 Cost drivers of user terminal

Table 12 Relative cost drivers of a user terminal using A1 architecture

	%/device @ 1000 systems p.a.	**%/device @ 100.000 systems p.a.**	**%/device @ 1M systems p.a.**	**%/device @ 10M systems p.a.**
RF-FE	7%	19%	19%	22%
Digital beamformer	4%	10%	13%	15%
Signal combining ASIC	7%	4%	4%	5%
µC Subsystem	5%	9%	7%	6%
Enclosure incl. radome	5%	9%	7%	8%
Interfacing devices	1%	3%	3%	3%
Passives & connectors	2%	5%	4%	5%
Clocking (PLLs, TCXOs, etc.)	1%	3%	3%	3%
Power supplies (DC/DC)	2%	6%	6%	7%
PCBs	9%	17%	22%	15%
Assembly & test	7%	13%	7%	8%
Product qualification	1%	0%	1%	1%
NRE / system	48%	2%	3%	1%

5.4 Complexity development

As the development of user terminals changes over time, we think that there will be also some related architecture changes to reduce complexity. Typical changes would be the integration of RF-IC and the digital beamformer into one chip. Another option would be to use fewer digital beamformers and longer chains of beamformers and RF-ICs. Other improvements might be in the mass-production efficiency. All these changes are estimated in the curves shown below.

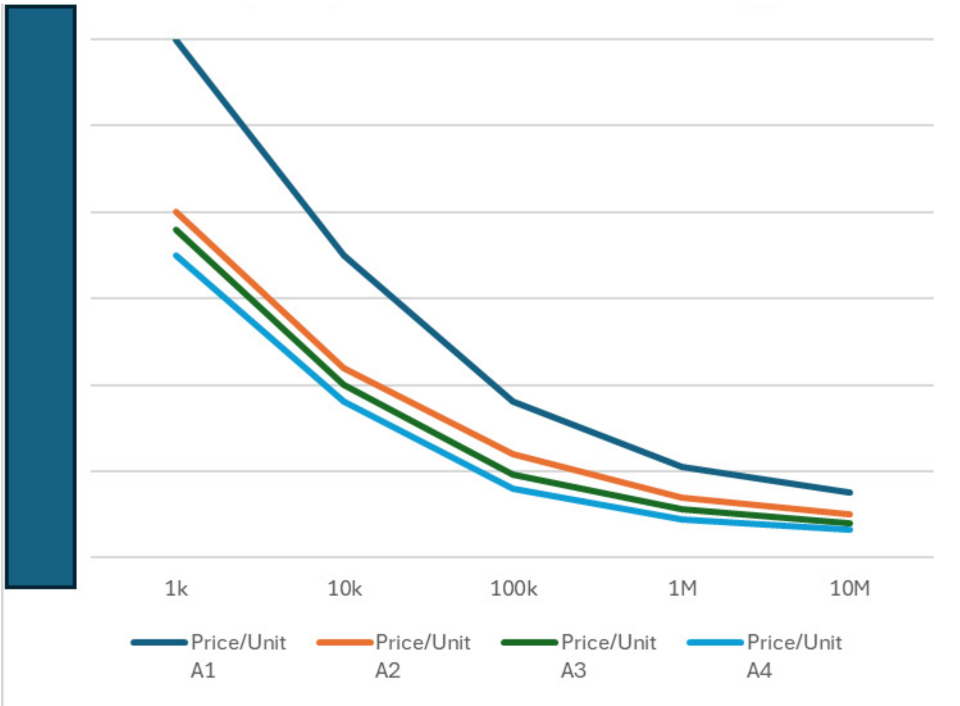


Figure 26 Complexity trend automotive UT over qty

5.5 Power mask requirements

In this section we perform a conformity analysis. We test if antennas with 20x20 elements for Ka- and Ku-bands meet the regulatory requirements. We did an equivalent-power flux density (EPFD) limits examination under ITU Article 22 (paragraph 22.32). The analysis considered a bandwidth of 720 kHz which corresponds to one 5G resource block with worst-case SCS of 120 kHz sub-carrier spacing.

The simulation assumptions are listed below:

Perform a conformity analysis if a system of 20x20 antenna elements fits the EPFD requirements e.g. ITU-R S.1503-4, FCC 25.218, CEPT mask and if the receive gain of the antenna meets the ITU requirements: ITUR-S.465.

Simulate with following parameters:

- **Number of elements: 400 in a 20x20 square array**
- **Element Gain: 3.5 dBi**
- **Cosine pattern with roll-off 1.3 coefficient**
- **Element Power: 13 dBm**
- **Noise Figure: 2 dB**
- **Scan angles: 0 (boresight) up to 60°**
- **Ka-Band FR2**

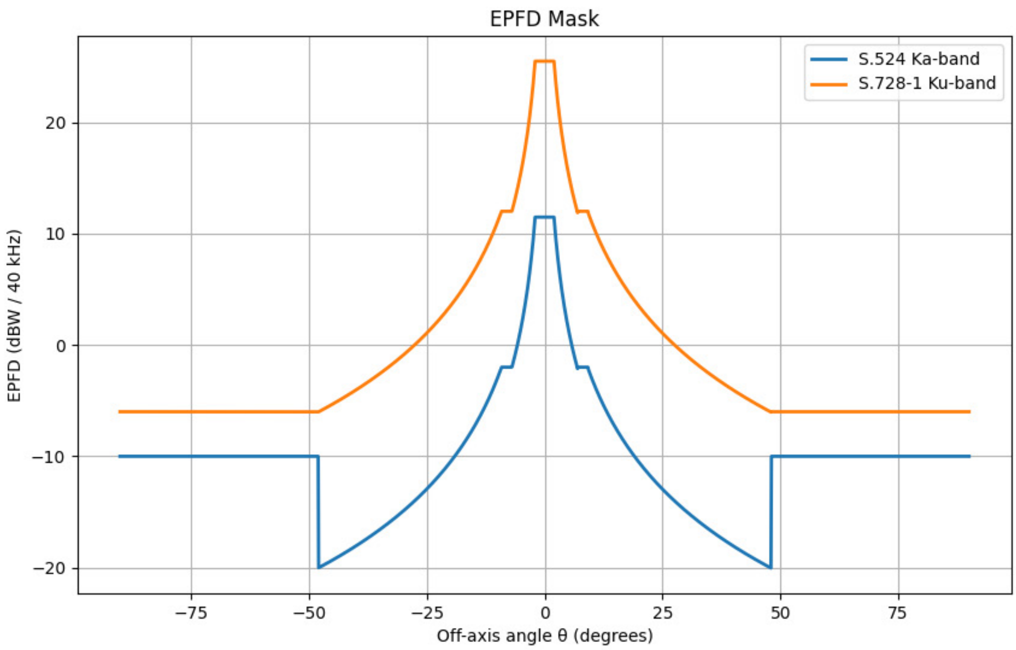
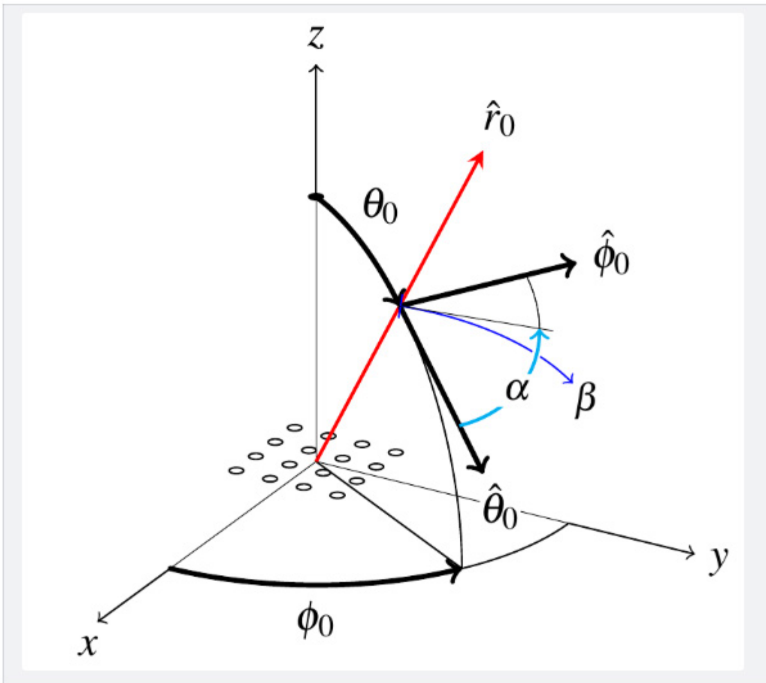


Figure 27 ITU-22 EPFD power masks



- θ_0 : Scan angle
- $\theta = 0$: Array normal, or broadside
- $\theta = \pi/2$: Array plane
- $\hat{r}_0$ or (θ_0, ϕ_0): Boresight
- $\hat{\theta}_0$: Tangent to elevation cut
- $\hat{\phi}_0$: Tangent to azimuth cut
- α: Cut angle, or angle around boresight
- β: Off-axis angle, or angle from boresight
- $\phi = \phi_0$ or $\alpha = 0$: Elevation plane
- $\alpha = \pi/2$: Azimuth plane

Figure 28 Reference system for the EPFD-limit analysis

5.5.1 Ka-band EPFD analysis

For a Ka-band antenna the dimensions and layout of the elements are shown below.

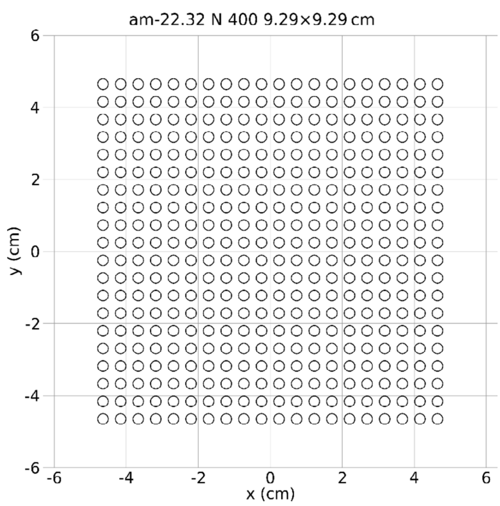


Figure 29 Ka-band antenna definition

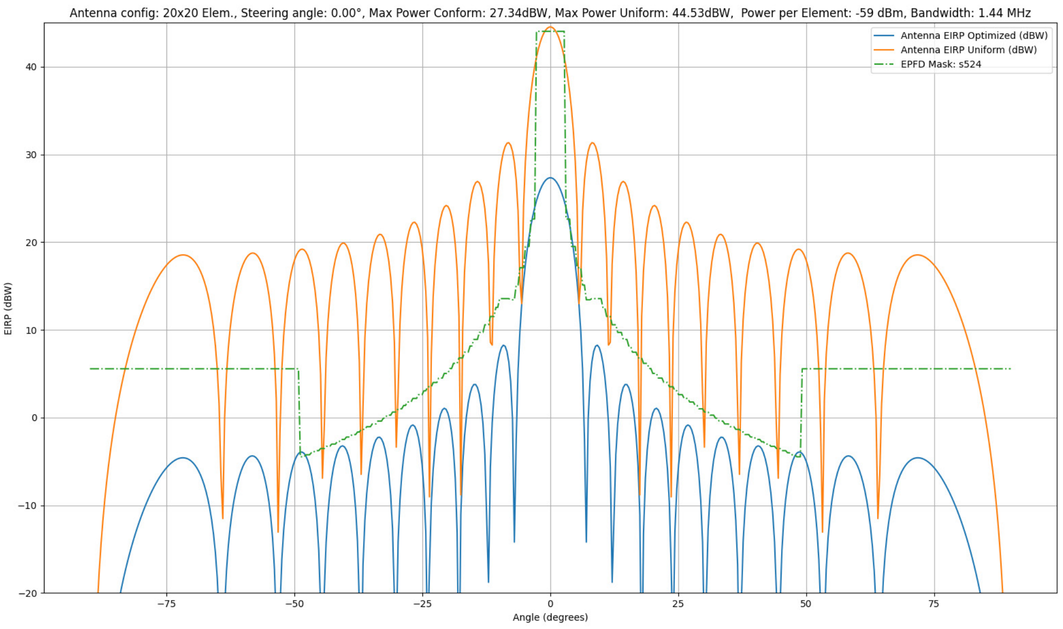


Figure 30 Scan 0 deg

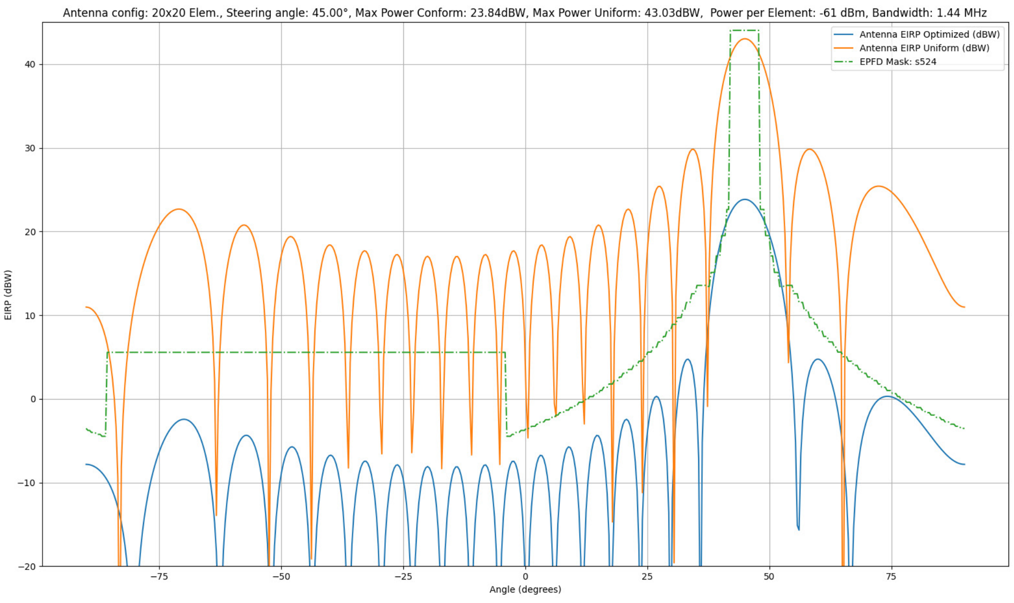


Figure 31 Scan 45 deg

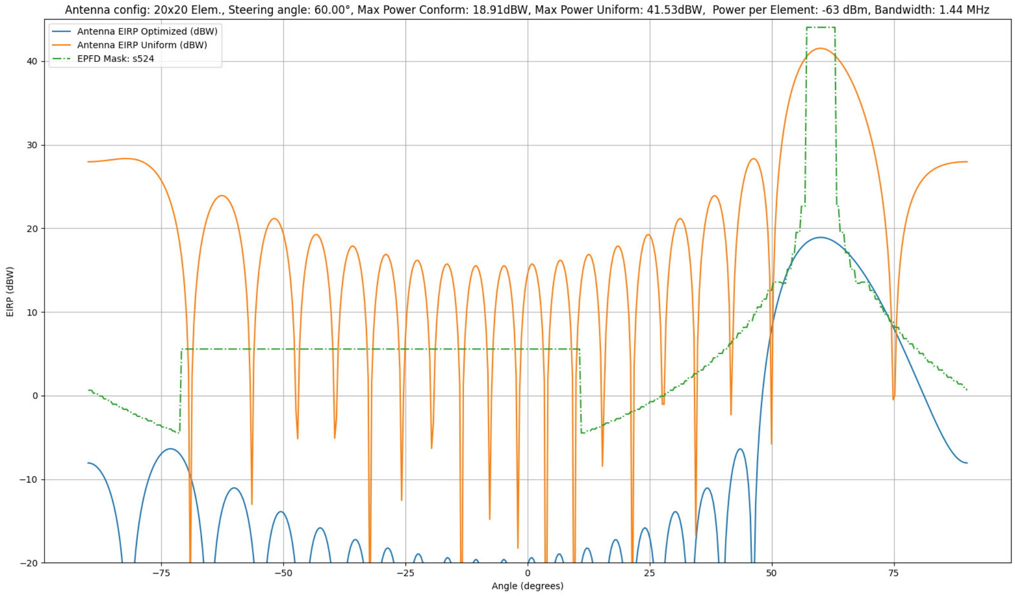


Figure 32 Scan 60 deg

5.5.2 Ku-band analysis

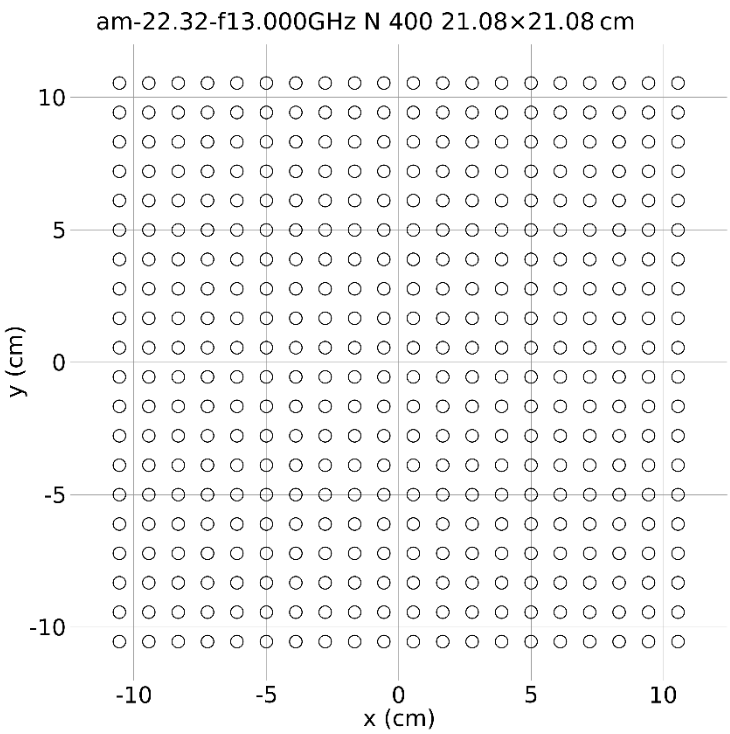


Figure 33 Antenna lattice for Ku-band antenna

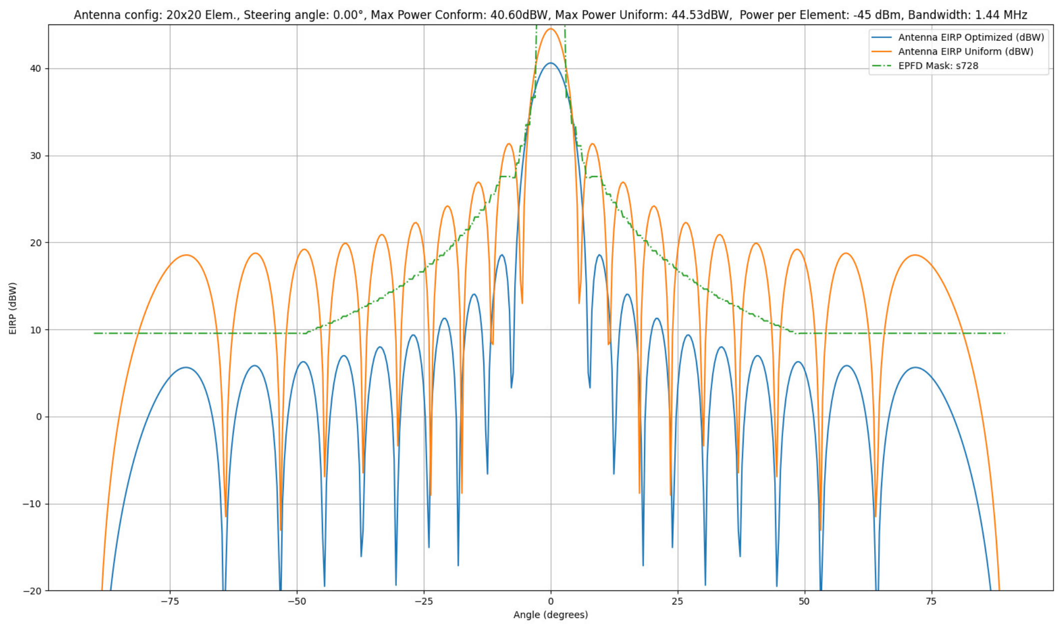


Figure 34 Scan: 0 deg

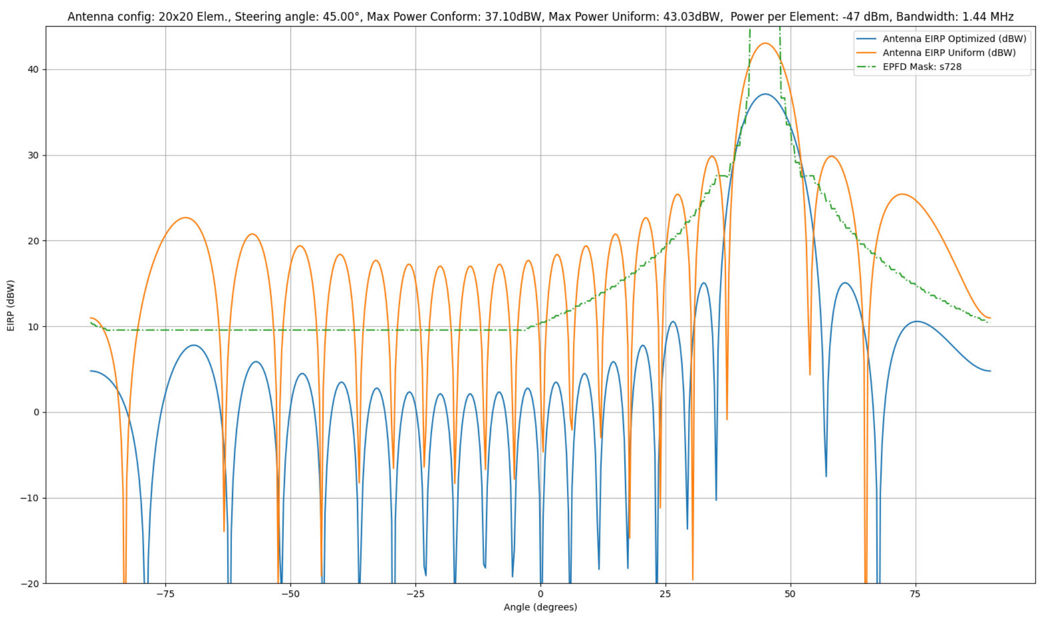


Figure 35 Scan 45 deg

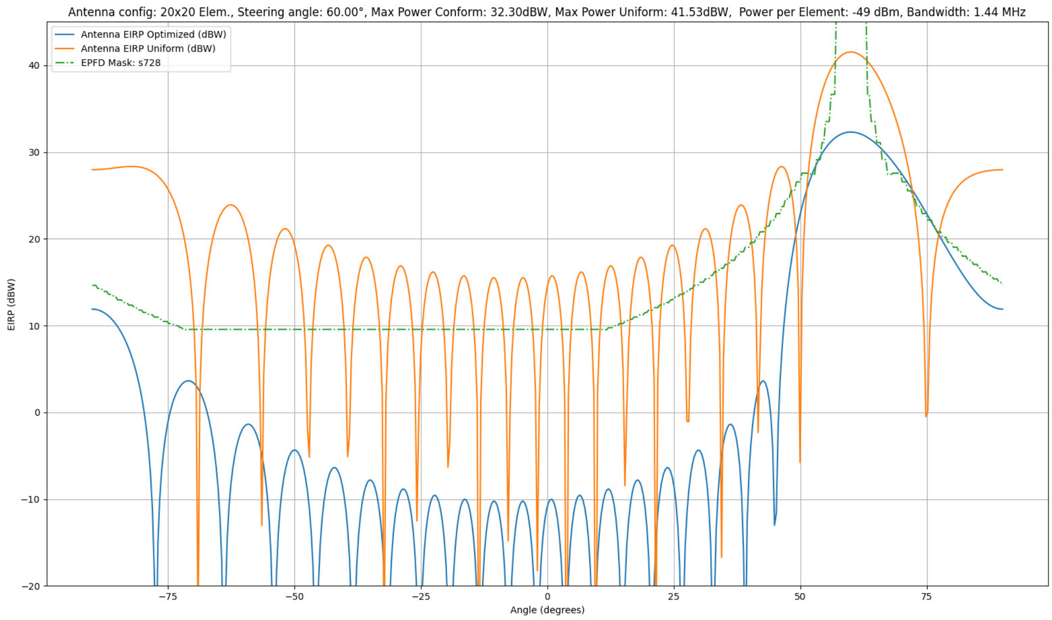


Figure 36 Scan 60 deg

5.5.3 EPFD-limit analysis conclusions

The analysis shows that a small antenna with 20x20 elements can fulfil the EPFD-limit requirements from ITU Article 22 both in Ku- and Ka-bands. This builds confidence that such an antenna can be compatible with the regulations for SATCOM communications when integrated in a car.

