EAGER

tEchnologies And techniques for satcom beyond 5G nEtwoRks

Executive Summary

Version 1.0

Leveraging the Rel. 17 Non-Terrestrial Network (NTN) standardization framework, finalised in 2022, this study aimed at **researching innovative technologies and techniques targeting highly efficient and deeply integrated satellite networks in beyond 5G cellular systems**.

More specifically, the following objectives have been pursued:

- to **evaluate and adopt discarded solutions** or use cases, including, *e.g.*, Multiple-Input Multiple-Output (MIMO) techniques, advanced payload with digital beamforming and active antennas, Artificial Intelligence (AI)/Machine Learning (ML) techniques, low Peak-to-Average-Power Ratio (PAPR) waveforms, handheld direct access for broadband communications with Very Low Earth Orbit (VLEO) constellations, massive Machine Type Communications (mMTC), self-driving car services and Vehicular-to-Everything (V2X) applications, etc.;
- to **identify and evaluate novel concepts** (both in the waveform and in the network domain, as well as in the space and ground segment technologies);
- to **develop the necessary software or analytical tools** in order to properly assess the performance of the most promising techniques and technologies.

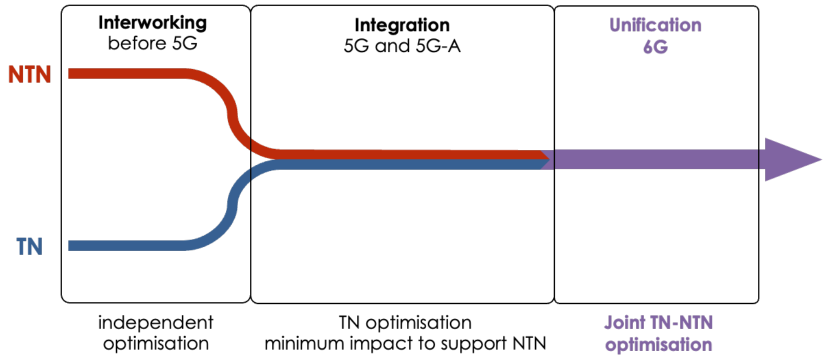


Figure 1. Evolution of the non-terrestrial and terrestrial networks design before 5G, with 5G/5G-Advanced, and vision for 6G communications.

Prior to 5G the satellite and terrestrial components were independently designed and optimised (see Figure 1); this made the *a posteriori* integration between the two infrastructures extremely challenging, if possible. With 5G and 5G-A, the paradigm shifted aiming at an integration by design, with the terrestrial network optimised with a minimum impact to support NTN. With 6G systems, the objective is that of a joint optimisation of the satellite and terrestrial network, capable of automatically and seamlessly managing both infrastructures. In such unified global network, the user will be completely unaware of the actual access network that is being exploited to provide the requested service.

Notably, NTN can bring an added value to complement the NG-RAN for (see 3GPP TR 22.822):

- service **continuity**: terrestrial networks are typically deployed based on the users' density. This approach led to the Digital Divide problem, in which many geographical areas have limited or no broadband access via terrestrial communications. In this context, NTN can be a viable solution to provide connectivity for pedestrian/fixed UE, or moving platforms (train, aircraft, maritime), which cannot be served by a single or a combination of terrestrial networks;
- service **ubiquity**: in addition to economic motivations leading to Digital Divide areas, terrestrial networks might also be temporarily or geographically unavailable due to natural disasters or terrorist attacks, partially or completely disrupting the communication infrastructure. In this context, NTN are again a viable solution to ensure both consumer service provisioning and a working communication infrastructure for the first responders on the area;
- service **scalability**: notably, NTN elements cover much larger areas compared to terrestrial cells. This unique feature makes satellites, HAPS, and drones extremely efficient in providing broadcasting and multicasting services. Moreover, NTN systems can also off-load the traffic of the terrestrial networks during peak hours.

5G-A is not expected to introduce new services via NTN, but rather to consolidate and, if possible, improve the performance for enhanced Mobile Broadband (eMBB+), massive Machine Type Communications (mMTC+), and High Reliability Communications (HRC+). Moreover, in the context of enhanced Multimedia Broadcast and Multicast Systems (eMBMS), in which an ever-increasing capacity request is being experienced (*e.g.*, due to the increase in the number of Ultra-High Definition (UHD) programs in broadcasting services), satellite networks provide an efficient access option to: i) serve users located in un-served areas; and ii) serve users with the required Quality of Service (QoS) when the MNO is saturating due to the large traffic requests, *i.e.*, for traffic off-loading.