5.5.4 User terminal assumptions for link budget

For the link budget calculations, the key satellite parameters are equivalent isotropically radiated power (EIRP) and figure of merit (G/T). These values are often confidential or not publicly disclosed, so we base our assumptions on public satellite data and 3GPP references. All EIRP values are converted to total EIRP using a reference bandwidth of 400 MHz.

5.5.4.1 Ku-band

For Ku-band calculations, publicly available satellite footprint data [7] indicate that a GEO satellite declares an EIRP of approximately 45 dBW using a DVB-S waveform. Since 5G NR-NTN uses an OFDM waveform, which has a higher peak-to-average power ratio, an output back-off of 5 dB is applied. This results in an effective total EIRP of 40 dBW for the GEO satellite. This value is consistent with the GEO satellite EIRP assumptions listed in Table 6.1.1.1-2 of 3GP TR 38.821 document.

To maintain the same radiation flux density at the Earth's surface, the EIRP of LEO satellites is scaled according to the ratio of orbital altitudes relative to GEO (35,786 km). This yields a total EIRP of approximately 25 dBW for a LEO satellite at 1200 km and 23 dBW for a LEO satellite at 600 km.

The satellite figure of merit (G/T) values for Ku-band are based on recommendations from 3GPP TSG-RAN WG4 [8]. The GEO satellite is assumed to have a G/T of 31.4 dB/K, while both LEO satellites at 1200 km and 600 km have a G/T of 11.4 dB/K.

5.5.4.2 Ka-band

For Ka-band, the satellite EIRP values are taken from 3GPP TR 38.821 (Table 6.1.1.1-2), which provides EIRP in spectral density (dBW/MHz). Assuming a 400 MHz bandwidth, the spectral densities are converted to total EIRP. This results in approximately 58 dBW for the GEO satellite, 28 dBW for the LEO satellite at 1,200 km, and 22 dBW for the LEO satellite at 600 km.

The corresponding G/T values for Ka-band are lower than Ku-band, reflecting typical payload characteristics. The GEO satellite is assumed to have a G/T of 20 dB/K, while both LEO satellites at 1,200 km and 600 km have 5 dB/K.

5.5.5 Satellite EIRP and G/T assumptions for link budget

Below are the simulation parameters used for the terminal in the link budget analysis. The values include both Ka-band and Ku-band terminals.

Table 13: Satellite parameter assumptions

Scan Angle	0°	45°	60°
G/T (dB/K)	0.8	2.8	4.7
Ground Ku EIRP (dBW/ 1.44 MHz)	40.6	37.1	32.3
Ground Ka EIRP (dBW/ 1.44 MHz)	27.34	23.84	18.91
Noise figure	2 dB		

5.5.6 Link budget results

Using 5G-NR numerology and a subcarrier spacing of 120 kHz as used in NTN we obtain the following data rates for Ka- and Ku-band systems. It is to be noted that in these calculations we assume no interference from other satellite constellations. Hence, such values are to be interpreted as the upper boundary of performance.

5.5.6.1 Ku-band

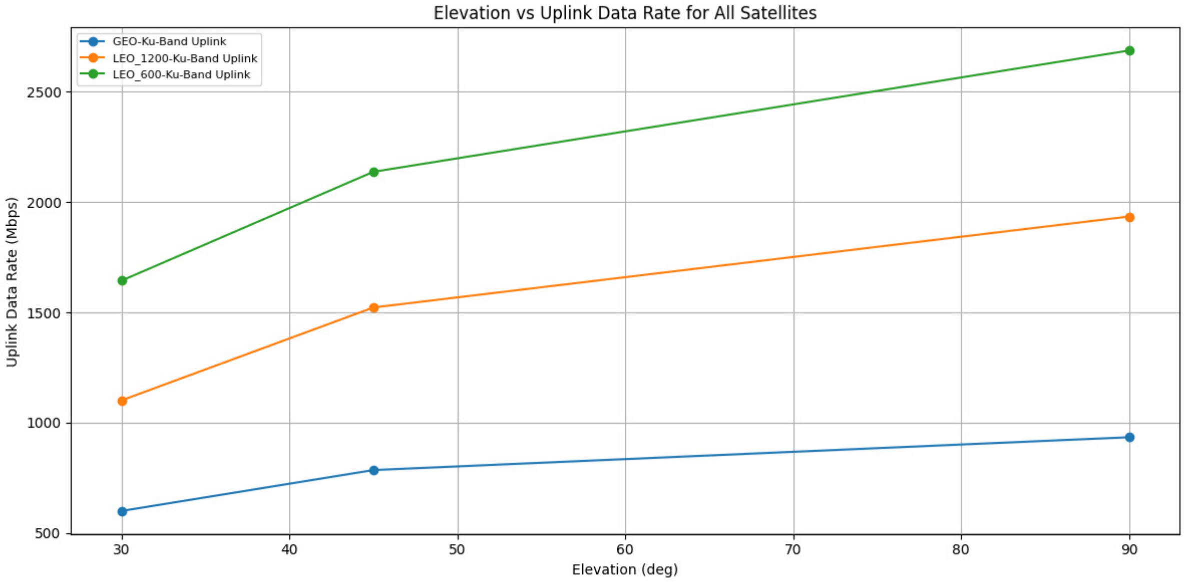


Figure 37 Elevation vs uplink data rate for all satellites in Ku band

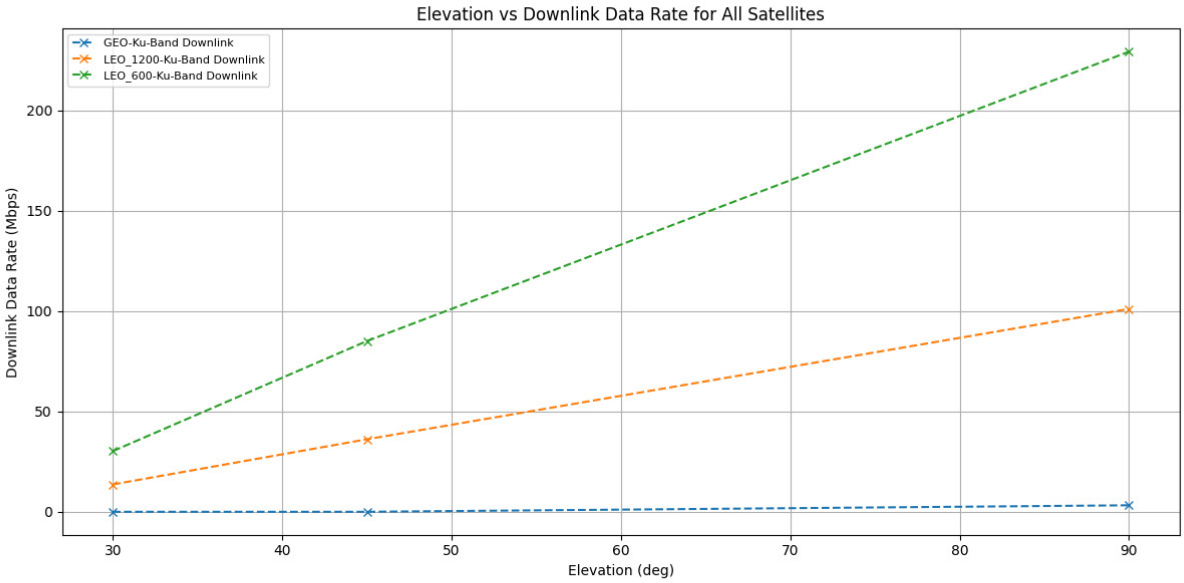


Figure 38 Elevation vs. Downlink data rate for all satellites in Ku band

5.5.6.2 Ka-band

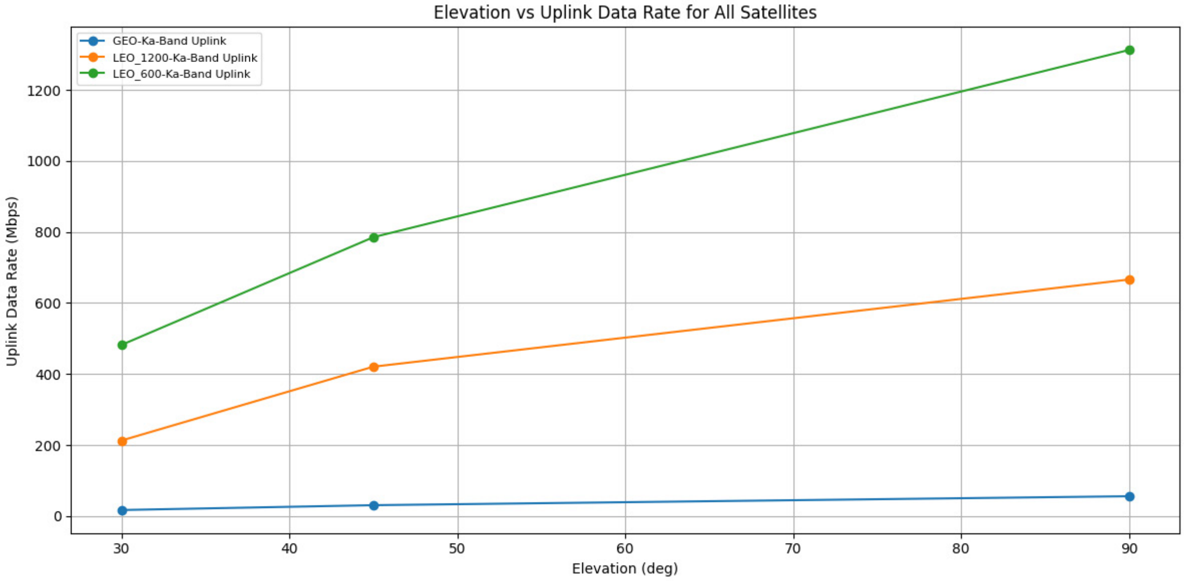


Figure 39 Elevation vs uplink data rate for all satellites in Ka-band

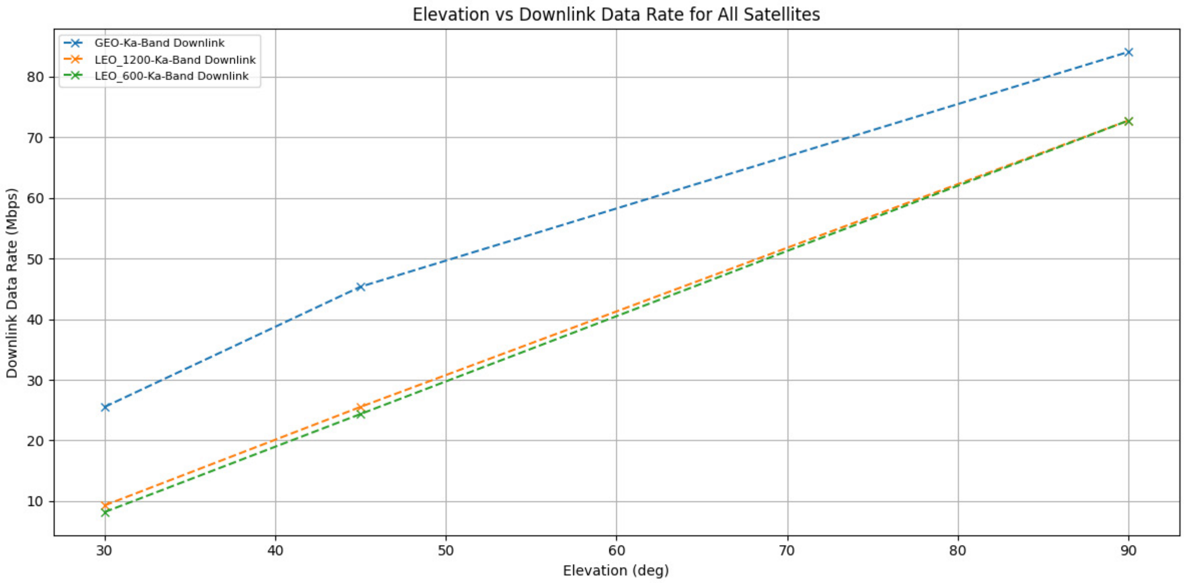


Figure 40 Elevation vs downlink data rate for all satellites in Ka-band

5.5.6.3 Discussion

A GEO satellite cannot be reached via DL in Ku-band due to the relatively small antenna size and the lower EIRP of the satellite compared to Ka-band satellites. In Ka-band, the situation is reversed; a user terminal works in DL but cannot perform well in uplink. Power to the Ka-band system is limited due to regulatory constraints, although the transmitter would be capable of higher uplink power. Regulatory limits in Ka-band are more stringent than Ku-band. In addition, propagation characteristics in Ka-band are less favourable than those in Ku-band due to higher free-space path loss.

LEO communications can maintain good uplink performance, offering data rates higher than 1 Gbps in boresight. Even in situations when a satellite is at 30° elevation (60 deg. scan angle) the antenna can still maintain an uplink connection in both Ku- and Ka-bands.

5.6 Conclusions

This work analysed the feasibility of compact satellite communication terminals for automotive applications, with particular focus on the implications of operating in Ku- and Ka-band frequencies as well as the resulting cost drivers. The comparison shows that both bands offer distinct advantages and trade-offs. Ku-band benefits from more favourable propagation characteristics and less stringent regulatory constraints, which simplify terminal design and reduce performance requirements for antenna systems. In contrast, Ka-band provides significantly larger available bandwidths, enabling higher potential data rates and smaller antenna element spacing due to the shorter wavelength.

However, these advantages come with notable challenges. Ka-band systems suffer from higher free-space path loss and increased sensitivity to atmospheric effects such as rain attenuation. Furthermore, stricter regulatory constraints on power masks and sidelobe levels require narrower beams and stronger sidelobe suppression. As a result, user terminals must employ larger antenna arrays with more aggressive tapering, which increases system complexity and reduces achievable EIRP for a given aperture size.

From a cost perspective, the study indicates that although compact terminals capable of meeting automotive OEM requirements are technically feasible, achieving the targeted performance at low cost remains challenging. The primary cost bottlenecks are the RF front end components, PCB manufacturing, and the digital beamforming architecture. These elements dominate the system cost and limit the expected economies of scale. Overall, the results demonstrate that while high-performance automotive satellite terminals are technically achievable, further innovations in RF integration, manufacturing processes and beamforming architectures will be necessary to reduce system costs and enable large-scale deployment.

6 Architectures and deployment options for NTN-TN interworking

5GAA has identified non-terrestrial networks as an important pillar for ubiquitous and seamless connectivity for automotive use cases [1, 9]. This section describes possible architectures for NTN-TN interworking and integration, assesses benefits and drawbacks of each deployment option, and analyses the impact on subscriber management (including security aspects).

In principle an NTN can be completely independent or indeed separate from a terrestrial network, as illustrated below.

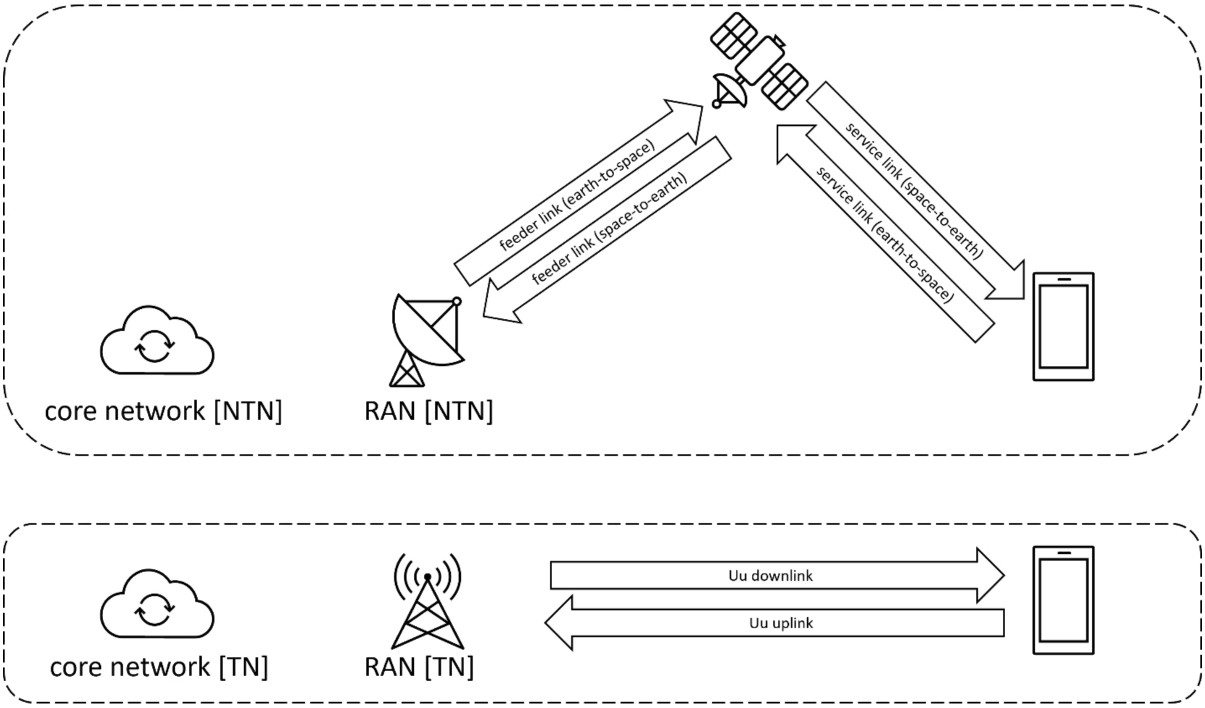


Figure 41 Independent NTN and TN deployments

One of the fundamental principles of 5GAA's studies on space-connected automobility is the conviction that future NTNs (in particular LEO constellations) need to be 3GPP standard-compliant in order to pave the way for global adoption of the technology and closer interworking between NTNs and TNs. For that interworking in 5G networks and finally a full integration in 6G networks several architecture options are possible, ranging from roaming to various forms of interworking up to tight integration of NTN into TN.

Possible variants could comprise permutations of different aspects, such as

- the number of operators (single vs. dual),
- ownership and operation of the RAN (MNO vs. MVNO, RAN sharing),

- the number of core networks (single core, dual core, MOCN),
- the licensee of the spectrum used for serving the vehicle from space,
- the radio access technology used by the NTN and the TN,
- roaming (limited to 5G, i.e. via SEPP),
- handling of subscriber management at the network (UDM, UDR),
- handling of subscriber management at the device (single-SIM vs. dual-SIM).

6.1 Roaming concepts in 3GPP

Roaming is a well-known procedure to connect mobile networks (PLMN) with each other and thus allows a mobile user to consume a mobile, digital service (literally) anywhere, i.e. while not being physically located in the home network. Technically, roaming is the ability for a subscriber of a home public land mobile network (HPLMN) to use the service while attached to a visited PLMN (VPLMN), typically in another country and using standardised inter-operator connectivity and procedures. In practice, roaming depends on a bilateral roaming agreement between home and visited network operators and on the technical set-up of interconnect, signalling, DNS/realms, security, and policy/charging. A roaming UE is identified by an IMSI (International Mobile Subscriber Identity), whose MCC and MNC (Mobile Country Code, Mobile Network Code) encode the home network identity, enabling visited networks to recognize which home network operator should be contacted and to apply roaming controls by operator identity. While for consumer devices (such as smartphone) national roaming is typically not allowed by the regulator, for IoT/M2M devices national roaming (roaming within the same country) is typically allowed.