6G will then enable diverse use cases with extreme range of requirements. Compared to legacy design requirements, the biggest difference is the diversity of use-cases that 6G networks must support and the new opportunities it will create compared to today's networks. These use cases can be grouped into the six usage scenarios for 6G scenarios illustrated in Figure 2. It shall be noticed that a two-fold advancement is expected to take place: i) improving the performance of eMBB, mMTC, and HRC (*ultra* services); and ii) provide new services, which include immersive communications (*e.g.*, tactile Internet), integrated AI solutions, and network sensing. In ITU-R, the latter two services are referred to as *beyond communications*, as they do not directly target connectivity to the users, but rather the optimisation of the overall network performance.

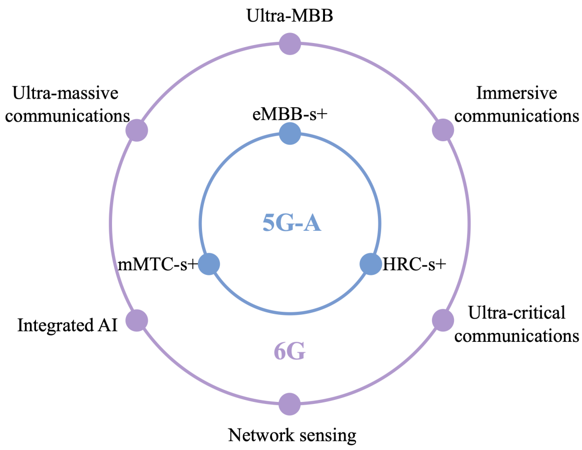


Figure 2. Six usage scenarios for 6G.

To achieve such challenging objectives, some disruptive concepts can be envisaged to further enhance the NTN connectivity services in terms of performance, usage, resiliency, and sustainability. The key elements for defining the characteristics of non-terrestrial networks used as component of the 6G system and to some extent the beyond 5G system are summarized in Figure 3.

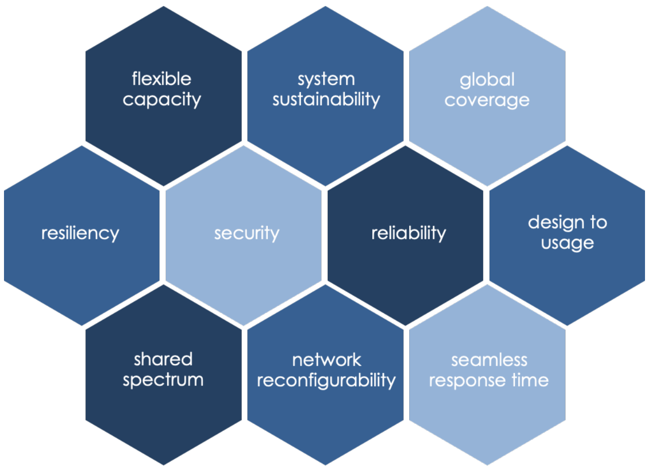


Figure 3. Key Elements of non-terrestrial networks for B5G/6G.

From an architecture point of view, Rel. 17 NTN is based on transparent payloads providing direct connectivity to handheld terminals in Frequency Range 1 (FR1), *i.e.*, L- or S-band. 5G-Advanced is expected to extend NTN to operate in FR2, *i.e.*, above 10 GHz, and to rely on more advanced architectures, encompassing: i) regenerative payloads; ii) Integrated Access and Backhaul (IAB) nodes; and iii) Multi-Connectivity (MC) concepts. The introduction of regenerative payloads will introduce the possibility to implement the functional split concepts in the NTN framework. In the initial implementations, it can be expected that a full gNB will be implemented on-board.

However, as mentioned above, 5G and 5G-A NTN systems are based on the NR standard, which has been specifically designed for terrestrial communications. From Rel. 17 onward, several enhancing features were introduce to support NTN, but still aiming at minimising the impact on the terrestrial component. With 6G, a further technology leap shall be introduced in which the terrestrial and non-terrestrial components will be jointly optimised. This will lead to a global 3D Multi-Dimensional Multi-Layered Multi-Band (MD-ML-MB) NTN architecture, as shown in Figure 4.

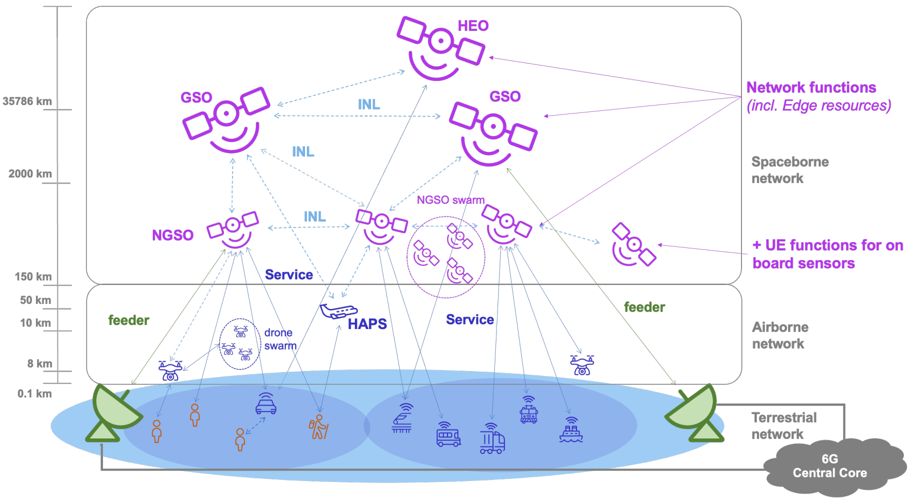


Figure 4. The 6G Multi-Dimensional Multi-Layered Multi-Band integrated architecture.

Table 1 summarises the evolution of services and deployment scenarios identified in the EAGER Study. It can be noticed that, for 6G NTN, in addition to the 3D ML-MO-MB architecture, which shall be designed according to the principles summarised in Figure 3, two additional key features will be introduced: the support of UEs without GNSS capabilities, *i.e.*, the introduction of network-based localisation, and advancements in spectrum coexistence between terrestrial and non-terrestrial systems.

Table 1. Summary of the identified use cases and deployment scenarios.

	5G	5G-Advanced	6G
Use cases	eMBB mMTC • global NB-IoT/mMTC coverage • remote control/monitoring of critical infrastructures • smart good tracking HRC • governmental services • emergency management	Broadcast/multicast through satellite	Ultra-MBB Immersive communications Ultra-critical communications Ultra-massive communications Network sensing Integrated AI
Deployment scenarios	Transparent payload in FR1 and FR2	Regenerative payloads IAB-based architecture Multi-Connectivity	3D ML-MO-MB architecture UE without GNSS NTN-TN spectrum coexistence

Table 2 reports a tentative identification of the target performance for the above-mentioned deployment scenarios in 5G-A and 6G NTN.

Table 2. Target performance requirements for 5G-Advanced and 6G services.

Terminal and deployment		Experienced data rate (DL/UL) [Mbps]	Latency [ms]		Reliability	Position error [m]	Position acquisition time [s]	UE speed [km/h]	Connection density [UE/km^2]
			UP	CP					
5G-A	Handheld, outdoor	1/0.1	GEO <600 MEO <180 LEO <50	<40	99.99%	<1	<2	3 (pedestrian)	[100]
	Handheld, outdoor Public Safety	5/5			99.999%	<1	<1	100	[50]
	Mobile platforms and building mounted VSATs	50/25			99.99%	<1	<2	<250	[100]
6G	Handheld, light indoor	1/0.1 (at least emergency services)			99.999%	<0.1	<1	N/A	[100]
	Handheld, outdoor	20/2			99.999%	<0.1	<1	3 (pedestrian)	[50]
	Vehicle or drone mounted	80/40 (<6 GHz) 300/150 (>6 GHz)			99.999%	<0.1	<1	100	[100]

In terms of enabling technologies, two parallel paths have been explored in EAGER: i) mid-term technologies, more industry oriented, focused on 5G-Advanced NTN (Rel. 18-19); and ii) long-term technology, more exploratory and research oriented, for 6G NTN (Rel. 20+). In this context, the following technologies have been identified as of interest together with ESA:

5G-Advanced

- Standalone Multi-User Multiple-Input Multiple-Output (MU-MIMO)
- Multi-Connectivity (MC) and Carrier Aggregation (CA)
- Beam management and Bandwidth Part Association (BWP)
- Support of Time Division Duplexing (TDD)
- Hybrid Duplexing
- Support of higher frequency bands
- Support of High Power User Equipments (HPUEs)
- NTN-TN/NTN-NTN mobility and service continuity
- Support of regenerative payloads

6G

- Joint Transmission (JT)
- Waveform constraints and design
- Artificial Intelligence (AI) and Machine Learning (ML)
- Inter-Satellite Links (ISLs)
- Non-Orthogonal Multiple Access (NOMA)
- Refractive Intelligent Surfaces (RISs)

As shown in Figure 5, a two-step prioritisation approach has been implemented: i) in **step 1**, a first **qualitative assessment** of the above-mentioned technologies has been implemented, taking into account the industrial interest and effort required to bring them in 3GPP, as well as the most relevant pros and cons; and ii) in **step 2**, a **quantitative assessment** of the technologies down-selected in step 1 has been implemented. This approach led to the identification of a subset of the considered technologies to be extensively evaluated by means of numerical simulations performed in the third and last step.