6.2 Options for roaming between NTN and TN

In the following table various options for roaming between terrestrial and non-terrestrial networks are listed.

Table 14 Deployment options for roaming between terrestrial and non-terrestrial networks

Option	NTN	TN		
		Name	TN core	TN RAN
Deployment#1	5G (NR-NTN)	5G SA	5GC	NR
Deployment#2	5G (NR-NTN)	5G NSA	EPC	NR
Deployment#3	4G (IoT-NTN)	5G SA	5GC	NR
Deployment#4	4G (IoT-NTN)	5G NSA	EPC	NR
Deployment#5	5G (NR-NTN)	4G	EPC	LTE
Deployment#6	4G (IoT-NTN)	4G	EPC	LTE

Roaming solutions between 4G TN and 4G IoT NTN are already in place for some GEO based solutions, with LEO-based solutions to follow soon. Further, roaming between 4G TN or 5G NSA TN and 5G NTN will be important during a transitional phase. This reflects real-world deployments in many regions, where 5GC-based TN coverage does not yet match that of EPC-based TN. While 5G SA roaming between TN MNOs is still evolving, 5G SA-based roaming between TN and NTN may take some more time but is envisioned to be available in the long term.

Moreover, the underlying operating model and the business relationships between NTN and TN operators are critical factors. It may be challenging in complex multi-operator relationships to implement an efficient architecture with a sustainable business model for all stakeholders. A positive business case is the prerequisite for the successful deployment and operation of NTN-TN architecture(s). This landscape is further complicated by the ownership of granted spectrum licenses used to serve connected vehicles from space (e.g., possible new MSS allocations in IMT spectrum, MSS spectrum of satellite operators). Throughout this report, we assume that satellite and terrestrial systems operate in accordance with 3GPP specifications and scenarios.

6.2.1 Roaming between 4G networks

In 4G, roaming spans the 4G radio access and the Evolved Packet Core (EPC), plus interconnect networks.

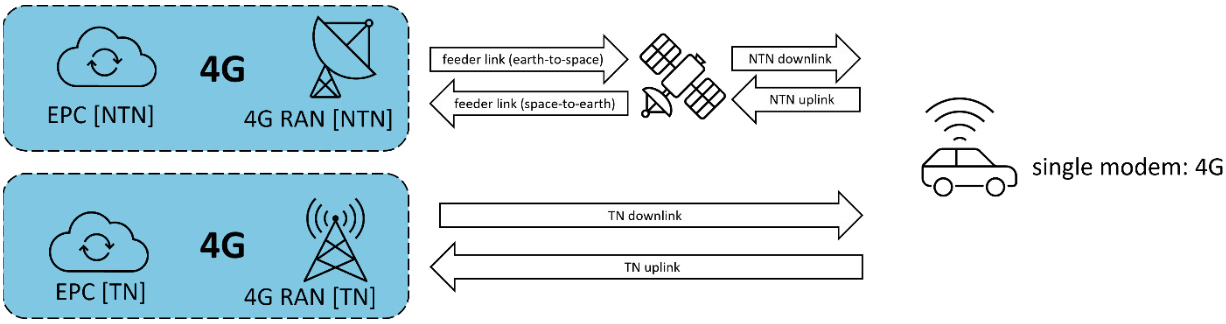


Figure 42 4G-4G roaming scenario

The visited network (VPLMN=NTN) provides satellite-based access via E-UTRAN (eNodeB) and core functions such as MME and Serving GW, and it must reach the home network's subscriber databases and policy/charging systems via standardized interfaces (S6a and S8). A key enabler is the USIM configuration of the mobile device, which contains a prioritized PLMN lists and even "PLMN lists with access technology", guiding whether LTE/E-UTRAN is permitted/available for that operator relationship.

The home network (HPLMN=TN) provides subscriber authentication/authorisation and often anchors services and policy/charging decisions via HSS, PCRF, and operator IP services. Roaming signalling and (depending on the roaming model) user plane traffic are carried over an interconnect network such as GRX/IPX. IPX supports "cascading responsibility" in addition to being an IP transport network.

The following interfaces are roaming-specific and marked as red line in Fig. 43:

- **S6a (Diameter)** between MME and HSS for authentication/subscription retrieval.
- **S8** for inter-PLMN connectivity between visited and home packet core

components in **home-routed** roaming (referenced usually as S8HR).

Home-routing refers to the set-up shown in Figure 43 where the data egress is in the home-network, i.e., the device connects to a data network, such as the internet, via the home network. The other option is local break-out (LBO), which is seldomly used in LTE-LTE roaming. However, that causes problems for IMS voice roaming (VoLTE), according to GSMA IR.65, where P-GW and P-CfSCF are located in the visited network (i.e., visited anchoring for IMS APN usage in that scenario).

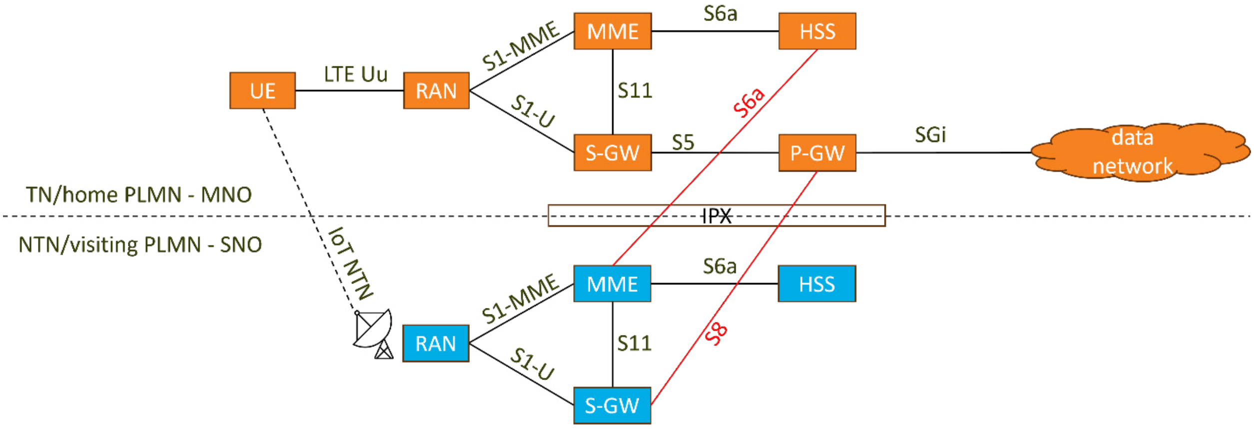


Figure 43 4G-4G roaming (home-routing)

6.2.2 Roaming between 5G networks

In 5G, roaming spans the 5G radio access and 5G Core (5GC) network, plus interconnect networks.

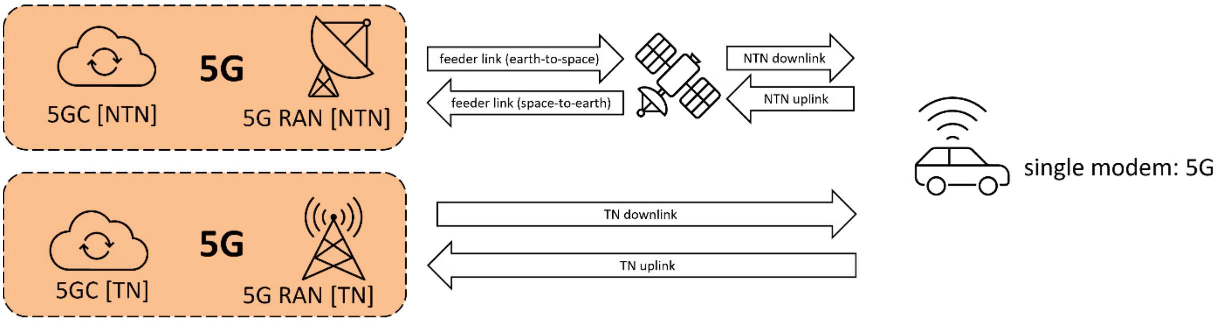


Figure 44 5G-5G SA roaming scenario

5G stand-alone roaming enables subscribers to access services in a VPLMN, while preserving HPLMN) control, policy, charging and security. Compared to LTE/EPC roaming, 5G SA introduces service-based architecture (SBA) and HTTP/2 signalling, slice-aware control, and the N32 (SEPP) inter-PLMN security framework. Operators typically deploy home routing (HR) for data and IMS voice (VoNR) with EPC interworking (N26) to support EPS fallback where needed.

The following paragraphs outline the roaming between two pure 5G networks (e.g., terrestrial 5G stand-alone and NR-NTN), reference interfaces, control/user plane flows, voice options, interworking, and security (SEPP/PRINS). In principle, two different roaming models (home-routing, local break-out) for the data termination of the user plane are defined:

- 5GS home routing (HR, N9 HR):
  - The preferred model for 5G data and IMS voice (VoNR) roaming.
  - User plane is home-routed via N9 between VPLMN UPF and HPLMN UPF; policy/charging anchored in HPLMN.
  - It provides service parity and consistent charging/policy across PLMNs, analogous to LTE S8HR.
- Local breakout (LBO):
  - Data breakout in the VPLMN UPF; typically used for certain enterprise or regulatory contexts.
  - Requires careful policy/charging coordination; less common for IMS voice due to QoS/continuity constraints.

For the much more common HR (user plane flow via N9) the GTP-U traffic from gNB arrives at VPLMN UPF (N3), which forwards via N9 to HPLMN UPF (anchor), then to DN via N6. So, the egress point of the user plane data is the home PLMN, although the device is physically located in another network/country (VPLMN).

Benefits are unified charging (CHF), policy enforcement (PCF), and consistent service exposure (NEF) in HPLMN.

While 3GPP and GSMA also defined LBO, this roaming model is much less implemented. In LBO VPLMN UPF breaks out to local DN (i.e., in the VPLMN region) but requires roaming charging agreements and policy synchronisation.

In Figure 45, the key roaming interfaces are illustrated:

- N1/N2: UE-AMF/NG-RAN (NAS/NGAP),
- N11: AMF-SMF,
- N3: gNB-UPF (GTP-U),
- N4: SMF-UPF (PFCP),
- N6: UPF-DN,
- N9: Inter-PLMN UPF-UPF user plane (HR data path),
- N32: Inter-PLMN security (SEPP to SEPP), including PRINS (protected inter-PLMN signalling),
- SBA interfaces (Namf/Nsmf/Npcf/Nudm/Nausf/Nnrf etc.) over HTTP/2 with TLS and OAuth2-based authorisation.

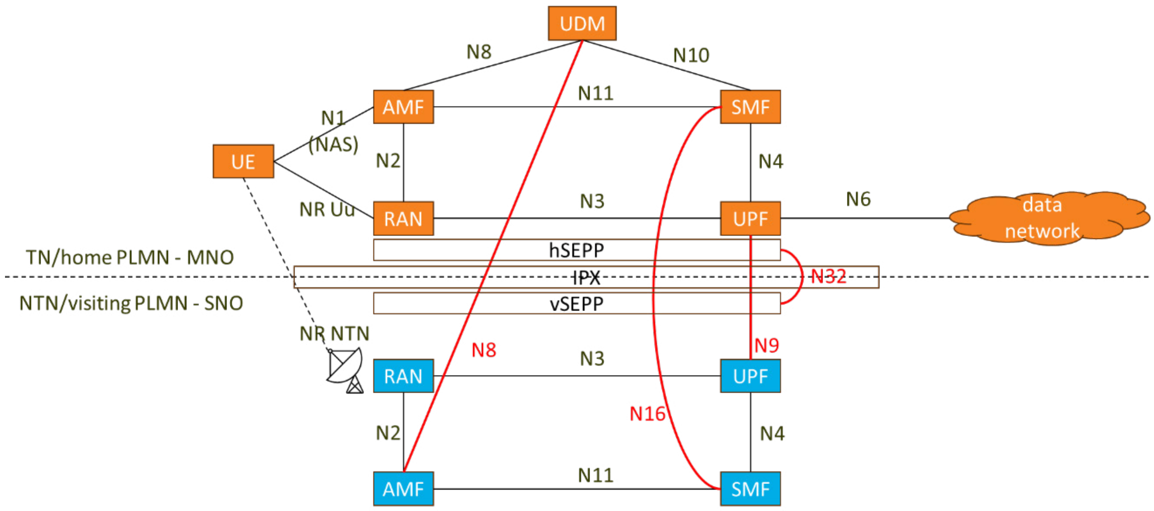


Figure 45 5G-5G roaming

The implementation of N14 (hAMF - vAMF) interface helps to improve inter-PLMN mobility.

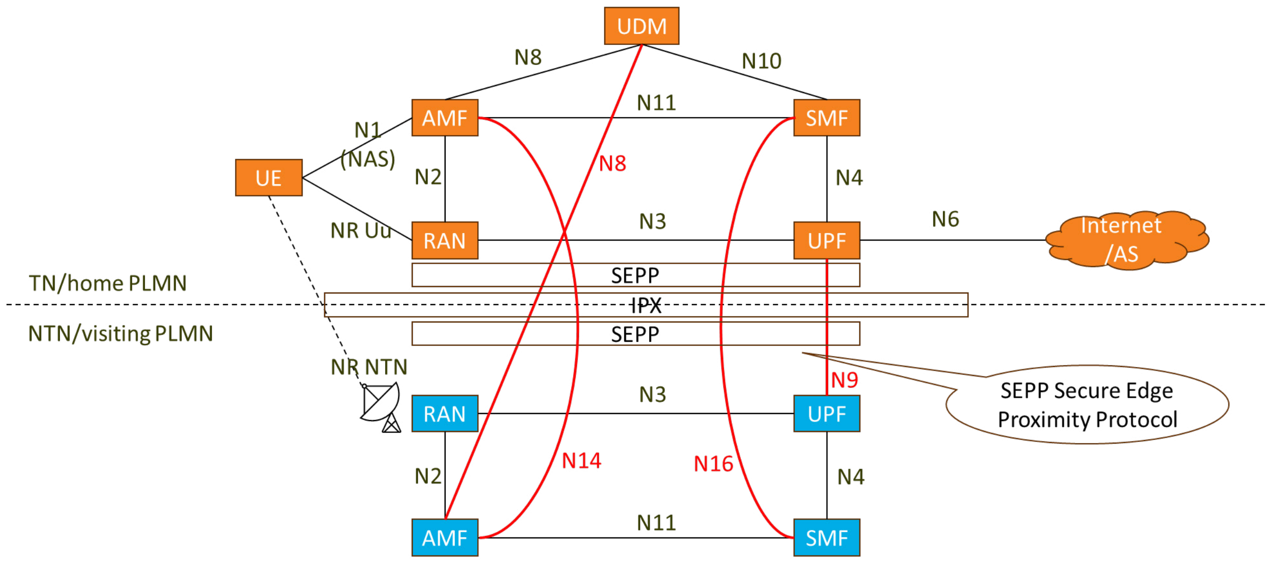


Figure 46 5G-5G roaming (enhanced with N14)

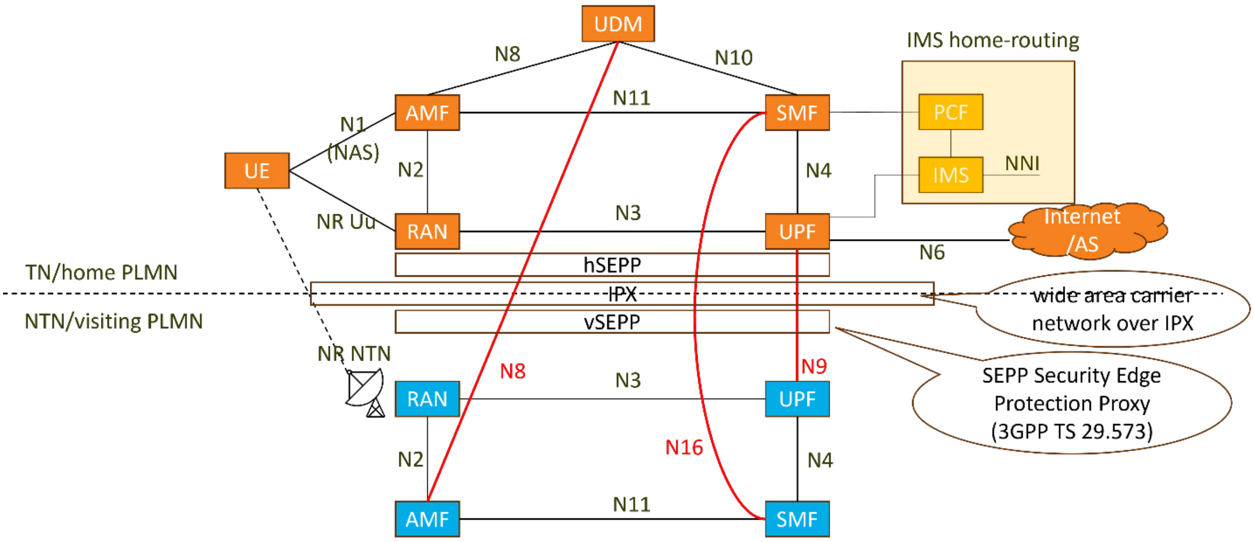


Figure 47 5G SA IMS roaming (IMS home-routing N9HR)

In principle IMS (IP Multimedia Subsystem) can be considered as an own data network, i.e., 5GC routes IMS traffic with dedicated PDU sessions. IMS roaming technically is not different from data roaming but roaming restriction control at H-PLMN may prevent the access to IMS. Hence, in addition to 5G roaming agreements between network operators additional IMS/voice roaming agreements might be needed.

6.2.3 Roaming between 4G-5G networks

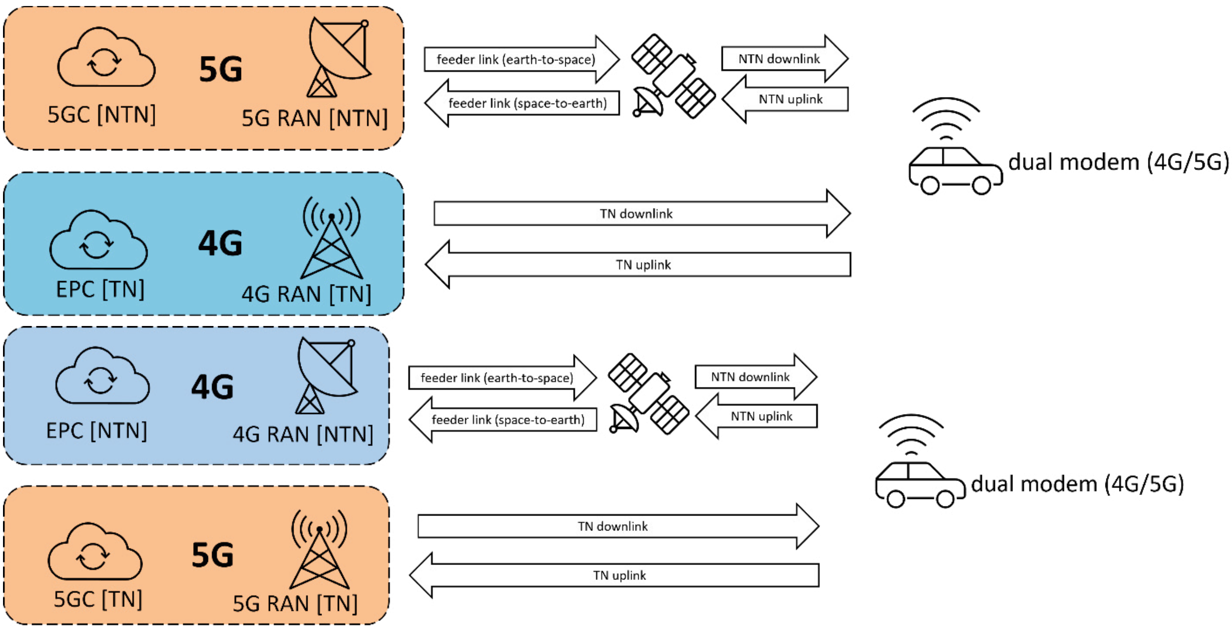


Figure 48 4G-5G roaming scenarios

If one out of the two networks is based on an EPC (which might be the case for a 5G NSA network or for a 4G/LTE network) then EPS interworking is required for roaming:

- For mixed LTE/NR coverage, interworking with EPC via N26 interface supports seamless mobility and EPS fallback for voice, when VoNR is not feasible.
- It avoids IP address change across 4G/5G mobility, which is essential for IMS bearer continuity.