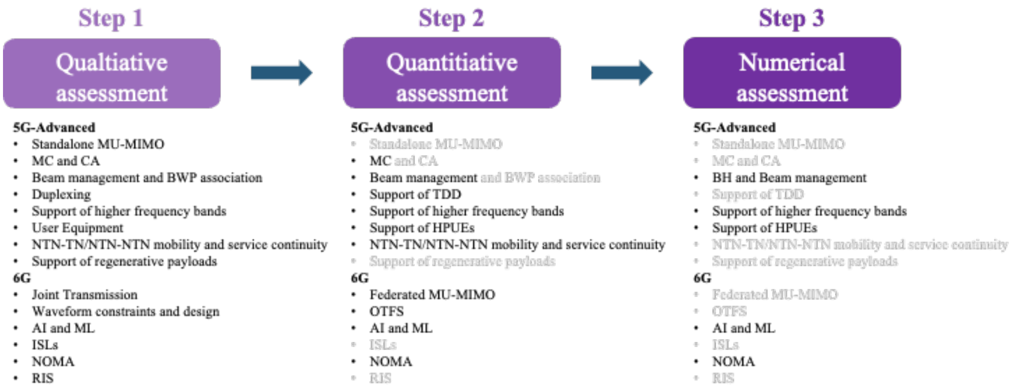


Figure 5. Prioritisation of the EAGER technologies.

During the qualitative assessment performed in step 1, after an exhaustive review of the State-of-the-Art, the major benefits and challenges for the implementation of each technology have been identified. Then, based on these considerations, the technologies have been classified in terms of industrial interest, effort required for their development in 3GPP, and availability of previously developed software within the Team (for their assessment in steps 2 and 3). This led to the identification of the technologies to be numerically assessed in step 2, summarised in Figure 5. Based on such quantitative assessment, the following techniques were retained for the detailed numerical evaluation in the last phase of the Study:

- 5G-Advanced
    - Support for higher frequency bands: as part of Rel. 18, a new WI was proposed to define enhancements for NG-RAN based NTN in order to support of new scenarios to cover deployments in frequency bands above 10 GHz. In this regards, relevant coexistence scenarios and analysis have been conducted in EAGER to ensure that satellite bands introduced in 3GPP for NTN would not impact the existing specifications and would not cause degradation to networks in 3GPP specified terrestrial bands adjacent to the NTN band assuming:
        - GSO and NGSO based satellite access.
        - Fixed and mobile VSAT.
        - FDD mode for satellite operation above 10 GHz, TDD mode for terrestrial operation in FR2.
        - ITU-R harmonized Ka-band as reference.
    - Support of HPUEs: during RAN#97, it was agreed that the decision to specify HP UE (*e.g.*, 26 dBm Tx power) for NTN FDD FR1 band(s), *i.e.*, Rx/Tx requirements would be discussed at RAN#99 (March 2023) as part of coverage enhancements of Rel. 18. Further, the Public Safety community expressed its interest in direct connectivity to handheld with wide band service (3.5 Mbps on both directions) such that it can support video communications. This is reflected in 3GPP TS 22.261. Based on our preliminary performance evaluation, HPUEs (*e.g.*, PC2) support in NTN is beneficial to satisfy the performance requirements for satellite access for public safety and automotive industry use cases.
- 6G
    - AI/ML: studies on the application of AI and ML are already on-going within 3GPP in dedicated WIs and it is globally recognised that native AI will be one of the pillars for future unified TN-NTN systems. Thus, AI/ML techniques have been selected for the numerical assessment for: i) CSI prediction; and ii) NOMA.

- NOMA: a preliminary performance assessment was performed in step 2, showing that this solution can provide a good performance (in terms of BER) on both AWGN and TDL channels. In addition, NOMA is currently of great interest within 3GPP. Finally, implementations based on AI solutions and the exploitation of the predicted CSI with AI are both viable options for further analyses. Based on these observations, NOMA was selected for the detailed numerical assessment.

Table 3. Selected techniques for the numerical assessment.

System	Technique	Comments
5G-Advanced	TN-NTN adjacent channel co-existence studies in FR2	Coexistence analyses targeting Rel. 18
	Support of HPUE	Assessment of DL channels Target data rates for public safety Support of PC1.5 and PC1 (FFS) Coexistence scenarios
6G	AI/ML	CSI prediction Application to NOMA
	NOMA	Exploitation of the AI-based CSI prediction FFS

Beam management and power saving

In addition to the above, also beam management solutions to implement Beam Hopping (BH) in NTN was discussed. In fact, considering the large number of satellite beams to be served, the total power allocated to the satellite payload may not be sufficient to have all beams active at the same time at the EIRP density defined in TR 38.821. For example, it could be that only 10% to 15% of satellite beams could be simultaneously active with a nominal DL power density of 34 dBW/MHz at LEO 600 km based NTN deployment in S-band. Thereby, efficient power and beam management are needed for optimized satellite beam illumination plan. To this goal, different solutions should be combined together to enable an efficient beam hopping in 5G NTN:

- Take benefit of beam management techniques specified in 5G NR and adopted as baseline in 5G NTN. This would allow to define/group a cluster of several satellite beams that are mapped to the same cell and for which the resources of the cell (including cell nominal power) will be shared based on beam management. In this case, 5G NR beam management techniques can allow an optimized satellite beam illumination plan. However, the 3GPP beam management algorithm is only operating at cell level and may de facto have some limitation and could be used alone to resolve the issue discussed above and enable an optimized satellite beam illumination plan.
- Satellite payload power saving techniques are also needed, leveraging the new techniques that are being studied and specified in 3GPP Rel. 18. Some of these techniques are not going to be specified as part of Rel. 18, and some other novel power/energy techniques may need to be explored. Thus, further study of satellite payload power saving techniques in Rel. 19 would be highly recommended, *e.g.*:
  - adapting transmission/reception of common channels/signals;
  - adaptation of UE specific signals and channels;
  - UE wake up signal (WUS) for gNB;
  - adaptation of DTX/DRX;
  - adaptation of SSB/SIB1 including on-demand SSB/SIB1;
  - legacy UE and RAN1 specification impacts;
  - higher layer aspects for network power savings;
  - cell selection/reselection, Connected mode mobility, Inter-node Beam Activation, Paging Enhancements.

- Downlink coverage enhancements: with limited total transmission power and based on the required SNR of physical channels supported for NR NTN up to Rel. 17, a satellite can only serve a small part of the potential coverage area at a time. Further, the satellite may have the capability to share Tx power among beams at a given time, resulting in reduced EIRP. To extend the number of satellite beams that could be simultaneously activated/illuminated the nominal available power per beam could be dynamically split between several beams (*e.g.*, between 4 beams which lead to a power reduction of 6 dB). Therefore, DL coverage enhancements techniques will be beneficial for an optimized satellite beam illumination plan to support a wider range of deployment scenarios and satellites in terms of aperture and transmission power.

The techniques enabling an efficient beam hopping in 5G NTN with an optimized satellite beam illumination plan are illustrated in Figure 6.

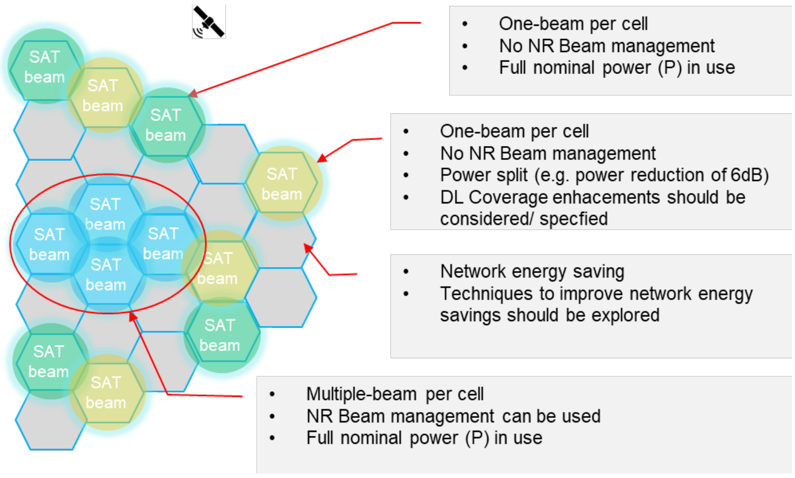


Figure 6. Techniques enabling an efficient beam hopping in 5G NTN.