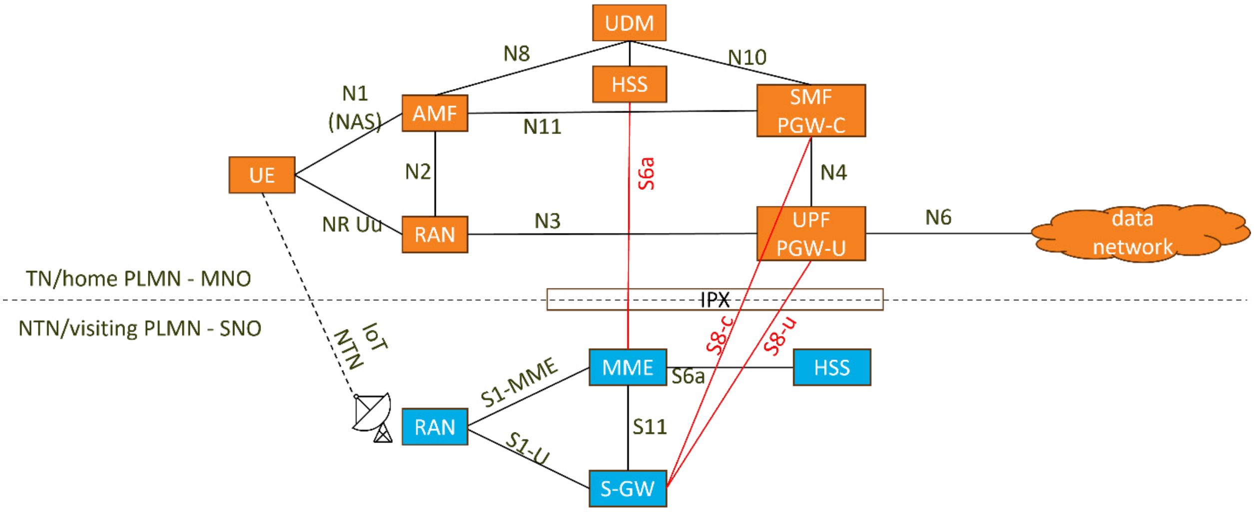


Figure 49 5G (NSA)-4G roaming

A potential enhancement, which enables handovers with a simultaneous MME change, can be realized by implementation of the S10 interface, as illustrated below:

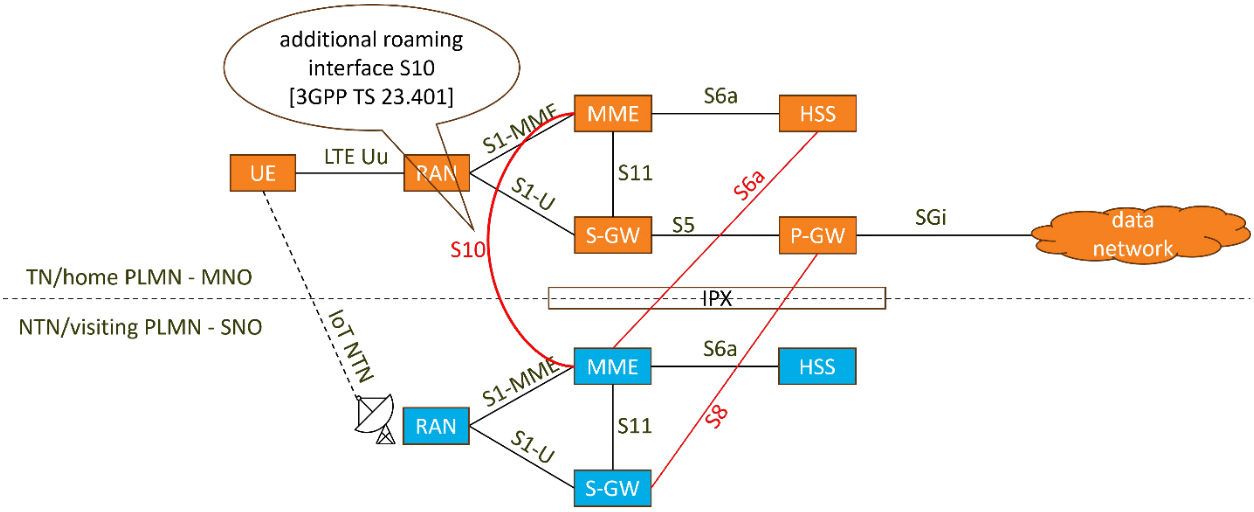


Figure 50 4G roaming (enhanced home-routing with MME interface)

6.2.4 Voice roaming

6.2.4.1 IMS (VoLTE/VoNR)

Typically, IMS/voice roaming is more prone for malfunction compared to pure data roaming. In principle, roaming for IMS/voice requires a separate contractual agreement that needs to include IMS/voice specifically and the set-up of technical prerequisites. Both 5G SA data and IMS voice roaming need to be supported so that a device can connect to the 5GC. Without 5GC/EPC interworking a connection switch between LTE and 5G will cause IP address change, which is not allowed for IMS voice. Without the 5GC/EPC interworking arrangement and corresponding roaming interfaces (N26 ensures continuity between EPS and 5GS for handovers and direct data forwarding), a switch between a 4G and a 5G network will necessitate an IP address change, which is detrimental for IMS bearer continuity. The corresponding voice roaming options are EPS fallback and VoNR.

6.2.4.2 Non-IP data delivery (NIDD)

Non-IDD-based solutions are feasible, e.g., using dedicated APIs as demonstrated in [Sec. 7.4]. However, due to its significant limitations regarding real-time call and session continuity, it is rather considered as a complementary fallback solution (e.g., for messaging or emergency communications).

6.3 Review of NTN mobility management in 3GPP

With respect to mobility, NTN differs from TN in that the satellites, carrying at least part of the base stations, can be moving, e.g. in low-earth orbit satellite constellations. Therefore, NTN mobility management in 3GPP needs to not only handle challenges like variable propagation delays, weak signals and minimal power variation between serving and neighbouring cells (which can cause ping-pong effects) but also provide solutions to prevent signalling bursts and massive amounts of handover events caused by the satellites' movements.

Since 3GPP NTN considers different technologies – namely, NB-IoT, LTE-M, and NR – the mobility solutions must address these technologies comprehensively. The following sections describe the main aspects of mobility management for NTN as introduced in Release 17 and beyond.

6.3.1 NTN network management aspects

3GPP NTN supports both earth-moving and earth-fixed cells. In the former variant, beams are fixed with respect to the satellite, and thus the cells on the ground will move along with the satellite, sweeping earth's surface. In the latter variant, the satellite continuously steers the spot beams towards a fixed area on the planet for as long as possible.

In both LTE (LTE-M and NB-IoT) and NR networks, cells are geographically grouped into tracking areas (TA). In NR, TAs are grouped further into registration areas (RA). UEs are required to inform the network whenever they cross the boundary of such an area. This procedure is known as a tracking area update (TAU) for LTE-M and NB-IoT, or a registration update for NR and ensures the network knows the set of cells in which a UE is reachable.

To avoid frequent TAUs or registration updates and the associated signalling overhead, 3GPP decided to keep TAs geographically fixed, even for earth-moving cells. For the satellite, however, this means that it must update its tracking area code (TAC) as it moves over different geographical areas, as shown in Figure 51. A key advantage of this approach is that it requires no implementation changes on the UE. Furthermore, registration updates and TAUs are triggered mainly by the UE's own movements, rather than those of the satellites. Notably, this mobility management solution is applicable to all considered NTN technologies.

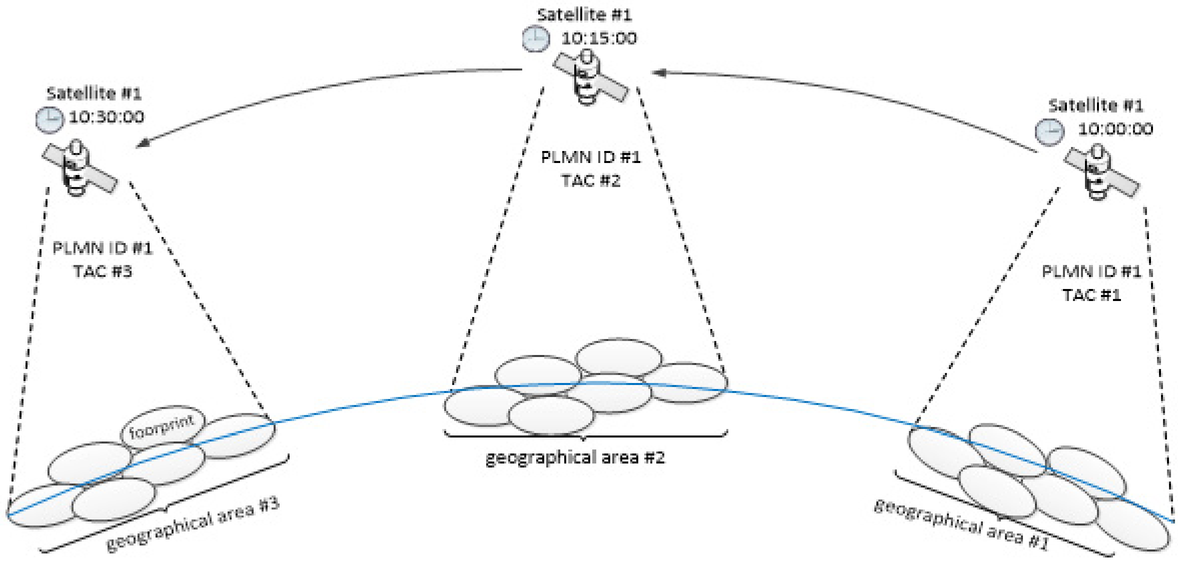


Figure 51 Tracking area code (TAC) update for earth-fixed TAs and moving satellites [10]

Another key aspect of satellite mobility is the feeder link switchover, which occurs when a satellite changes its connecting ground station and, for a transparent architecture, its gNB. In this scenario, the served UEs must be transferred from the outgoing to the incoming gNB. If the satellite cannot maintain simultaneous feeder link connections, a *hard switchover* occurs, resulting in a temporary service outage for the UEs. However, if the satellite supports simultaneous connections to both ground stations, it can perform a *soft switchover* without service interruptions.

6.3.2 NTN mobility enhancements

The mobility management mechanisms depend on the UE state, with distinct procedures and NTN-related enhancements for RRC_CONNECTED and RRC_IDLE/RRC_INACTIVE states.

6.3.2.1 Mobility in RRC_CONNECTED state

In RRC_CONNECTED state, UE mobility is controlled by the network. The primary mobility procedure in TN is that the serving cell can command a handover (HO) to a target cell based on UE measurement reports. An alternative is conditional handover (CHO), where the UE can execute the HO directly, once a condition configured by the network is fulfilled.

While all legacy mobility algorithms (based on measurements of serving and neighbour cell signal strength) are still available for NTN, some dedicated enhancements have been specified. This includes, in particular, new trigger conditions for CHO based on time and location. The location-based trigger uses the distance between the UE and defined reference points for both the serving and neighbouring cells. This allows the handover to be initiated when the UE moves closer to the neighbouring cell. The time-based trigger utilises the satellite's predictable movement to initiate HO from a departing satellite to an incoming one; this ensures it can be completed before the connection to the serving cell is lost.

RACH-less HO, introduced in Rel-18 with NTN scenarios in mind, offers a faster HO procedure with less interruption to the data connection. However, it requires the timing advance for the target cell to be known *a priori*. In addition, the target cell needs to reserve resources for the incoming UE. The main scenario for RACH-less HO in NTN is satellite switching of an earth-fixed cell from one satellite to another. In this scenario, neither of the aforementioned requirements poses a challenge because the target cell is completely empty, and the UE can calculate the target cell's timing advance with sufficient accuracy. This calculation is based on the new satellite's ephemeris and the common timing advance parameters included in the HO command. RACH-less HO can be combined with the time-based CHO described above.

In NGSO deployments, the continuous movement of satellites causes frequent handovers, even for stationary UEs. While enhancements like CHO or RACH-less HO can mitigate congestion when handing over large numbers of UEs, the signalling overhead remains high, and UEs still suffer from interruption due to frequent HO. One way to further reduce this signalling overhead is to use the same physical cell ID (PCI) before and after the satellite switch. In this case, the serving cell does not change, and L3 mobility is not required. However, the new satellite is always associated with a different propagation delay and Doppler shift, meaning the UE must adapt its pre-compensation. Consequently, this process cannot be made fully transparent. In Rel-18, 3GPP specified the necessary methods for the network to inform the UE about an upcoming switch with an unchanged PCI and how to adapt its pre-compensation. This feature is known as 'satellite switch with resynchronisation'.

While all the mobility features described above can, in principle, also be used between TN and NTN, this assumes that both are 5G NR networks. However, mobility from an LTE TN to an NR NTN is arguably a more important scenario, as rural areas bordering NTN coverage zones often have only LTE coverage. Thus, the possibility to provide information about NR NTN neighbouring cells has been added to terrestrial LTE networks, as well. NB-IoT does not support mobility in RRC_CONNECTED mode.

6.3.2.2 Mobility in RRC_IDLE/RRC_INACTIVE state

The gNB may release UEs to RRC_IDLE or RRC_INACTIVE (NR only) states after a period of traffic inactivity. While in these states, the UE camps on the strongest cell and monitors both TN and NTN cells. If a neighbouring cell offers a better signal strength than the current serving cell, the UE performs cell reselection.

Even here, NTN-specific enhancements based on location and time have been defined. For example, the network can provide UEs with a time value indicating when the serving satellite will stop covering the current area. The UE shall start neighbour cell measurements before this time expires. In addition, a UE can relax neighbour cell measurements when it is deep within a large NTN cell, which is communicated to the

UE in the form of a distance threshold from a reference location.

Similarly, to reduce the number of unnecessary measurements of TN neighbour cells, and thus improve UE energy consumption, a solution has been specified to provide a rough approximation of the geographical area where the UE can expect TN coverage. This is achieved by using a list of (possibly overlapping) circular areas, each defined by its centre location and radius. Outside of this area, a UE is not required to perform TN neighbour cell measurements.

6.4 Cross-border roaming trials in terrestrial networks

Mobility between TN and NTN operated by different MNOs is in many respects very similar to terrestrial mobility across country borders, which has been studied in the EU-funded projects 5GCroCo [11], 5G-ROUTES [12], and 5G-MOBIX [13]. In particular, in the context of the 5GCroCo project, inter-PLMN handovers across country borders have been implemented and tested. Inter-PLMN HO were already included in the 4G requirements defined by 3GPP SA1 in 2006 (*"It shall be possible to support inter-PLMN handover with seamless service continuity within a 3GPP specified access system"* [14]). For 4G (and 5G NSA), inter-PLMN HOs have been specified by defining the inter-MME interface S10 and making it available between different MNOs (see figure below). The S10 interface allows HOs with a simultaneous MME change. Different from inter-MME HOs within the same PLMN, forwarding misrouted data via the S8 interface is not supported during inter-PLMN HOs. This rarely affects more than a few packets, however. Another difference is that UEs will usually not measure cells from other PLMNs. Since there is also no X2 interface available between neighbour cells in different PLMNs, some manual configuration is needed to ensure that the base stations along the border configure the appropriate neighbour cell measurements to the UEs.

Inter-PLMN HOs were implemented and trialled in the 5GCroCo project, and it was found that they are technically feasible and achieve service interruption times as low as 120 ms, compared to interruption times of 730 ms and much more with other solutions like release-with-redirect. Despite these tests and trials, inter-PLMN HOs are not widely deployed in commercial set-ups. One possible reason is scalability: the trials considered one MNO on each side of the border. In a commercial reality, at three-country intersections there could be >10 MNOs involved, resulting in significant organisational challenges in order to share cell IDs and frequencies, and establish S10 interfaces between the involved players.

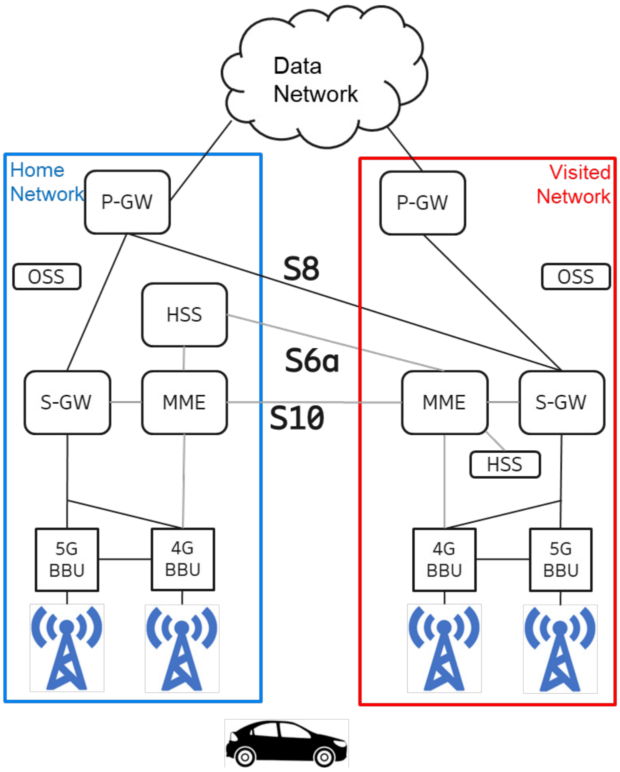


Figure 52 Architecture for Inter-PLMN HO as implemented and trialled in the 5GCroCo [11] project

6.5 Subscriber and SIM management for NTN-TN

Subscriber and SIM management is a critical architectural pillar for the integration of non-terrestrial networks with terrestrial networks in automotive connectivity. Vehicles are globally mobile with long-lived endpoints that must maintain service continuity, regulatory compliance and operational predictability while seamlessly transitioning between cellular and satellite access in future.

This section proposes a standards-based subscriber and SIM management framework for NTN-TN, aligned with:

- 3GPP roaming and interworking principles, such as GSMA eSIM architectures (M2M, consumer, IoT)
- Automotive requirements for lifecycle control, regulatory compliance, and global scalability

The focus is on how subscriber identity, authentication, authorisation, and the profile lifecycle can be managed consistently across TN and NTN, rather than on specific commercial implementations.

6.5.1 Automotive subscriber management requirements

From an automotive perspective, subscriber and SIM management must support:

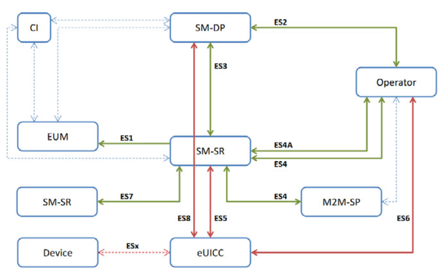
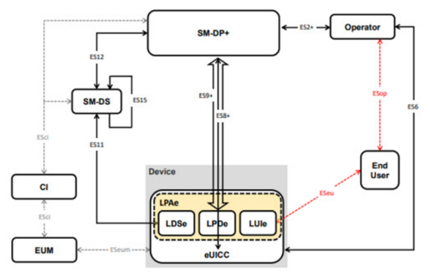
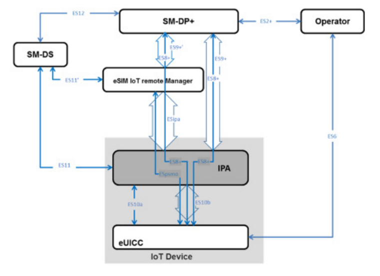
- Long lifecycle (10-20 years) with multiple potential operator changes,
- Cross-border and cross-access mobility (TN ↔ NTN),
- Regulatory adaptation (permanent roaming restrictions, localisation),
- Always-on reachability for safety, OTA, and fleet services,
- No user interaction (headless devices).

These requirements differ significantly from consumer smartphones and directly influence the choice of SIM architecture and subscriber management model.

6.5.2 Relevant GSMA eSIM architectures for remote subscription management (RSP)

Based on GSMA public specifications, three eSIM architectures are relevant: SGP.02 [15], SGP.22 [16], SGP.32 [17].

Table 15 Overview and differences of different eSIM architectures

<table>
<tr><th>M2M Architecture – SGP.02</th><th>Consumer Architecture – SGP.22</th><th>IoT Architecture – SGP.32</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>▸ Centralised control via SM-SR
▸ Profiles are pushed to the eUICC
▸ Well established in automotive
▸ Strong lifecycle and fleet control
▸ Higher complexity and integration overhead</td><td>▸ Pull-based profile download via SM-DP+
▸ Activation code driven
▸ Designed for user-centric devices
▸ Limited suitability for unattended vehicles</td><td>▸ Extension of consumer architecture for IoT
▸ Introduces eIM (eSIM IoT remote manager)
▸ Retains pull-based model
▸ Designed for headless devices and automation
▸ Emerging ecosystem and adoption</td></tr>
</table>

These architectures are publicly defined by GSMA and independent of vendor implementation. A key distinction impacting subscriber management is the profile delivery model, as described below.

Table 16 Overview of differences in profile delivery

Aspect	M2M (SGP.02)	IoT / Consumer (SGP.32 / SGP.22)
Profile delivery	Push (network-initiated)	Pull (device-initiated)
Central orchestration	Yes (SM-SR)	No
Scalability in Automotive	Proven	Emerging

These standards enable the provisioning and lifecycle management of multiple SIM profiles in accordance with automotive requirements, including long operational lifecycles, regulatory compliance, always-on connectivity, and unattended SIM activation.

Across all GSMA remote SIM provisioning variants (SGP.02, SGP.22, and SGP.32), switching an active SIM profile from MNO-A to MNO-B typically requires a managed procedure on the order of minutes to tens of minutes – depending on architecture, network conditions and security handshakes – and, as such, these technologies are designed for lifecycle and regulatory management rather than for real-time or seamless TN ↔ NTN mobility support.

Table 17 Comparison of different architectures

Dimension	Based on Roaming integration (TN ↔ NTN)	SGP.02 (M2M RSP)	SGP.22 (Consumer RSP)	SGP.32 (IoT RSP)
Primary design intent	Real-time access continuity while moving between TN and NTN	Lifecycle & fleet SIM management	User-driven subscription change	Headless IoT lifecycle management
Typical procedure trigger	Network-initiated handover / fallback	Backend-initiated profile change	User / application-initiated pull	Backend-assisted pull via eSIM
Typical RSP execution time	Sub-second to few seconds	Minutes to tens of minutes	Minutes	Minutes
Determinism of timing	Highly deterministic and predictable	Low (depends on backend sequencing, retries, reachability)	Low (user/app/device dependent)	Low to medium (device reachability dependent)
Service interruption during procedure	None or minimal (make-before-break or break-before-make)	Yes (profile disable / enable cycle)	Yes (profile swap requires re-registration)	Yes (profile swap requires re-registration)
IP session continuity	Required (no IP change or fast re-anchoring)	Not supported	Not supported	Not supported
IMS / voice continuity	Required for safety and telephony services	Not supported	Not supported	Not supported
Suitable for fast fallback (TN → NTN)	Yes (mobility procedures)	No	No	No
Suitable for fast recovery (NTN → TN)	Yes (mobility procedures)	No	No	No
Designed for unattended execution	Yes	Yes	No (consumer-centric)	Yes
Scalability for mass mobility events	Required (many vehicles simultaneously)	Not designed for simultaneous mobility	Not designed for mobility	Not designed for mobility
Role in NTN-TN architecture	Access-level mobility mechanism	Long-term profile selection	Subscription management	Long-term profile and regulation management
Conclusion vs. TN ↔ NTN mobility	✓ support of TN <-> NTN mobility	X Not suitable	X Not suitable	X Not suitable

6.5.3 Subscriber identity and PLMN strategy for TN <-> NTN mobility

As per 3GPP standardisation, the promise of NTN is to leverage the same infrastructure (modems and antennas) and provide access to cellular and non-terrestrial networks. To achieve that, different techniques with regards to the network operator access via SIMs can be considered:

- Dedicated SIM profile per access technology – TN & NTN,
- Single SIM profile that supports TN and NTN in parallel.