TN-NTN coexistence

3GPP Rel. 18 NR NTN enhancements WI lists "NR-NTN deployment in above 10 GHz bands" as one of the key features. A major factor in making this happen is to make sure that existing FR2, *i.e.*, frequencies between 24.25 and 71.0 GHz terrestrial TDD deployments, are not impacted by potential NTN FDD FR2 deployments. RAN4 co-existence studies aim to specify Rx/Tx requirements for SANs and different VSAT UEs. The same process used for FR1 co-existence should be used and

Table 4 lists the coexistence scenarios for this assessment. The objective of the EAGER analyses was to specify the NTN Rx/Tx requirements, namely ACS and ACLR, for SAN and VSAT UEs. The 3GPP co-existence results were obtained with the C-DReAM simulator developed by Magister Solutions.

It was observed that the NTN SAN ACLR and SAN requirements are very low at well below 10 dB. And for the NTN UT, only 10 dB ACLR is required in scenario 1 where the NTN UT uplink is interfering TN uplink reception at gNB. NTN UT ACS has a stricter requirement of 20 dB in scenario 5 where TN gNB downlink transmission interferes the NTN UT downlink reception.

Table 4. 3GPP RAN3 FR2 Co-existence Scenarios.

No.	Combination	Aggressor	Victim	Freq band	Variate	TN ACI config
1	TN with NTN	NTN UL	TN UL	27 GHz	ACLR NTN UT to be varied	TN gNB ACS **24 dB**
2	TN with NTN	TN UL	NTN UL	27 GHz	ACS NTN SAN to be varied	TN UE ACLR **17 dB**
3	TN with NTN	NTN UL	TN DL	27 GHz	ACLR NTN UT to be varied	TN UE ACS **23 dB**
4	TN with NTN	TN DL	NTN UL	27 GHz	ACS NTN SAN to be varied	TN gNB ACLR **28 dB**
5	TN with NTN	TN DL	NTN DL	17 GHz	ACS NTN UT to be varied	TN gNB ACLR **30 dB***

6	TN with NTN	NTN DL	TN DL	17 GHz	ACLR NTN SAN to be varied	TN UE ACS **25 dB***
7	TN with NTN	NTN DL	TN UL	17 GHz	ACLR NTN SAN to be varied	TN gNB ACS **26 dB***
8	TN with NTN	TN UL	NTN DL	17 GHz	ACS NTN UT to be varied	TN UE ACLR **19 dB***
NOTE 1: For coexistence between Ka-Band DL and adjacent TN bands, there are no 3GPP defined/specified TN bands. *17 GHz TN ACS/ACLR values have not been agreed upon and are subject to change.						

Table 5. Co-existence results and sensitivity analysis.

Scenario	Aggressor-victim	Required NTN ACS / ACLR	TN scaling impact	SAT elev. angle impact /w 1.5m NTN UT*	NTN UT height impact	SAT elev. angle impact /w 22.5m NTN UT	NTN UT antenna sidelobe impact /w 1.5m UT	NTN UT-gNB isolation distance impact	NTN UT – TN UE isolation distance impact	NTN UT outside TN cluster impact
SC1	NTN UL-TN UL	~ 10 dB	None	----	+++	-	----	+	None	+++
SC2	TN UL-NTN UL	< 10 dB	-	-	None	-	None	None	None	None
SC3	NTN UL-TN DL	< 10 dB	None	--	++	-	---	None	++	+++
SC4	TN DL-NTN UL	< 10 dB	--	-	None	-	None	None	None	None
SC5	TN DL-NTN DL	~ 20 dB	None	----	++	-	----	+	None	+++
SC6	NTN DL-TN DL	< 10 dB	None	--	None	--	None	None	None	None
SC7	NTN DL-TN UL	< 10 dB	None	-	None	-	None	None	None	None
SC8	TN UL-NTN DL	~ 10 dB	None	--	+	-	--	None	++	+++

None: No impact; ----: 1 to 4 negative points. More ACI; ++++: 1 to 4 positive points. Less ACI.
**Low elevation, 1.5 m NTN UT, and urban is not a likely scenario combination*

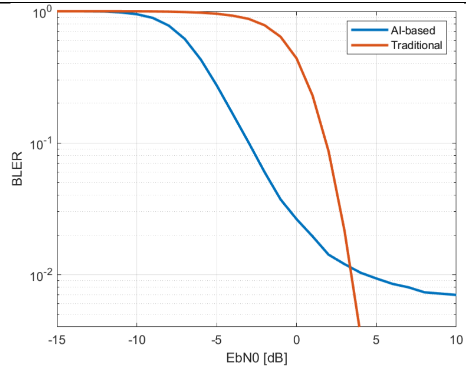
However, there are many uncertainties with the results which are captured in Table 5. There we have marked how each change could impact ACI results on a relative -4 to 4 scale based on the results and analysis. The two most critical aspects are low satellite elevation and less ideal NTN UT antenna sidelobes when the NTN UT is at 1.5 m in height. The most affected cases are 1 and 5, *i.e.*, NTN UT ACLR and ACS are impacted. For both scenarios, higher NTN UT, and isolation to gNB would help. TN scaling, *i.e.*, a larger TN network does not seem to be a problem for the NTN reception. The sensitivity analysis table should be treated as a priority list for further studies, not yet definitive.