As per current status of GSMA RSP standardisation, only the consumer (SGP.22) standards support multiple enabled profiles (MEP) for switching between different parallel activated SIM profiles at the same eUICC in order to support a scenario of dedicated SIMs per access technology (cellular and satellite). At the same time, this standard is designed with a user-centric approach that has limitations when adapted to automotive connectivity needs.

Therefore, the most efficient approach to support mobility between terrestrial and non-terrestrial networks is based on a single SIM profile, where both TN and NTN access are provided either through a dedicated NTN PLMN or via roaming onto an NTN PLMN under the same subscription. This model builds directly on established 3GPP roaming concepts described in this report, allowing TN and NTN to be treated as complementary 3GPP access networks rather than distinct connectivity domains. By maintaining a single subscriber identity, this approach maximises interoperability with existing cellular ecosystems, minimises complexity at the vehicle level, and aligns with the long-term vision of NTN as an extension of 3GPP-compliant mobile networks rather than a parallel or proprietary solution.

The IMSI remains constant for a given active profile, ensuring authentication (AKA / 5G-AKA), policy control, charging, and service exposure remain anchored in the HPLMN, irrespective of whether access is provided by TN or NTN. This is consistent with established roaming concepts described earlier.

6.6 Deployment aspects and options in 5G/ NR network sharing

6.6.1 MOCN and MORAN

Multi-operator core network (MOCN) [18]

In MOCN, multiple operators share the RAN infrastructure, including the radio access (BBU/DU/RU, spectrum), while each operator maintains its own independent core network (CN). The shared RAN broadcasts multiple public land mobile network IDs simultaneously via the same cell(s). UEs detect all broadcast PLMNs and select/register with their home operator's core network through the shared gNB/eNB.

Key mechanisms:

- The gNB broadcasts up to 12 PLMN IDs in SIB1.
- Spectrum can be shared (same carriers) or split per operator.
- Each operator's traffic is tunnelled separately to its own AMF/SMF/UPF via separate NG interfaces.
- The RAN scheduler must enforce per-operator resource partitioning (static, semi-static, or dynamic).
- Network slicing (S-NSSAI) can further segment traffic per operator per slice.

Typical use case: National roaming agreements, rural coverage sharing, greenfield 5G rollouts where CAPEX reduction is critical.

Multi-operator radio access network (MORAN) [18]

In MORAN, multiple operators share only the passive and active RAN hardware (sites, antennas, BBUs), but each operator retains its own dedicated radio carriers/frequencies and its own CN. Unlike MOCN, there is no spectrum sharing, each operator uses its own licensed spectrum on the shared physical infrastructure.

Key mechanisms:

- Each operator's cells broadcast only their own PLMN ID.
- Logically separated radio resources per operator on shared hardware.
- Operators are isolated at both the radio and core levels.
- Coordination is limited to physical site and hardware sharing (power, shelter, antennas, backhaul infrastructure).
- Each operator controls its own RRM, scheduling, and QoS independently.

Typical use case: Tower/mast sharing between operators who are unwilling to share spectrum or RAN management, common in mature markets with regulatory spectrum ownership constraints.

Table 18 Pros and cons of MOCN and MORAN

Dimension	**MOCN**		**MORAN**	
	Pros	**Cons**	**Pros**	**Cons**
CAPEX savings	Very high – shared spectrum, antennas, BBU, sites	Requires complex multi-operator scheduling agreements	Moderate – shared hardware/sites only	Lower savings vs. MOCN; each operator deploys own carriers
OPEX savings	High – shared network operations and maintenance	Inter-operator SLA management adds overhead	Moderate – shared site O&M	Each operator manages its own RAN separately
Spectrum efficiency	High – pooled spectrum gains via statistical multiplexing across operators	Complex dynamic resource partitioning; risk of unfair allocation	Standard per-operator efficiency	No spectrum pooling; dedicated carriers may sit underutilised

Operator independence	/	Lower; dependent on shared RAN scheduling policies	High – full control of own spectrum and RRM	Site access still depends on sharing agreement
QoS / SLA control	Possible via slice-aware scheduling	Harder to enforce strict per-operator KPIs	Strong – each operator controls own scheduler	/
Security isolation	Core networks fully separate	RAN-level side-channel risks; shared scheduler exposure	Full radio + core isolation	/
Regulatory complexity	/	Spectrum sharing requires national regulatory approval	Lower – spectrum ownership unchanged	Each operator must retain full spectrum license
Deployment complexity	/	High – requires multi-PLMN coordination, NG interface per operator, shared O&M SLAs	Low to moderate; standard deployment per operator	Site acquisition simplified but RF planning still per-operator
Handover / Mobility	Seamless within shared RAN	PLMN selection conflicts possible at cell edge	Standard per-operator mobility	Inter-operator handovers require standard roaming/X2
5G / Network slicing	Naturally aligned with S-NSSAI per operator	Slice-level isolation across operators still evolving	Compatible	Less synergy with shared slicing
Scalability	Scales well in dense urban sharing	Scheduler complexity grows with operator count	Scales independently per operator	Spectral scalability limited by per-operator carrier plan

6.6.2 Single operator (single core) with two separate RANs

One possible tight integration of TN and NTN networks can be realised, if their carriers are operating on the same core network with a single PLMN. In this case, a user device only needs a single-SIM (as there is just a single operator from the device's perspective), as illustrated in the figure below.

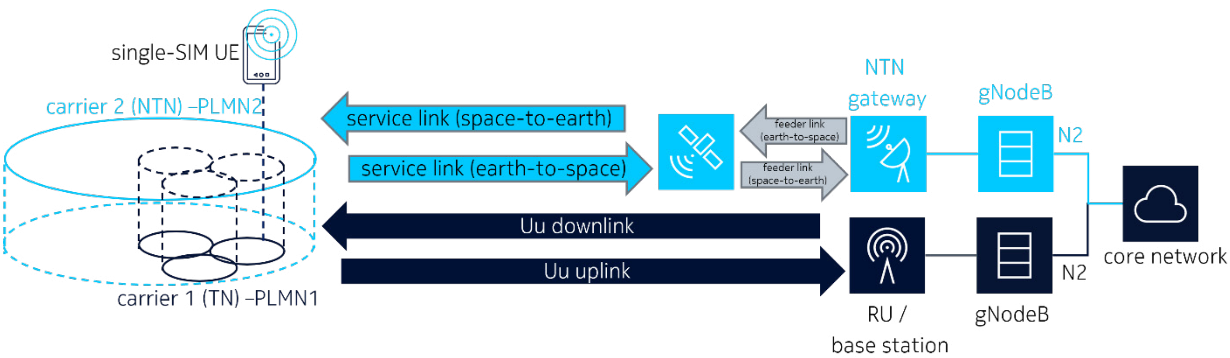


Figure 53 Single operator (single core) with two separate RANs

7 Demonstrations of car-integrated satellite connectivity

7.1 Introduction

The ongoing digitalisation of vehicles requires reliable, always-on connectivity – even beyond the coverage of terrestrial mobile networks. Non-terrestrial networks, particularly satellite-based communication systems, represent a key technological enabler in this context. By complementing existing cellular infrastructure, NTN enables near-global connectivity, especially in rural, remote and infrastructure-limited areas.

In the automotive domain, NTN significantly enhances safety, service availability, and overall user experience. Safety-critical applications, such as emergency call systems and hazard warnings, benefit in particular from increased coverage and built-in redundancy. At the same time, the integration of NTN into hybrid communication architectures – combining terrestrial networks and satellite connectivity – opens new possibilities for seamless connectivity and robust system design.

The demonstrations presented in Paris by 5GAA highlight the maturity and practical feasibility of these technologies. They focus particularly on safety-relevant applications that ensure reliable communication even in scenarios where terrestrial network coverage is unavailable.

7.2 Overview of the NTN demonstrations

The showcased NTN demonstrations cover a broad range of satellite-enabled automotive communication scenarios, with a strong focus on safety applications, network interoperability, and system performance.

A central use case demonstrates the value of NTN for automotive safety applications. It shows how vehicles can reliably transmit emergency alerts to response services even in areas without terrestrial network coverage. In addition, regional hazard warnings, such as severe weather alerts, are transmitted from backend systems directly to vehicles, enabling early risk mitigation and enhanced situational awareness for drivers.

Another key focus is the seamless integration of terrestrial and non-terrestrial networks. A vehicle-based telematics control unit demonstrates dynamic switching between TN and NTN without service interruption. The demonstration includes real-world driving scenarios in public traffic and highlights the use of voice and assistant services over satellite connectivity, alongside real-time monitoring of performance metrics to ensure stable and reliable communication.

The bi-directional emergency messaging via NB-NTN compliant with 3GPP Release 17 represents another important aspect. A production-ready telematics system is used to demonstrate how emergency messages can be transmitted via satellite when terrestrial networks are unavailable, ensuring reliable communication in critical situations.

In addition, the role of NTN in the context of the next-generation eCall (NG eCall) is highlighted. The ability to establish emergency calls via satellite connectivity to public safety answering points represents a significant step towards a resilient and ubiquitous emergency communication infrastructure, independent of local network conditions.

Another demonstration focuses on the performance evaluation and system analysis of NTN connectivity. Based on field measurements across different network configurations, key performance indicators such as latency, availability and handover behaviour are assessed, providing valuable insights for large-scale deployment and integration into production vehicles.

Lastly, the interoperability and testing of NTN-capable devices are addressed. Using specialised test systems, seamless transitions between NTN and TN are validated under realistic conditions, including demanding use cases such as in-vehicle video communication. This demonstrates the technology's potential to further enhance both connectivity and user experience.

Overall, the seven demonstrations clearly illustrate that NTN technologies are a critical enabler for resilient, globally available vehicle connectivity and deliver immediate value, particularly in the domain of automotive safety.

7.3 Showcase of NTN safety use cases

7.3.1 Objectives

This demonstration by BMW, DT, Jember, Skylo, Viasat and Anritsu demonstrates NTN connectivity following the road map of the automotive use cases defined by the 5GAA. The architecture leverages satellite-based communication to enable critical vehicle-to-network (V2N) services in scenarios where terrestrial coverage may be limited or unavailable.

The project highlights the following key aspects:

- NTN connectivity in the automotive sector: a collaborative effort bringing together Skylo, Viasat and Deutsche Telekom to validate satellite-based communication for connected vehicles.
- Deep integration of NB IoT NTN in the vehicle: the solution incorporates NB IoT NTN communications components directly into the vehicle architecture, demonstrating a path towards future production implementations.
- Communication from the BE to the vehicle to receive safety-related messages: local hazard warning, traffic administration in disaster situations.
- Communication from the vehicle to the BE by sending an MSD emergency message.
- Live demonstration of safety use cases delivering real-world validation of safety-critical automotive scenarios over satellite connectivity.
- In depth KPI network analysis, thanks to Anritsu's participation, the project

includes comprehensive performance measurement and analysis to characterise network behaviour under realistic conditions.

7.3.2 Technical set-up

The demonstration addresses the following safety automotive use-cases:

Emergency message: Enables vehicles to transmit emergency notifications via satellite when terrestrial networks are unavailable, ensuring critical alerts reach emergency services regardless of location.

Local hazard warning: Supports the dissemination of localised hazard information to vehicles in affected areas, improving driver awareness and road safety.

Traffic management in disaster situations: Provides notification capabilities to vehicles in affected areas, improving driver awareness and road safety.

The end-to-end architecture integrates contributions from multiple partners across distinct functional domains:

Core network: Deutsche Telekom provides the mobile core network infrastructure and SIM-cards, enabling device authentication and connectivity management.

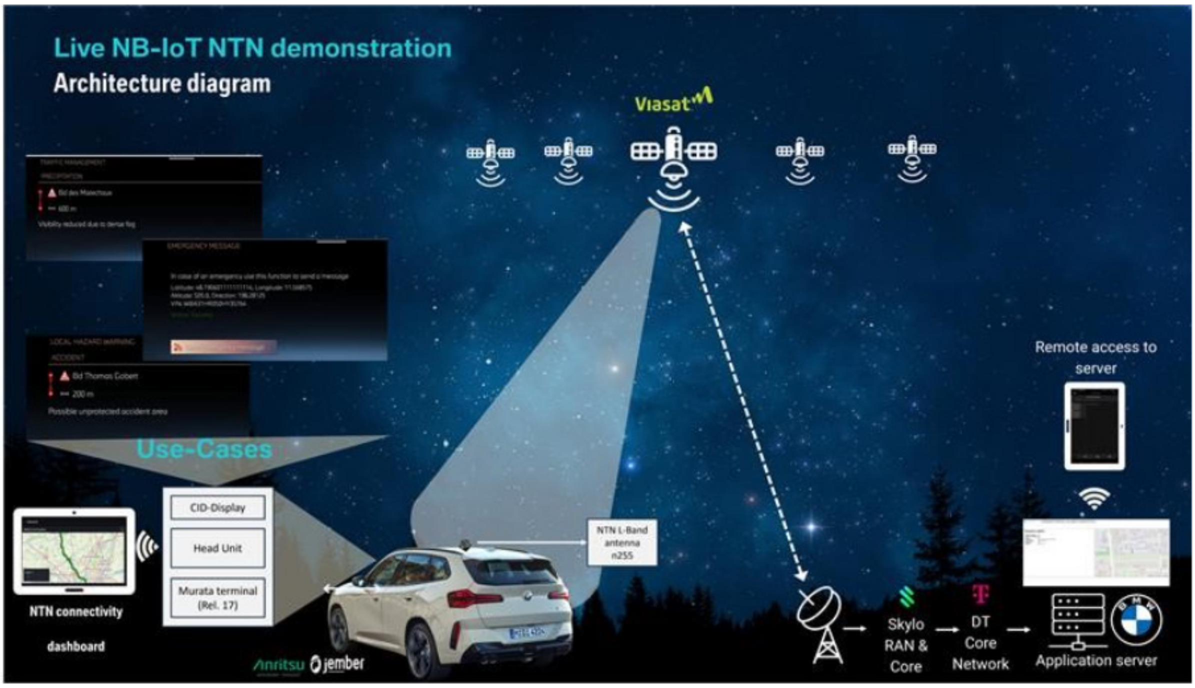
Radio access network (RAN): Skylo delivers the NTN RAN components, bridging the satellite link to the core network.

Satellite segment: Viasat operates geostationary (GEO) satellite infrastructure utilising L-band spectrum for the space-to-ground communication link. The GEO orbit at approximately 35,786 Km altitude provides continuous coverage but introduces inherent propagation delay.

Vehicle integration and application layer: BMW leads the selection of use cases and with the support of Jember the definition and monitoring of KPIs is realised as well as the implementation of the application within an integrated vehicle solution.

KPI analysis: Anritsu conducts extended analysis of network performance metrics to validate system behaviour and compliance with use-case requirements.

7.3.3 Architecture considerations



The application layer follows a client server model with dedicated hardware for satellite connectivity:

NTN modem: A type 1SC-NTN module provided by Murata, which handles the NTN protocol stack following 3GPP Rel-17 and manages the satellite connectivity.

L-band antenna: Supplied by Kyocera, the antenna is specifically designed for NTN L-band operation (1.6 GHz uplink/1.5 GHz downlink).

Client application (head unit): The in-vehicle application runs on the car's head unit, serving as the user interface and local processing point for all three use cases. It captures events, formats messages, and it communicates with the backend via the NTN link.

Backend (BE) application (server): Hosted at BMW, the server-side application simulates the emergency centre, receiving and processing all incoming emergency messages from the vehicle. In the case of local hazard warnings and traffic management in disaster situations, the BE functions as the entity in charge of disseminating the safety notifications.

Data flow: The message path from the vehicle to backend goes through the following stages:

Uplink flow (vehicle to BE):

- The head unit application generates a use-case message (e.g. emergency message) and encapsulates it in a UDP datagram (179-203 Bytes)
- The NTN modem applies the NTN protocol stack and prepares it for transmission over the satellite link.
- The L-band antenna transmits the signal to the Viasat GEO satellite.
- The satellite relays the signal via feeder link to the ground-based Skylo RAN.

- The RAN forwards the traffic to the Deutsche Telekom core network for routing.
- The core network delivers the message to the BMW backend server, completing the end-to-end path with an approximated target latency of 8-10 seconds.

Downlink flow (BE to vehicle)

The reverse path enables the backend to send safety notifications to the vehicle, following the same chain but in the opposite direction, showing the capability of bi-directional communication.

The system employs a lightweight messaging approach optimised for Narrowband satellite connectivity:

Parameter	Specification
Transport protocol	UDP
Payload size	179-203 Bytes
Expected latency	8-10 seconds

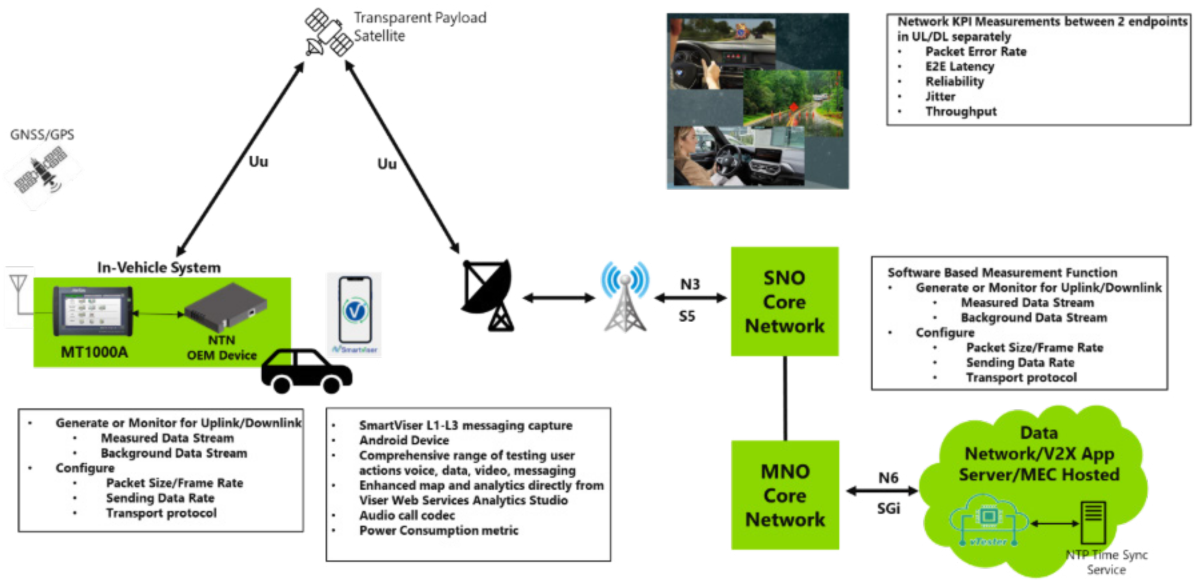
The use of UDP minimises protocol overhead, which is well-suited for the constrained bandwidth of NB IoT NTN links, and it aligns with typical NB IoT transmission unit capabilities. The expected latency reflects the inherent propagation delays of GEO satellites combined with network processing across the full communication chain.

7.3.4 Measurement results

Available data sets

1. Saturday: Connectivity mapping of the area around telecom Paris
    - Highlights on the RSRP values obtained in the measurement campaign
    - Saturday: Connectivity mapping of the BMW-5GAA proposed route
        - Highlights on the RSRP values obtained in the measurement campaign
        - Monday-Friday: Connectivity map + application statistics of the BMW-5GAA proposed route
    - Highlights on the RSRP values obtained in the measurement campaign
    - Summary of the applications triggered and the success status and recorded latency
2. Anritsu's KPIs

Anritsu collected a comprehensive set of KPIs at both the physical (L1) and transport layers to characterise RSRP, SNR, GNSS performance, and uplink/downlink latency. The high-level test architecture is illustrated below.

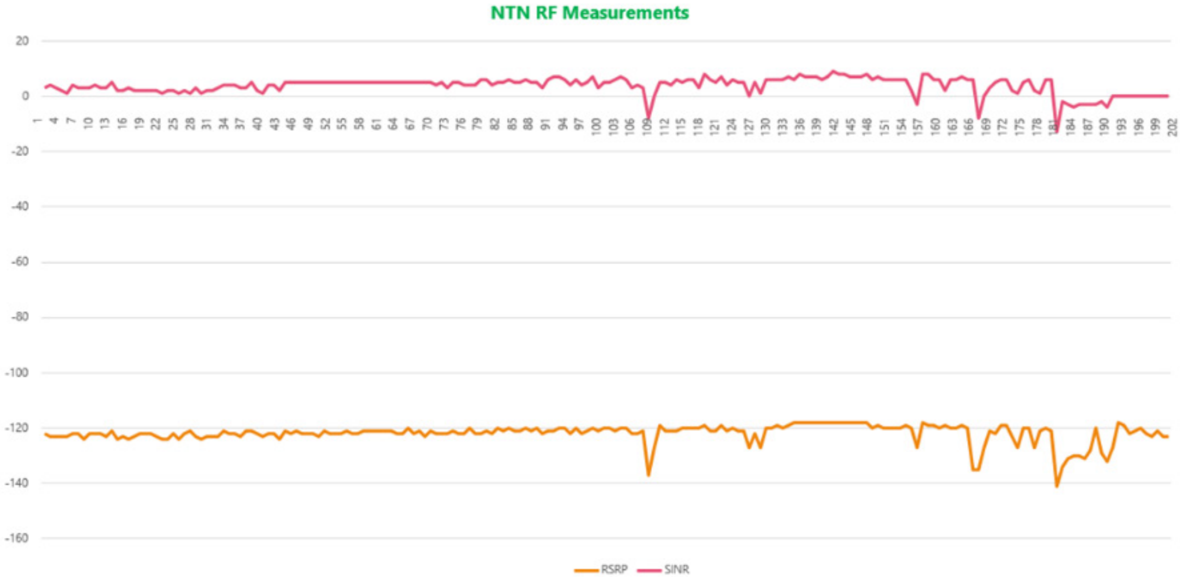


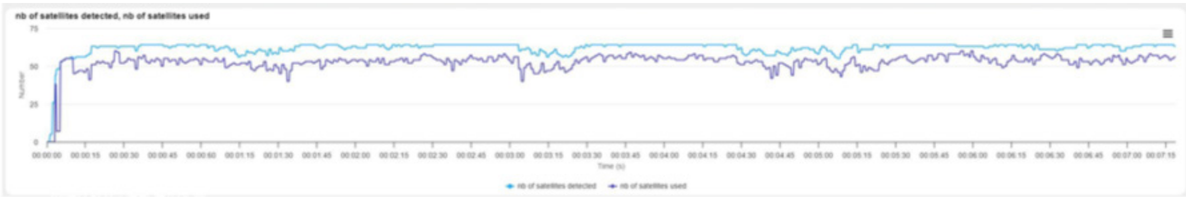
In the test vehicle operating in Paris, Anritsu's Network Master Pro MT1000A was directly interfaced with the TCU module. The MT1000A served as the primary transport-layer test instrument, enabling configuration of multiple packet profiles, traffic generation, and independent UL/DL performance measurements, as shown in the diagram.

At the other end of the network side in Munich, a virtual network master (VNM) – software-based equivalent of the MT1000A – was deployed on the BMW application server. The MT1000A and VNM together formed the end-to-end test pair, enabling accurate measurement of transport KPIs including latency, jitter, packet loss, and throughput for both uplink and downlink paths.

In parallel, SmartViser software running on an Android device captured L1-L3 KPIs, including RF metrics and GNSS quality indicators.

The SmartViser output below summarises RF and GNSS performance recorded along the test route.

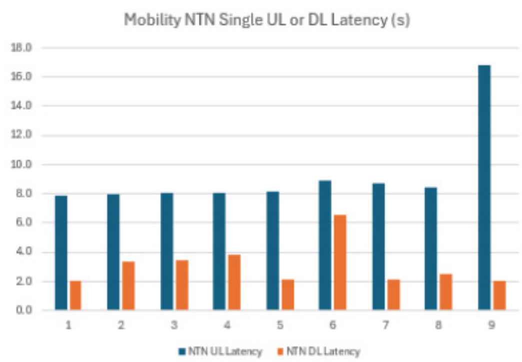




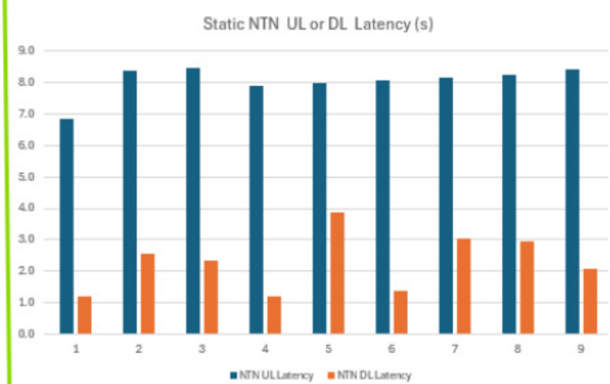
The RSRP of the received satellite signal remained largely stable around -121 dBm, with several segments dipping toward -138 dBm, approaching the TCU's sensitivity threshold.

The GNSS trace shows discrepancies between the number of satellites detected and those successfully demodulated. Such gaps can directly affect message reliability and may contribute to increased UE processing load and power consumption.

The below charts present minimum, average and maximum uplink and downlink latencies measured during both drive-test (mobile) and stationary conditions.



Latency	Average (s)	Min (s)	Max (s)
DL	3.1	2.1	6.6
UL	8.9	7.9	16.8

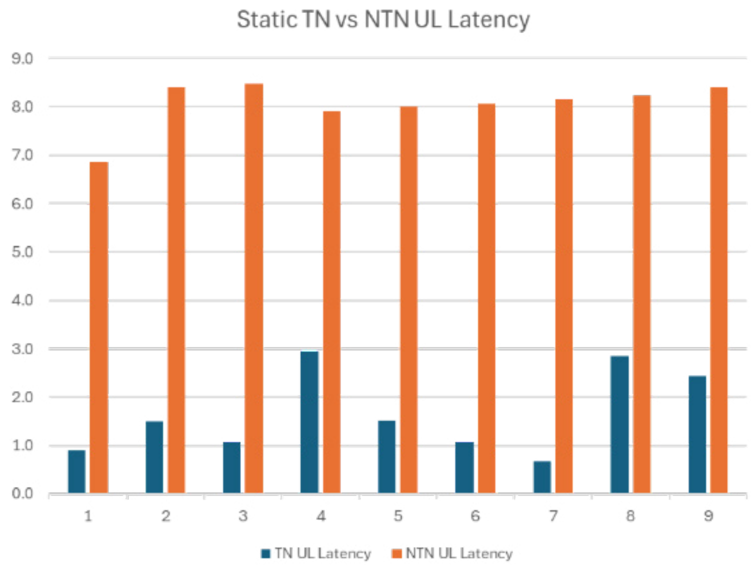


Latency	Average (s)	Min (s)	Max (s)
DL	2.3	1.2	3.9
UL	8.1	6.9	8.5

Mobile scenario (left chart): During the mobility phase, uplink latency was consistently higher than downlink latency – typically 3X greater – driven by satellite UL scheduling behaviour, repetition schemes and extended propagation distance. Several UL samples showed extreme spikes, reaching 16.8 s, indicating sporadic access or scheduling delays.

Stationary scenario (right chart): When the vehicle was stationary, latency performance improved with reduced variability. No abnormal UL spikes were observed; however, uplink latency still remained more than three times higher than downlink latency, suggesting inherent UL-side constraints rather than mobility-induced factors.

Comparison of TN vs. NTN uplink latency: Additional testing compared uplink latency between TN and NTN under matched packet profiles and data rates. As shown in the chart below, TN average UL latency was 1.7 s, while NTN average UL latency was 8.1 s.



Latency	Average (s)	Min (s)	Max (s)
TN UL	1.7	0.7	3.0
NTN UL	8.1	6.9	8.4

The resulting 6.4 s delta (difference) significantly exceeds the theoretical delay budget for GEO/GSO satellite links. The one-way satellite propagation delay is approximately 240 ms, and combined service-link and feeder-link traversal time should introduce <300 ms of additional latency. Therefore, the observed gap indicates that the dominant contributor to NTN UL latency is not satellite signal propagation but other factors such as access procedures, UL grants, repetition mechanisms, and core/backhaul processing behaviour.

Summary of key observations:

Lesson 1: NTN uplink latency is consistently ~3× downlink latency.

Lesson 2: NTN UL latency is significantly higher than TN UL latency. Further investigation is required to determine causes beyond the expected ~240 ms satellite propagation delay, including gateway and backhaul processing.

Lesson 3: Areas with weak GNSS availability but good NTN RF conditions showed degraded message reliability and elevated UE power consumption. This highlights the need for robust GNSS performance in UE positioning, or alternative GNSS-resilient solutions in NTN environments.

Lesson 4: Performance under challenging environments.

Lesson 5: Environments that are non-clear sky conditions or that have partial occlusion (i.e. foliage of trees, medium-size buildings).

Lesson 6: Signal blockage due to high buildings/bridges/manmade structures was the main factor for unsuccessful transmission of messages in urban and semi-urban environments.

7.4 Enhancing automotive safety with satellite connectivity

7.4.1 Objectives

The demonstration by Stellantis, Cubic3, Rolling Wireless, Vedecom, Viasat on ways to enhance automative safety with satellite connectivity had the objectives to use satellite connectivity for safety and security improvement and extend coverage and to integrate a prototype user terminal in a vehicle for NTN communication.

7.4.2 Technical set-up

Figure 61 Stellantis cars with its cellular antenna

Figure 62 Embedded PoC in the Stellantis vehicle

The technical set-up for the demonstration is composed of three main components:

1. The Stellantis vehicle (see Figure 61) with the PoC (see Figure 62) inside including:
   a. The network access device (NAD) supporting NB-NTN for two-way communication via rolling wireless (RN941YNAD module)
   b. The VEDECOM prototype telematic control unit (TCU), connected to the CAN bus in order to have access to the sensors
   c. The roof cellular antenna (see Figure 61)
2. The backend server or a service provider server (SPS) could be from any original equipment manufacturer.
3. The satellite constellation permitting the narrow-band NTN connectivity between vehicle and SPS exchanges messages through NTN connectivity based on Release 17 provided by Cubic3 via integration with GEO Skylo/Viasat on band n256 (see below). The NB-NTN module communicates with the satellite by using 5G antenna Taoglas Steedan MA350.

The frequency band details for the demo:

Band n256	UL: 1980 MHz – 2010 MHz	DL: 2170 MHz – 2200 MHz	FDD

7.4.3 Architecture considerations

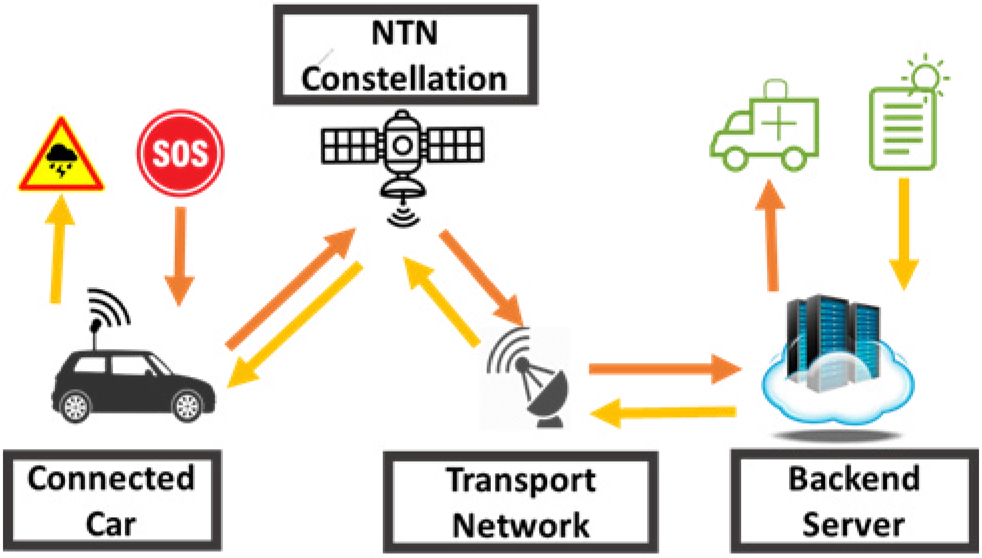


Figure 63 Vehicular communication architecture via NTN

The demo architecture is presented in Figure 63 where vehicles exchange information with SPS through NB-NTN in two communication phases. The first phase, vehicle-originated, is where vehicles transmit messages to SPS as an uplink. The second vehicle-terminated phase is where SPS sends messages to the vehicle as a downlink. Each communication phase is represented by an automative use case developed to operate on NB-NTN, as follows:

For uplink, the eCall use case is an emergency alert with of minimum set of data (MSD) transmitted from a connected vehicle to a backend server. For downlink, the adverse weather use case sends alerts based on ETSI DENM from a remote server to the vehicle.

For each use case, we apply a human-machine interface on the vehicle and SPS sides to assist both vehicle users and SPS agents. Figure 64 depicts the platform developed on the vehicle-side. For vehicle users, it ensures the seamless transmission and reception of various messages while providing real-time information on the stability of satellite connection, and the processing phase of each use case.

Figure 65 presents the developed platform to assist SPS agents by offering vehicle tracking and service management capabilities.

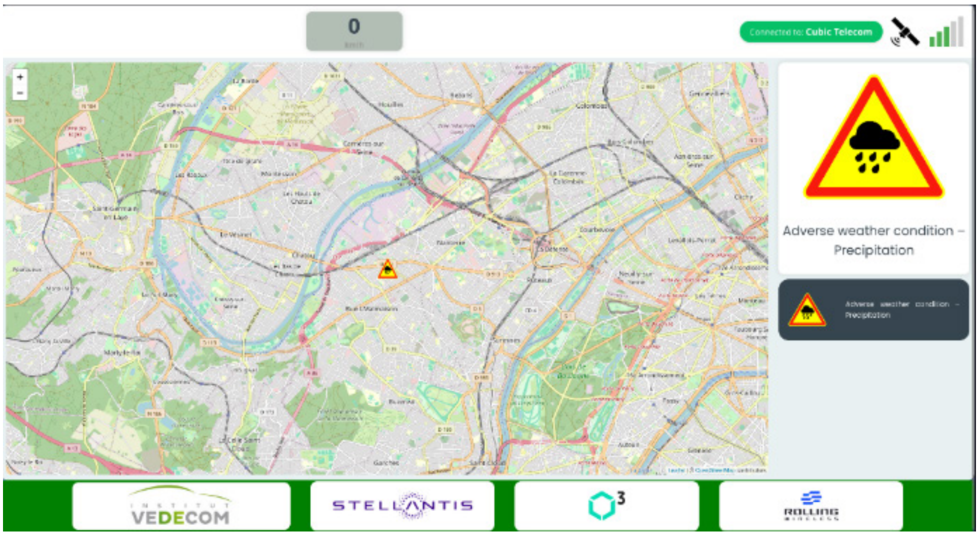


Figure 64 Human-machine interface for the use case eCall and AWC on the vehicle-side

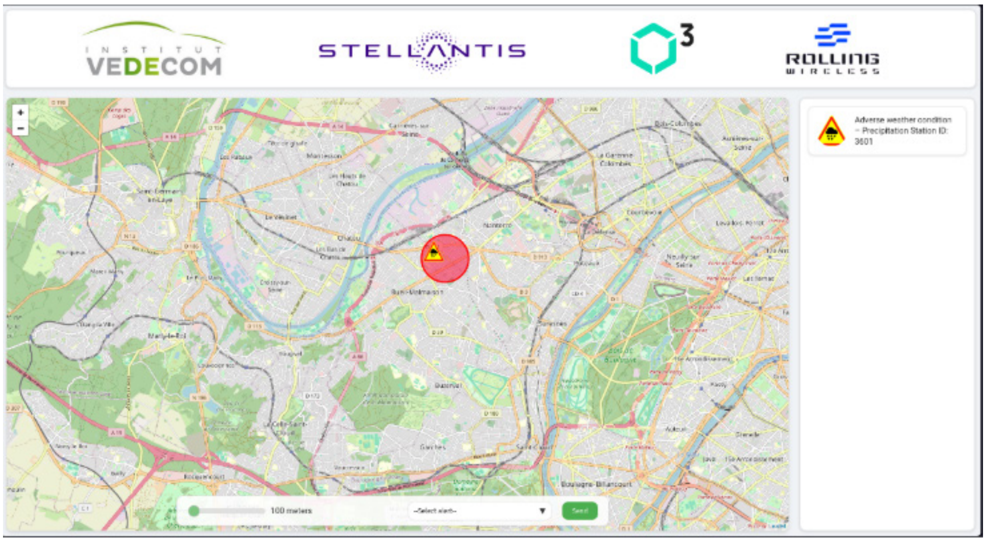


Figure 65 Human-machine interface for the use case eCall and AWC on the server-side

7.4.4 Measurement results

The eCall use case has been tested onsite in Paris-Saclay during the 5GAA demo. The test has considered two scenarios.

Scenario one was static scenario where the signal quality metrics received signal strength indicator (RSSI), reference signal receive power (RSRP), reference signal receiver quality (RSRQ), and signal to interference and noise ratio (SINR) – are evaluated in different static locations. Each location has different surroundings, such as free space, tall buildings and high trees, which have an impact on the signal quality results presented below. The signal quality metrics are measured at different locations in Paris-Saclay, such as a bus stop, parking area and around the Telecom Paris buildings. For instance, as the figure below shows, the RSRP is found to have an average of -129 dBm with a lowest value of -130 dBm. Meanwhile, higher signal quality is measured at the parking area and Telecom Paris with average of -126 dBm and -127 dBm, respectively.

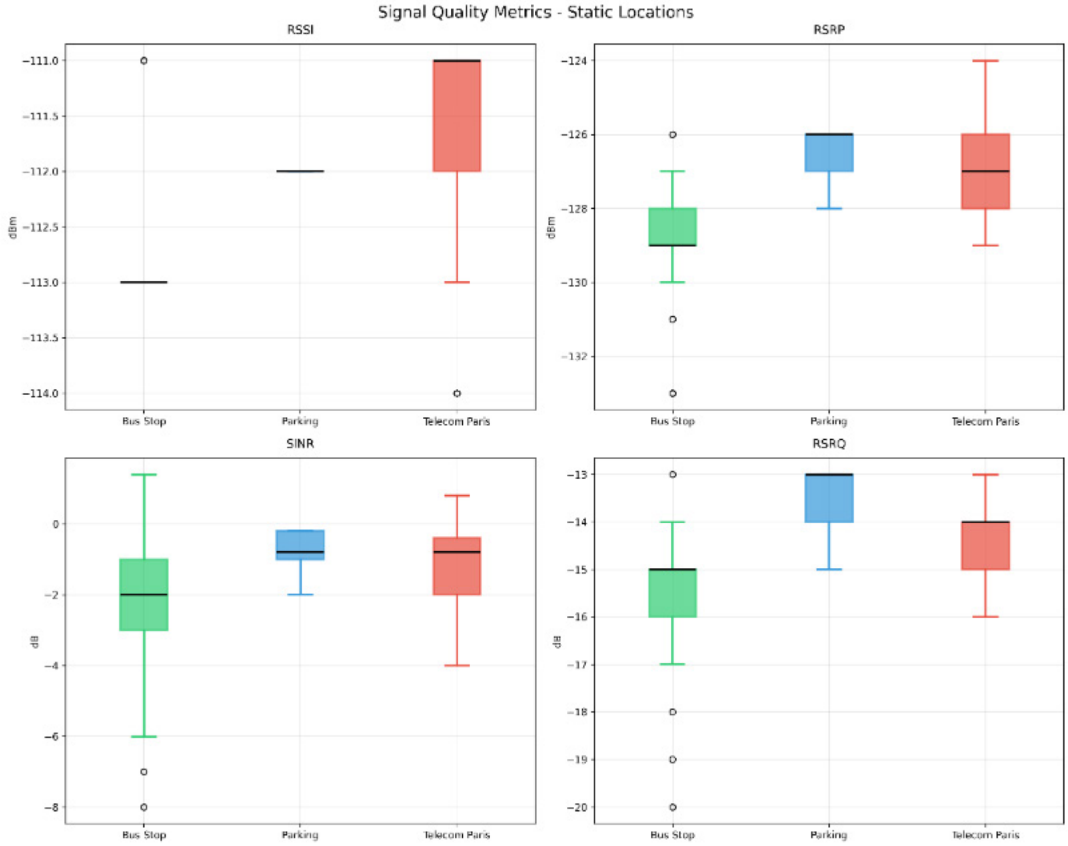


Figure 66 Signal quality results for the use case eCall at static scenario

Scenario two is a dynamic setting where the signal quality results are obtained by considering two different trajectories, as presented in Figures 67 and 68. The signal quality measurements for both trajectories are presented in Figure 69. For each trajectory, the signal quality metrics are measured. As illustrated on the next page, the RSRP is found to have an average of -125 dBm with lowest recorded value around -140 dBm.