NOMA and AI

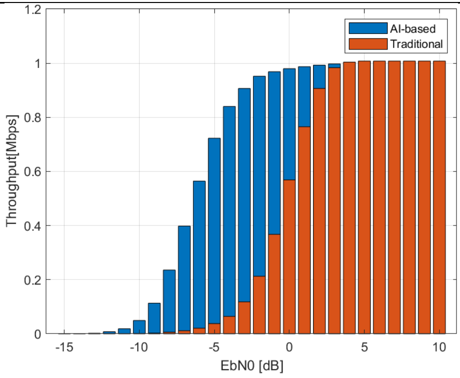
With respect to NOMA, a (6,4) SCMA scheme was considered, *i.e.*, 6 UEs transmitting on 4 subcarriers. The numerical assessment showed that, with an ideal estimation, the BLER can be as low as 10^{-4} for E_b/N_0 equal to 2 dB and a code rate equal to 193/1024, while larger code rates require higher values of the received E_b/N_0. In terms of throughput, the benefit compared to a single-user scenario is massive: when considering a code rate equal to 602/1024, the throughput is increased from approximately 0.3 Mbps to 1 Mbps. The simulations clearly highlight that in order to allow the SCMA to properly work in the NTN scenario same enhancements need to be considered. These solutions can be either at the transmitter side, e.g., by designing a mother constellation that does not provide information only in the phase; and/or at the transmitter side, by exploiting pilots within the time slots and implementing SIC to continuously update the estimate of the channel coefficients.

When implementing AI-based NOMA demodulation, the BLER is massively reduced (with a gain up to 5 dB at 10^{-1}), showing the great potential that this technology yields. However, an error floor was observed after 10^{-2}, highlighting conditions in which the Neural Network is not able to demodulate the received grid. To understand the motivation for this floor, the AI network has also been trained and tested on a reduced dataset. This test allowed to verify that the smaller the dataset, the sooner the error floor arises. Thus, the above-mentioned issue related to the error floor can be tackled by training the NN on larger datasets. The computational complexity of the AI-based demodulator has then been assessed in terms of the number of additions, multiplications, exponentials, and maximum, showing that the improved demodulation performance comes at the expense of an increased complexity. Finally, it was shown that the average demodulation duration with the AI-based demodulator is 3.43 times that with the traditional scheme. However, the demodulation with the trained NN can be efficiently parallelized using AI-dedicated hardware such as Graphic Processing Units and Tensor Processing Units, leading to a further possible reduction in the average demodulation duration.

With respect to AI-based CSI prediction, the performance has been assessed in terms of the MSE between the reference CSIs included in the test dataset and the CSIs predicted by the NN module. The MSE has been computed for both the amplitude and the phase, as well as an aggregated measure. In general, it was observed that the amplitude has a better prediction performance compared to that on the phase, due to the dataset statistics in which a weak phase correlation is present. The prediction performance was also evaluated as a function of the elevation angle; it was observed that no particular trend is present, *i.e.*, the NN can be proficiently exploited in extended coverage areas without losing accuracy.



(a) BLER

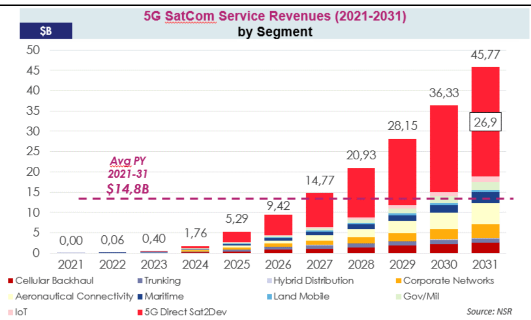


(b) theoretical throughput

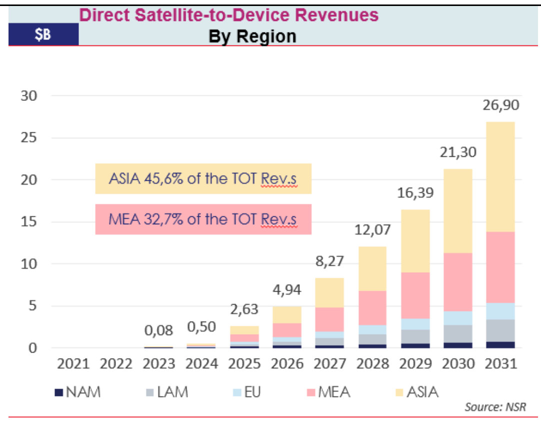
Table 6. Comparison between traditional and AI-based NOMA demodulation.