Figure 67 Trajectory for the use case e-call at the scenario dynamic 1

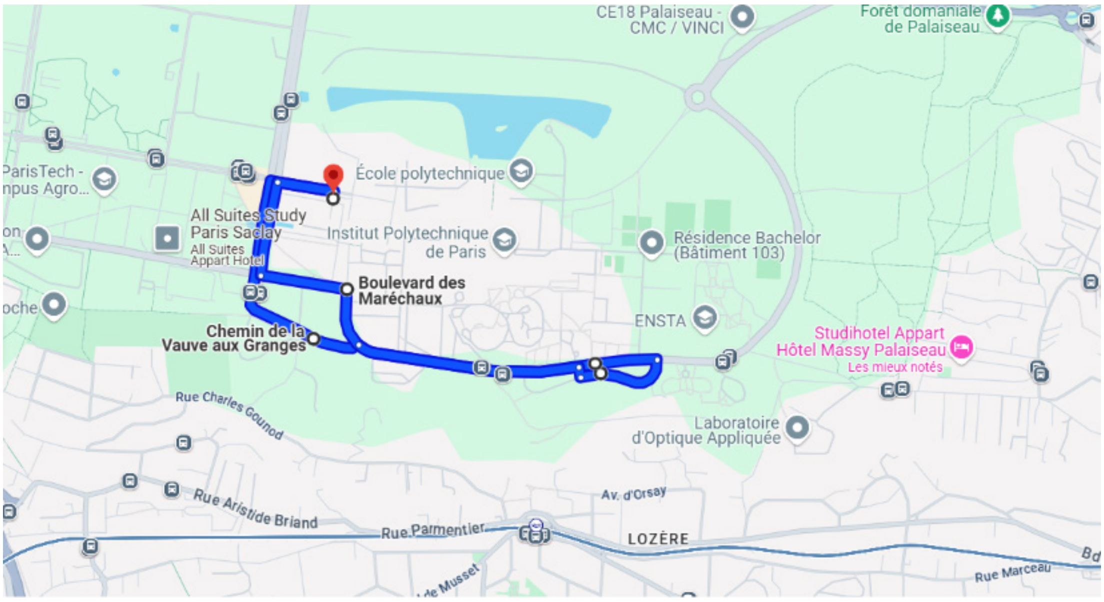


Figure 68 Trajectory for the use case eCall at the scenario dynamic 2

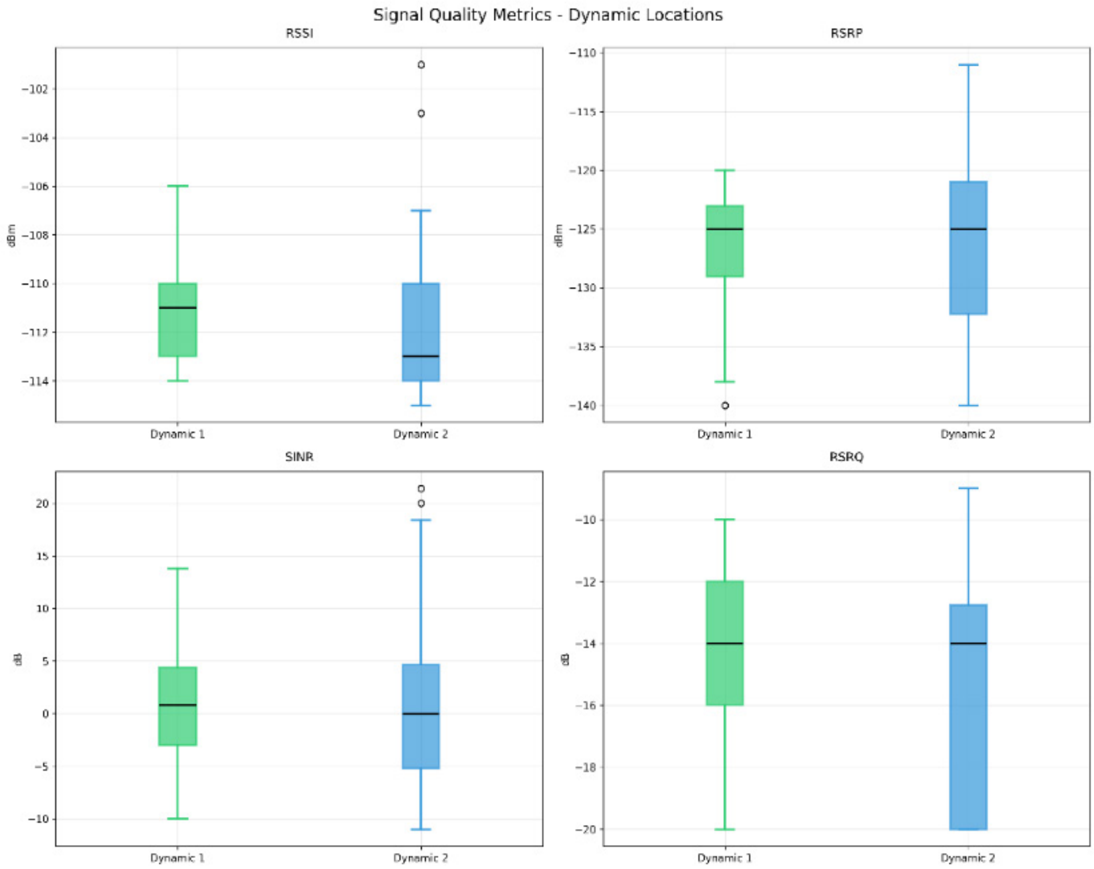


Figure 69 Signal quality results for the use case eCall at dynamic scenario

7.4.5 Lessons learned and overall conclusion

This demonstration provided valuable insights into the deployment and operation of NB-NTN technology based on 3GPP Release 17, implemented on a representative NAD platform. It successfully showcased two safety-oriented vehicular use cases, demonstrating the potential of satellite connectivity to enhance end-customer protection and ensure service continuity even in challenging environments.

We also confirmed that generating accurate NB-NTN performance measurements requires a rigorous, iterative methodology, particularly to account for environmental and weather-related effects on the satellite link. Moreover, the success of this proof-of-concept was made possible thanks to the strong collaboration between multiple technical and operational teams, whose combined expertise enabled the reliable integration and validation of NB-NTN connectivity in compliance with the latest 3GPP standards.

The demonstration relied on the transmission of short bi-directional messages – from the vehicle to the backend and from the backend to the vehicle – effectively validating NB-NTN support for MSD-type safety messages and initial control signalling.

The next phase of development will focus on further enhancing the physical integration of the satellite subsystem within the demonstrator vehicle. This includes evaluating a more automotive-representative satellite antenna, improving RF performance and overall robustness in a real operational environment. Looking forward, the objective is to extend the capabilities beyond short messages and enable two-way voice communication over NB-NTN. This evolution would provide an even broader set of safety and emergency services, reinforcing the role of satellite connectivity as a key enabler for resilient, always-available communication.

7.5 Reliable emergency messaging via satellite in automotive telematics

During the 5GAA face-to-face meeting in Paris in May 2025, Harman, in collaboration with Qualcomm, Rohde & Schwarz (R&S) and Skylo, demonstrated text-based emergency messaging over NTN. This demo was implemented on a production-ready TCU using a Qualcomm SA522/525-based modem, enabling communication with a geostationary satellite via the Skylo network. This configuration illustrates a viable approach to addressing the coverage gaps present in terrestrial cellular networks, which currently cover only around 40% of the globe. The demonstrated solution can support a range of emergency use cases, including assistance for stranded vehicles, medical emergencies, vehicle accidents, and other critical situations where reliable connectivity is essential.

7.5.1 Objectives

The primary objective of the demonstration was to highlight the capabilities of a commercially available modem, built around a Qualcomm chipset and integrated into a Harman production-ready TCU, known as Ready Connect. This modem, in addition to supporting 5G communications, is equipped to facilitate NB-NTN communication via the L- and S-band frequencies.

The demonstration specifically focused on the transmitting emergency messages use case. These messages, which are limited in size, can be sent with longer latency – typically within a matter of seconds. Such a configuration is suitable for a broad range of critical scenarios, including emergency services, motorist assistance, and the dissemination of traffic information. This capability is particularly significant in regions where cellular coverage is sparse or non-existent, such as parts of the southern United States. It is also vital in situations where terrestrial networks may be compromised or rendered inoperable (e.g. during natural disasters).

7.5.2 Technical set-up

Ready connect SATCOM is an advanced, pre-developed and upgradable TCU solution, designed to offer comprehensive connectivity capabilities. The system uses a modular network access device (NAD) architecture, providing seamless upgrade paths from 4G to 5G and, ultimately, to satellite communication, thereby supporting evolving connectivity requirements in automotive applications.

Central to the Ready Connect SATCOM package is the integration of internal antennas, developed in partnership with Samsung. These antennas are engineered to optimise both the integration within vehicles and the overall connectivity performance, while also minimising cable and signal losses. By incorporating the antenna directly within the TCU, the solution allows for straightforward and seamless installation into the vehicle. Although an internal antenna may be less efficient than an external dedicated antenna, the removal of cable losses enhances the system's overall sensitivity, making installation more efficient and effective.

The communication system is based on the 3GPP Release 17 NB-NTN standard, also referred to as IoT-NTN. For the demonstration in Paris, band B256 from a geostationary satellite was used, leveraging the Skylo network to establish a link to the backend server. The architecture showcased the ability to send relatively short messages from the TCU to a ground station; these messages are then routed onwards to the server, which can respond to the TCU over the NTN connection. This demonstration highlights the potential of Ready Connect SATCOM to support the transmission and reception of critical emergency messages as well as essential intelligent transport system messages.

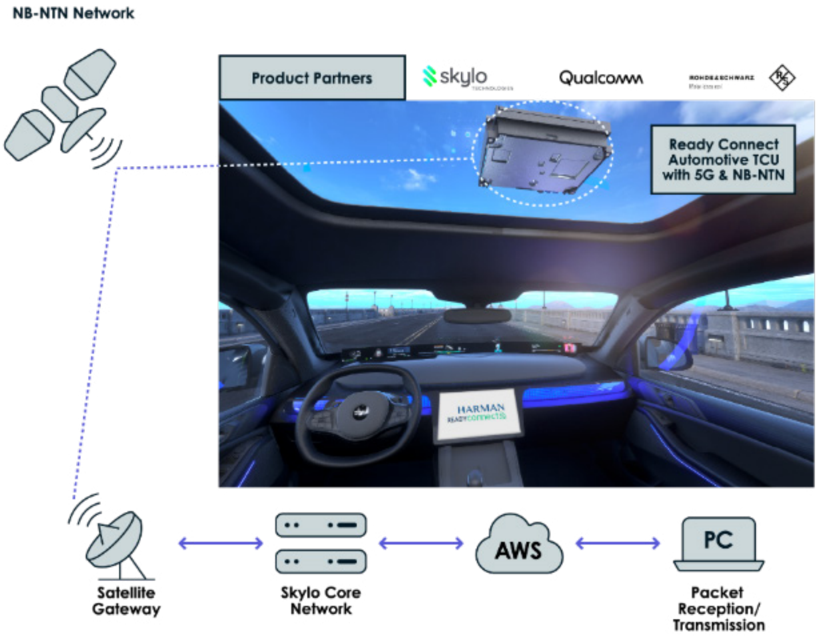


Figure 70 Harman ready connect NB-NTN architecture

Due to the limited bandwidth available, the communication system is best suited for emergency situations, where the transmission of concise, urgent messages is paramount.

7.5.3 Measurement results

As part of the demo and during integration and testing phases, we collected significant data related to the NB-NTN link performance, specifically for short text messages. The table below shows the typical parameters of a text message used for the testing and the demo.

Table 19 Emergency message packet details for testing and demo

Item	Description
Use case	Emergency message
Packet size	Up to 200Bytes (Skylo network can support up to 1,200 Bytes)
Time between messages	1 minute

The following table shows the key parameters of the RF link to the GEO satellite; these numbers were measured in Northern California which is at the lower latitude of 37.5 degrees compared to the demo location in France (at 48.7 degrees) but from experience the results are in line given the altitude of the GEO satellite.

Table 20 Mobility measurements

Signal Characteristics	Range	Values	Remarks
RSSI [dBm]	High	Greater than -113	E-UTRA
	Medium	Between -117 & -113	RSSI comprises the linear average of the total received power (in [dBm]) observed only in OFDM containing reference symbols in the measurement bandwidth, over the number of resource blocks (RBs) by the UE from all sources, including co-channel serving and non-serving cells, adjacent channel interference, thermal noise etc..
	Low	Less than -117	
RSRP [dBm]	High	Greater than -126	RSRP is determined for a considered cell as the linear average over the power contributions (in [dBm]) of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth.
	Medium	Between -134 & -126	
	Low	Less than -134	
RSRQ [dB]	High	Greater than -13	RSRQ is defined as the ratio N×RSRP / (E-UTRA carrier RSSI), where N is the number of RBs of the E-UTRA carrier RSSI measurement bandwidth. The measurements in the numerator and denominator shall be made over the same set of resource blocks.
	Medium	Between -17 & -13	
	Low	Less than -17	
SNR (or SINR) [dB]	High	Greater than 2	SNPR; P (desired signal) / P (noise). In reality, this metric includes contribution from interference, resulting in P (desired signal) / P (noise + interference). SNR is a decent KPI to represent signal quality.
	Medium	Between -6 & 2	
	Low	Less than -6	

The main KPIs for the testing and demonstration in Paris are show in the table below, indicating the RF performance of the TCU for both antenna 0 and 1, which in this case shows a reduction in performance for antenna 1, but the RF performance on antenna 1 compensated for this issue. We can see that even with the challenging RF link, we got more than reasonable latency for the use case of emergency messages.

Table 21 Demo/Test KPIs

KPI	Internal Antenna		
	Minimum	**Maximum**	**Average**
Latency (s)	7.95	11.64	8.74
RSRP (dBm)	-131	-123	-125.9
SNR (dB)	-5.0	4.45	0.44

7.5.4 Rohde & Schwarz test equipment used for the demo

Mobile communication providers aim to serve customers with communications services that meet the required performance based on the operated applications. Performance can be measured, for instance, in terms of average or maximum data throughput, latency and coverage. The fundamental questions are the same in NTN as they are in TN. However, NTN adds another dimension compared to TN, namely the different satellite orbits that can be used to provide communications services. To assess coverage and, importantly for automotive applications, continuous connectivity, the capabilities of the R&S®TSMx scanner for drive- and walk tests were demonstrated. Generally, the use of scanners is crucial due to their superior sensitivity, measurement accuracy and ability to receive all downlink signals compared to UEs. The R&S®TSMx scanner is a calibrated measuring instrument. The goal of the demonstration was to determine the coverage of the serving satellites through passive measurements.

Figure 71 R&S®TSMA6 scanner for passive measurements

The R&S®TSMx scanner receives the radio signals transmitted from the satellites in geostationary orbit and low-earth orbit via the service link in the DL direction and can measure and graphically display a set of basic parameters over time. Examples of the values presented during the demonstration include:

- **RSRP:** The signal strength at the measurement location.
- **SINR:** Signal quality as important parameter that indicates the expected data rate.
- **Number of visible satellites:** In the case of non-geostationary satellites, a sufficient number of satellites in orbit are necessary to ensure continuous connectivity.
- **Spectrum usage:** The signal strength received in different MSS channels can be measured and visualised, providing information about the utilisation of the entire spectrum.

Using the R&S®TSMx scanner at the 5GAA pilot location, we were able to demonstrate the presence of mobile communication coverage from satellites, particularly in geostationary orbit. The measured values confirmed the availability of the NB-NTN service and verified the necessary NB-NTN performance quality to successfully operate applications in the field.

7.5.5 Lessons learned and overall conclusion

Through testing and integrating the NB-NTN for the demo, as well as gathering information to assess the solution's effectiveness, we learned about its advantages, capabilities and challenges. NB-NTN clearly offers a way to support text-based emergency messages and possibly limited voice communications. This ability meets the need for emergency messaging (and potentially eCall) across various scenarios where cellular coverage is unavailable or during emergencies when cellular networks fail.

One of the primary challenges associated with using the NB-NTN system is its reliance on GEO satellites positioned along the equator; as a result, the satellite elevation angle typically ranges between 30 and 40 degrees above the horizon. Given the low signal-to-noise ratio (SNR) in which the system operates, maintaining a clear line of sight to the satellite at all times is essential to achieve a low packet error rate. This requirement can present difficulties in urban areas or mountainous terrain. However, cloud cover and adverse weather conditions have not had a significant impact on system performance, based on the results and experience.

One of the benefits of the Ready Connect concept presented in the demo is its ability to use an internal antenna in the TCU. This approach has obvious benefits when integrating it in cars because it can be installed in the roof panelling and thus reduce the wiring required to connect to the system. The internal antennas used in the TCU are shared with the 5G modem and have relatively low gain. Even with higher antenna gain, the reduced RF cabling means typical losses experienced with external antennas (5-6 dB) can be redeemed – proving the performance benefits of internal antennas.

7.6 Seamless in-vehicle TN/NTN switching

7.6.1 Objectives

This demonstration among LGE, Anritsu, Cubic[3], Skylo, Viasat aimed to validate that automotive services can remain available and responsive when terrestrial connectivity becomes unreliable. It did so by combining seamless in-vehicle TN/NTN switching with passenger-relevant use cases in a moving vehicle on public roads in the Paris-Saclay area. Using a live IoT-NTN S-band network and an LGE satellite-integrated TCU, the demo focused on sustaining service continuity as the vehicle entered and exited a defined TN coverage hole. The system switched to NTN and then returned to TN with minimal user-visible disruption.

The key objectives were to prove seamless TN/NTN switching under real driving conditions and preserve the user experience during coverage loss and recovery, to demonstrate practical NTN-enabled services, including interactive AI voice and satellite assistant or emergency support functions backed by LGE cloud services, to validate an end-to-end 'voice message' scenario with a cloud-based PSAP concept, where a message can be sent on one access network (TN or NTN) and the response can still be received on the other. Finally, one goal was to collect KPI evidence in parallel with the live service experience, in collaboration with Anritsu and Cubic[3] to link measured performance to perceived service quality.

7.6.2 Technical set-up

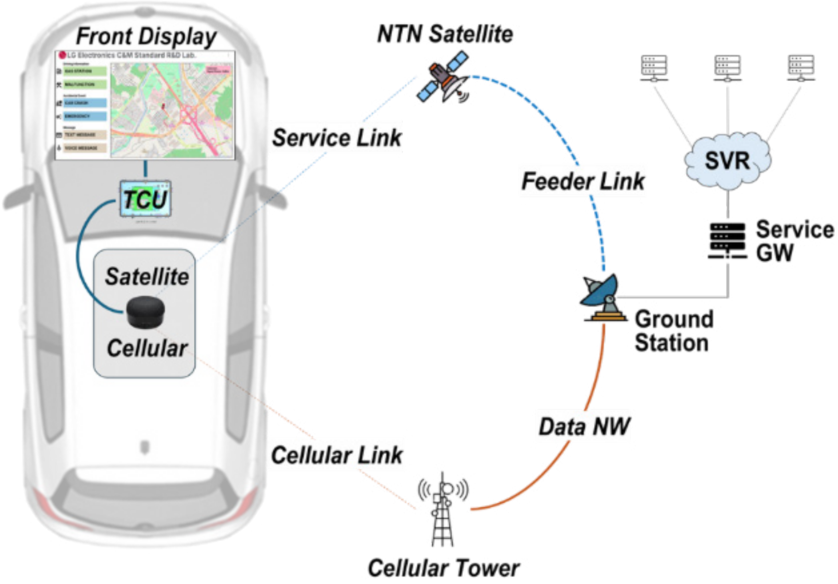


Figure 72 Illustrates the end-to-end technical set-up used for the live IoT-NTN demonstration

In-vehicle components:

- Front IVI display used by the operator to trigger the voice message and assistant functions.
- LGE TCU functions as the TN/NTN connectivity and service gateway.
- Roof antennas for satellite (NTN) and cellular (TN) access.

NTN path (satellite access):

- Vehicle → Satellite: Satellite antenna over the service link.
- Satellite → Ground: Feeder link to the ground station.
- Ground → Backend: Ground station to service gateway and SVR hosting LG services including a PSAP concept.
- Downlink: Response returns via the same NTN path, then IVI displays messages and plays audio.

7.6.3 Architecture considerations

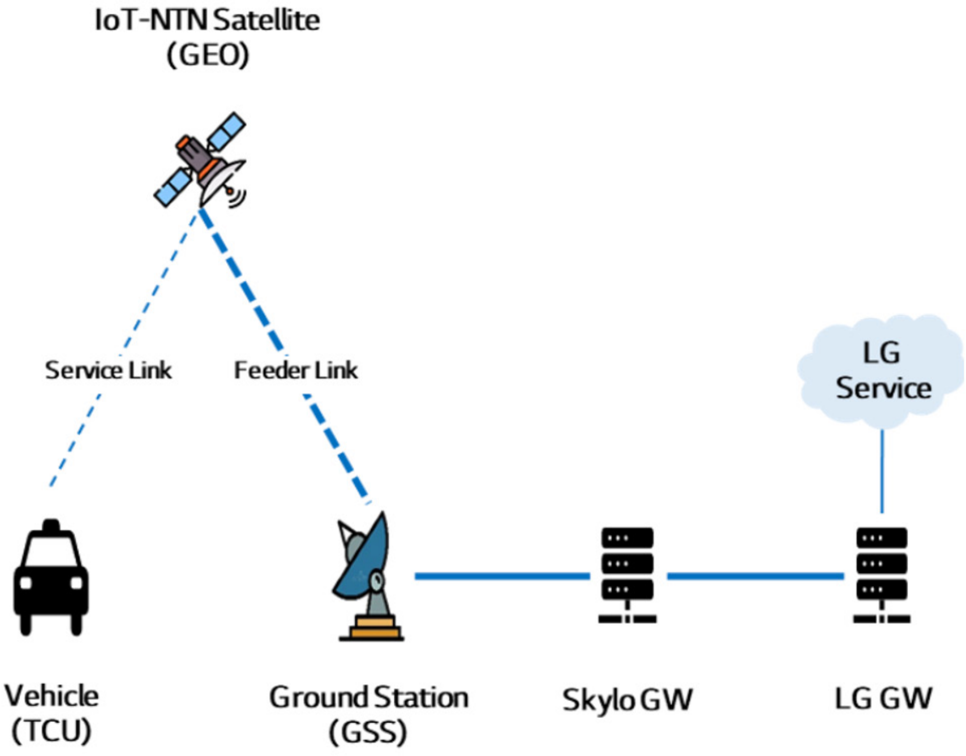


Figure 73 High-level IoT-NTN architecture for the demonstration

The demonstration architecture was designed to deliver a practical automotive IoT-NTN service over a GEO satellite network while maintaining a clear separation between the satellite access domain and the LG service domain. The figure above summarises the end-to-end chain from the vehicle to the LG service through the IoT-NTN ecosystem.

A key architectural principle was to keep the in-vehicle domain, the NTN access domain and the service domain independently manageable. The vehicle side (TCU) functions as the service endpoint in the car and provides the connectivity anchor towards NTN. The satellite system provides the over-the-air access and relays traffic to the ground segment. The service domain (LG services) remains independent of the satellite specifics by relying on standard IP connectivity provided through gateways. This separation enables service logic to evolve without requiring changes in the NTN access network and vice versa.

The architecture explicitly distinguishes two satellite-related segments to clarify responsibilities and expected behaviour:

- **Service link**: The radio segment between the vehicle satellite antenna and the IoT-NTN GEO satellite.
- **Feeder link**: The segment between the satellite and the ground station.

This segmentation is useful when analysing performance because the service link is primarily impacted by the mobile environment and antenna conditions, while the feeder link and ground segment are typically influenced by satellite network routing and terrestrial backhaul.

Gateway roles and interconnection points

Behind the ground station, the architecture introduces gateway layers to provide a clean interface between the NTN access domain and the LG domain:

- **Skylo gateway**: Used as the NTN service gateway providing IP reachability from NTN system towards external service domains.
- **LG gateway**: Used as the entry point to the LG service environment enabling controlled routing, security enforcement and service exposure towards the backend services.
- **LG service**: Application servers implementing the PSAP concept and other services that generate responses back to the vehicle.

This layered gateway approach supports operational clarity. It also reduces tight coupling between the NTN provider environment and the service environment.

7.6.4 Measurement results

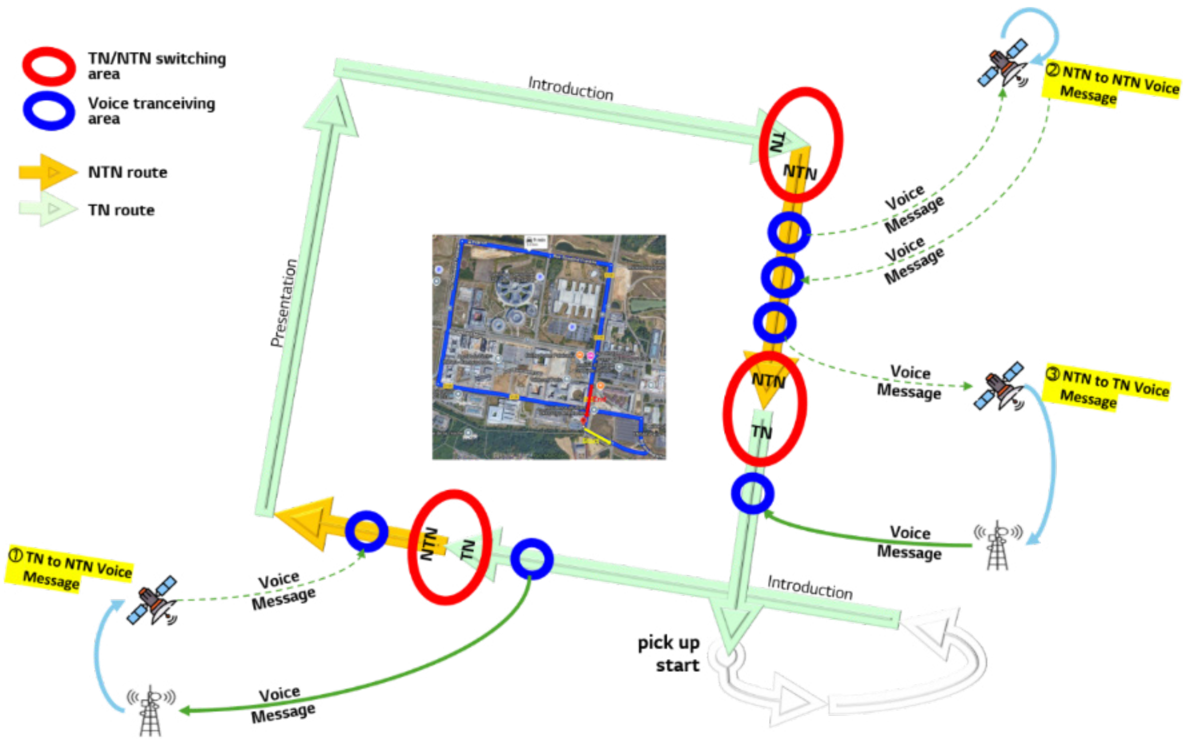


Figure 74 Seamless in-vehicle TN/NTN switching demonstration route

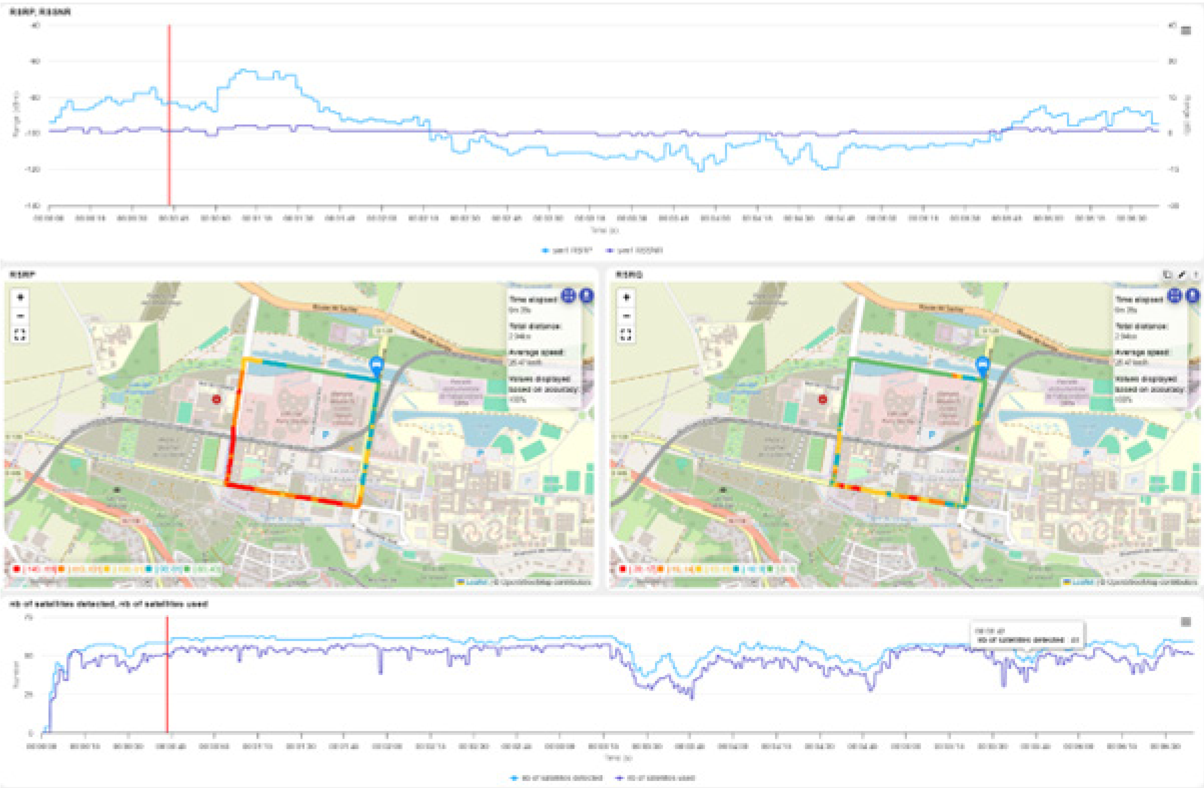


Figure 75 Demonstration route TN/GNSS mapping result

Table 22 NTN measurement KPIs

Latency	Average (s)	Min (s)	Max (s)
UL (64 bytes)	6.2	3.5	8.9
UL (200 bytes)	9.2	8.9	9.5

LGE-Anritsu measurement observations and key findings:

- No packet loss was observed in UL or DL conditions.
- NTN UL latency was approximately 2x higher than NTN DL latency.
- Packet size changed from 64 bytes to 200 bytes in the demonstration increased the UL latency from ~6 s to ~9 s.
- Having good GNSS coverage is essential for improving NTN connectivity.

7.6.5 Lessons learned and overall conclusion

- **Service continuity is achievable**: IoT-NTN can sustain automotive services in TN coverage gaps when switching control and service behaviour are designed together.
- **Gateway integration is essential**: Stable service delivery depended on a clean separation of domains and Skylo coordinated interconnection between Skylo gateway and LG gateway.
- **Service flows should be NTN-aware**: Message-oriented request/response, payload minimisation and on-device preprocessing are preferred for IoT-NTN.

- **Uplink performance remained the stronger constraint**: Both UL and DL latency were significant in the IoT-NTN environment. However, UL latency was higher and more payload size sensitive. This indicates that both UL and DL payloads should be carefully managed while UL optimisation remains more critical for improving end-to-end service responsiveness.
- **GNSS availability remains important**: Good GNSS coverage was important for stable NTN connectivity during the moving vehicle demonstration.

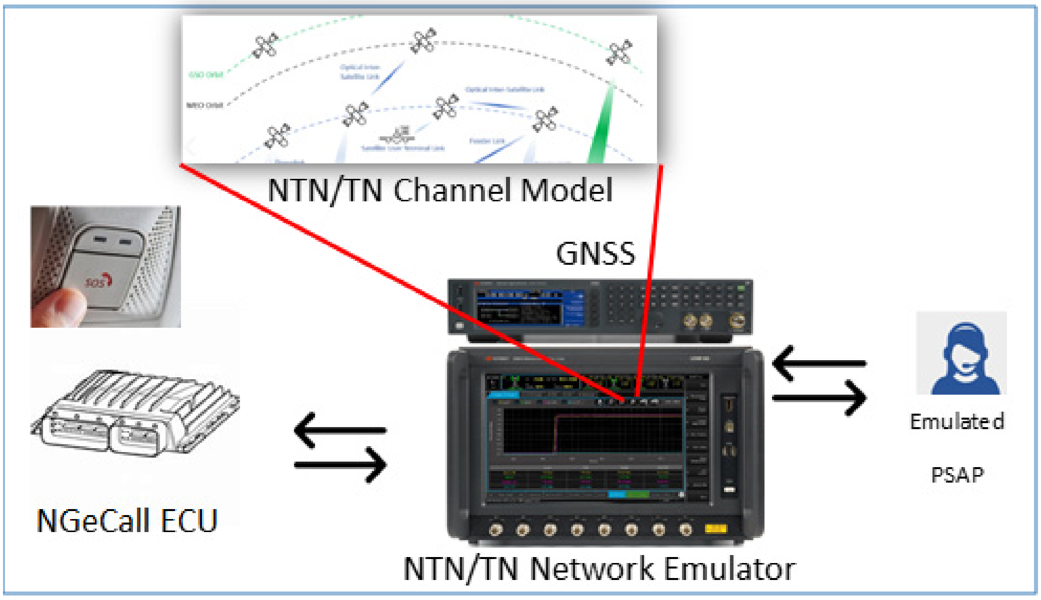
The Paris live demo validated the feasibility of seamless in-vehicle TN/NTN switching and NTN backend automotive services using a GEO IoT-NTN network, with satellite integrated TCU as the core platform. The results also indicate that future implementations and standardisation should further improve switching robustness and service continuity across TN/NTN transitions.

7.7 Next-generation emergency call (NGeCall) over NTN

7.7.1 Objectives

The advent of ubiquitous network coverage via NTN enables vehicles to send emergency calls even when out of TN coverage enhances passenger safety in the event of an accident. The demonstration sought to test and show the ability of a NGeCall device to establish a connection to a (emulated) PSAP over both NTN and TN, and transferring relevant information (MSD).

7.7.2 Technical set-up



7.7.3 Architecture considerations

The demo was for NGeCall over LTE unmodified, hence the device used for the demo does not require any implementation of NTN standards.

The UXM emulates the terrestrial eNB, and adds NTN channel emulations with variable delay and Doppler. LEO satellites move at great speed, resulting in Doppler shift and propagation delay. In the case of LTE unmodified, the eNB compensates for these issues because it knows the position and velocity of the satellite.

7.7.4 Measurement results

The demo did not include any measurements per se but did prove that an unmodified device could perform an NGeCall. This is of interest to the automotive industry as there are many existing cars which have modems that do not currently support NTN.

7.7.5 Lessons learned and overall conclusion

The questions raised were mainly about the link budget, power consumption when 'talking' to a satellite, and the audio quality of the NGeCall.

7.8 New radio non-terrestrial network device testing

7.8.1 Objectives

The objective was to showcase the capabilities and performance of NR-NTN, demonstrating the readiness of both the technology and devices for automotive use cases requiring high data-rate communication services. The demonstration utilised laboratory test equipment and a reference device.

Particular emphasis was placed on continuous connectivity, which is critical for automotive applications supporting mobility. In mobile communication networks, handovers are routinely performed to maintain connection to the best available serving station. With NTN, switching between cells, mobile technologies, and operators is no longer restricted to TN deployments, potentially enabling communication services even in rural environments.

Unlike terrestrial deployments, both devices and space-borne transceivers might be mobile. While satellites in geostationary orbit appear stationary from earth's perspective, satellites in non-geostationary orbit (NGSO) are in motion. This introduces additional complexity to communications network operations, specifically handover between serving satellites and beams operated by individual satellites providing cellular coverage on earth's surface. The image below shows the Rohde & Schwarz booth at the 5GAA meeting in Paris with the laboratory test equipment.

Figure 77 Demo set-up with R&S®CMX500

7.8.2 Technical set-up

The R&S one-box mobile communication tester, R&S®CMX500 depicted below was used to emulate the satellite access node (SAN) and run demo test scenarios focusing on performance testing of handovers between TN and NTN, NTN and NTN, and NTN to TN.

Figure 78 R&S®CMX500 one-box mobile communication tester

The use case investigated was a video call using Microsoft Teams, established and operated between a legacy smartphone and a TN and NR-NTN-capable reference device from MediaTek (MTK) – a single device integrating satellite and terrestrial mobile networks offering pervasive global connectivity.

The MediaTek device was considered to be in a moving vehicle, while the legacy smartphone was assumed to be stationary.

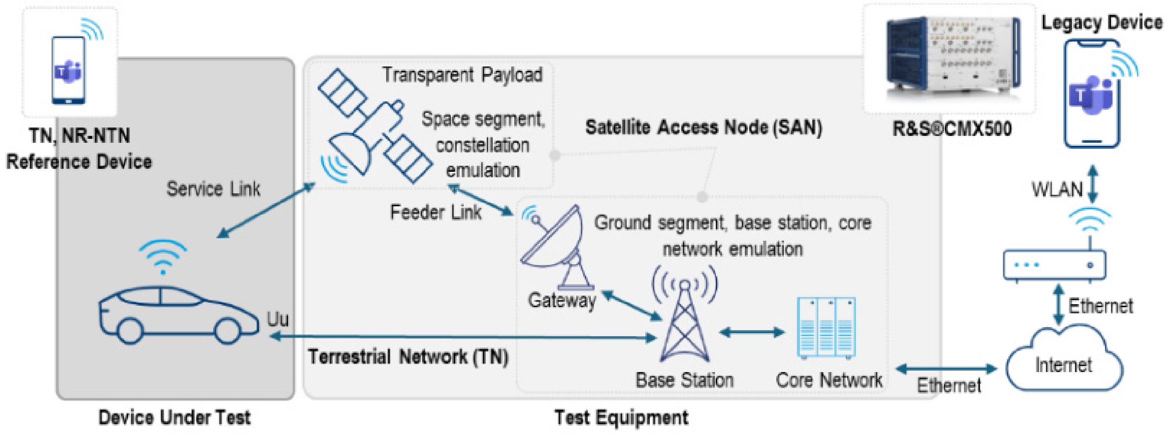


Figure 79 Test set-up with TN, NR-NTN reference device from MediaTek and R&S®CMX500 for NTN SAN and TN emulation

The SAN emulation by the R&S®CMX500 involved emulating satellites operating with fully 3GPP-compliant NR-NTN technology and transparent payloads, assuming a LEO constellation. Alongside satellite movement, path loss, delay and Doppler effects were considered and varied over time, computed, and applied to the emulated RF signal using the same R&S®CMX500 communication tester. Concurrently with the SAN emulation, the R&S®CMX500 emulated the terrestrial network, spanning cellular cells to serve the device under test (DUT) with 4G and 5G mobile communication technologies. The legacy smartphone was connected to the R&S®CMX500 over the internet with an ethernet/IP connection. Performance testing focused solely on the TN- and NTN-capable reference device. The emulation of the service link considers frequencies related to the L/S frequency bands for mobile satellite service, while the frequencies for TN were from FR1.

7.8.3 Architecture considerations

Table 23 Features and capabilities demonstrated

Feature	Description
Technology	NTN: NR-NTN (Rel-17) TN: 5G NR (5G Advanced)
Satellite orbit	Low-earth orbit (LEO)
Frequency	NTN: L/S bands TN: FR1
Handover	Inter- and intra- satellite, NTN to TN and vice versa
Radio channel	Channel emulation with Doppler and signal propagation delay
Satellite payload	Transparent
Applications	Video call

The table immediately above summarises the demonstrated capabilities and features.

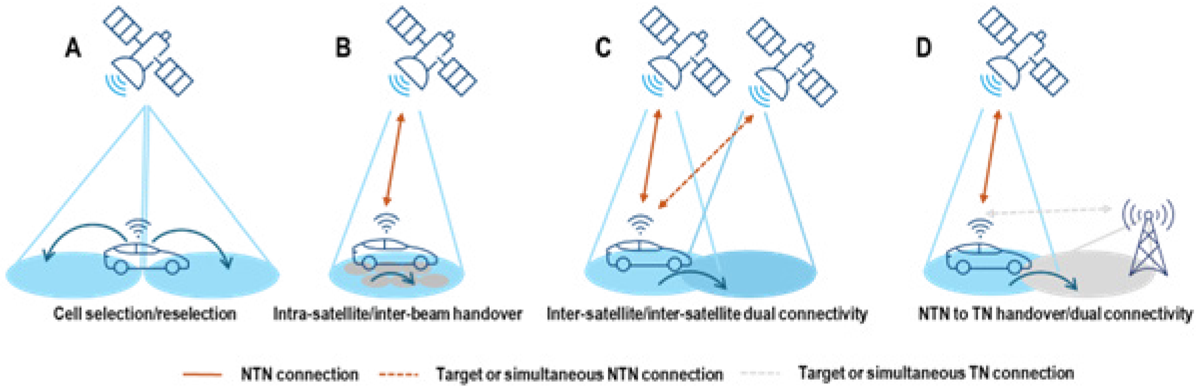


Figure 80 TN and NTN handover scenarios supported by R&S®CMX500

The test scenario assumed a vehicle driving on a road and experienced varying cellular network performance, which necessitates handovers by the TCU/reference device to maintain connectivity. Handovers were performed between TN and NTN and within the NTN (NTN to NTN). The handover scenarios generally supported by the R&S®CMX500 are depicted in the above figure. The demonstration comprised the scenarios shown relating to B to C.

7.8.4 Measurement results

The established video call between the reference device and the legacy smartphone generally showed very good performance. The quality of experience was more than sufficient to operate a smooth and continuous video call. Handover had a brief impact on the video quality. The change in video quality was noticeable, but did not result in any significantly disruptive effects.

7.8.5 Lessons learned and overall conclusion

The demonstration showcased the video call use case.

Using a TN and NTN-capable single reference device from MediaTek allows continuous connectivity, either over the terrestrial network or the non-terrestrial network. Continuous connectivity results from successful handovers. The demonstration proved the performance of handovers, considering test scenarios where the network was dynamically changed from TN to NTN, inter-NTN and within NTN. Participants were able to verify that NR-NTN was capable of achieving sufficient performance for the video call in the emulated environment.

8 Conclusion of demonstrations

The demonstrations collectively confirm that 3GPP-based satellite connectivity (NB-NTN and NR-NTN) has matured from a conceptual technology into a viable automotive connectivity extension, capable of delivering safety-critical services beyond terrestrial network coverage. Across multiple implementations, emergency messaging, hazard warnings, traffic management notifications and NGeCall-related services were successfully demonstrated over satellite links.

A key outcome is that NTN provides meaningful additional coverage and resilience, particularly for safety functions where continuity of communication is more important than high data throughput. All demonstrations confirmed that short message-based services can be reliably delivered in remote areas and during terrestrial network outages.

The field measurements also revealed important limitations. Uplink and downlink latency remains the dominant challenge, with typical values around 6-10 s and significantly higher than terrestrial networks as long geostationary satellites are involved. But the observed delays cannot be explained by satellite propagation alone and are largely driven by access procedures, scheduling mechanisms and network processing.

Another consistent learning is the importance of GNSS availability and line-of-sight conditions. Several demonstrations showed that degraded GNSS performance, urban obstructions, bridges or buildings can negatively affect NTN reliability, sometimes more than the radio link itself.

Lastly, the demonstrations showed that hybrid TN/NTN architectures are the preferred long-term solution. Seamless switching between terrestrial and satellite connectivity was successfully demonstrated, maintaining service continuity while minimising user-visible disruption.

Future connected vehicles will therefore rely on intelligent orchestration of both access technologies rather than NTN as a standalone solution.

8.1 Recommendations for the automotive industry

1. Prioritise safety and resilience use cases first. Emergency messaging, hazard warnings, disaster notifications and future NGeCall services clearly represent the strongest near-term business case for NTN.
2. Design vehicle architectures around hybrid TN/NTN operation. Seamless switching between terrestrial and satellite connectivity should become a core design objective for future telematics platforms.
3. Optimise applications for NTN constraints. Message-oriented communication, small payloads, local processing and efficient uplink utilisation are essential

due to limited throughput and uplink latency characteristics.

4. Continue investment in antenna integration, GNSS robustness and performance optimisation. These areas emerged as key enablers for reliable large-scale deployment and production readiness.
5. Prepare for future high-bandwidth NTN capabilities but focus current deployments on low-data-rate safety services. While NR-NTN demonstrations showed promising results for applications, such as video communication and advanced connectivity, current NB-NTN solutions are best suited for safety messaging and service continuity.

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- For a specific reference, subsequent revisions do not apply.
- For a non-specific reference, the latest version applies.

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The 5G Automotive Association (5GAA) is a global, cross-industry organisation of over 100 members, including leading global automakers, Tier-1 suppliers, mobile operators, semiconductor companies, and test equipment vendors. 5GAA members work together to develop end-to-end solutions for future mobility and transport services. 5GAA is committed to helping define and develop the next generation of connected mobility, automated vehicles, and intelligent transport solutions based on C-V2X. For more information, please visit https://5gaa.org

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