Market analysis and TRL

In the last phase of the Study, an extensive market analysis was performed covering both 5G-A and 6G NTN, with a focus on existing and impending satellite constellations offering services in three areas: broadband and Internet, IoT connectivity, and Direct satellite to Device (D2D). 5G is expected to have a significant impact in multiple areas, including D2D, IoT, backhaul, airborne, maritime, and enterprise networks. The total cumulative revenue for these areas is expected to reach $162.9 billion between 2021 and 2023. With the approval of Rel. 17, D2D could become the largest satellite market, with a cumulative revenue of $93.1 billion (57% of the total) between 2021 and 2031. This is expected to reach $26.9 billion by 2031.



(a) SatCom revenues



(b) D2D revenues

Figure 7. SatCom and D2D revenues, with forecast, between 2021 and 2031.

Today, broadband connections are already offered by several NTN operators with proprietary technology, using VSAT/dish antennas at the user equipment for reception of broadband speeds on Ka or Ku bands. Most of the focus in NTN deployments is on the use of GEO and LEO satellites, with the most common approach for GEO satellites to be used for fixed broadband and IoT (*i.e.*, for non-delay-critical services), whereas LEOs are more attractive for their low delay and better link budget due to the much lower distance. These providers offer communication services to fixed user devices, but devices can be moved from one location to another. In the ever-evolving landscape of Satellite Communications, a triumvirate of LEO constellations has emerged as the vanguard of technological innovation. Starlink, OneWeb, and Kuiper, each with their unique aspirations and designs, spearhead the race towards a new era of global connectivity.

The use of NTN technologies has numerous potential use-cases also for IoT applications, which can be served from both LEO or GEO satellites, particularly in remote and hard-to-reach areas. For example, precision agriculture systems can leverage real-time data from sensors placed on unmanned aerial vehicles to optimize crop yields and reduce resource waste. Similarly, remote monitoring and control of critical infrastructure such as oil rigs, wind turbines, and mining sites can be made more efficient and secure with the help of NTN-enabled sensors and actuators. Direct-to-cellular services are also emerging, offering emergency and messaging services with the promise to evolve to higher speeds over LEO networks. Today, many IoT and D2D service providers and partnerships are arising, including, among the others, pre-Rel. 17 (T-Mobile/SpaceX, AT&T/AST, Vodafone/AST), Rel. 17 NB-IoT (Sateliot, Ligado), and Rel. 17 NR-NTN (MediaTek/Skylo/Bullitt, Skylo/Ligado/Viasat) solutions.

Finally, Table 10 summarises the TRL of the considered 5G-Advanced and 6G technologies.

Table 7. Summary of the TRL for the considered 5G-Advanced and 6G technologies.

Generation	Technology		TRL	Observations
5G-Advanced	Standalone MU-MIMO		2	• CSI/location estimation available • Partially supported by the standard • Need for additional laboratory evaluation in different use cases (FR1-2, SCS, beam management, …)
	Multi-Connectivity		3	• Detailed signalling mechanisms • Effect of TN/NTN propagation delays • Impact of regenerative payloads
	TDD		2	• Need for adjustments to procedures • Need for tight coordination and synchronisation
	Higher bands		2	• No Proof of Concept is available
	NTN-TN/NTN-NTN mobility and service continuity		2	• No Proof of Concept is available
	Regenerative payloads			•
6G	Federated MU-MIMO		2	• The same considerations as per standalone MU-MIMO techniques hold • Need for close to ideal ISL • Need for additional laboratory evaluations
	NOMA		2	• PoC for terrestrial network under the RRC connected state hypothesis • More scenarios need to be considered • In NTN challenges in synchronization and CSI estimation
	AI	On-ground processing	5	• TRL varies between use cases • TRL 5 reached in Project ATRIA's use cases • TRL 3 reached in other investigated use cases
		On-board processing	2	• Need for low-power AI computing
	OTFS		3	• PoC for TN • For NTN more scenarios need to be considered