



Unlocking The Potential of Non-Terrestrial Networks with 6G Technologies

eBook

 **KEYSIGHT**

INTRODUCTION

If you happen to look up at the sky at dawn or dusk, chances are it is easier to spot a satellite now vs a decade ago. Since the very first artificial satellite – Sputnik 1 – was launched on October 4th, 1957, there are now an estimated 12,000 to 15,000 satellites orbiting the Earth (see Figure 1).

An **estimated 88%** or almost 9 out of 10 of these satellites operate in low earth orbit, or LEO. LEO satellite systems are a key enabler for current 5G and upcoming 6G non-terrestrial networks (NTNs). With their low latency and high capacity for global coverage, LEO satellites are proliferating in space.

The much-anticipated 3GPP Releases 20 and 21 will advance the integration of LEO satellites with terrestrial networks, defining technical standards that support regenerative satellite payloads, expanded spectrum usage, and seamless handovers. Beyond LEO, these releases will include working towards stronger terrestrial-non-terrestrial network (TN-NTN) convergence, AI-powered air interface enhancements, and new spectrum bands. These are all aimed at meeting IMT-2030 goals (see Figure 2).

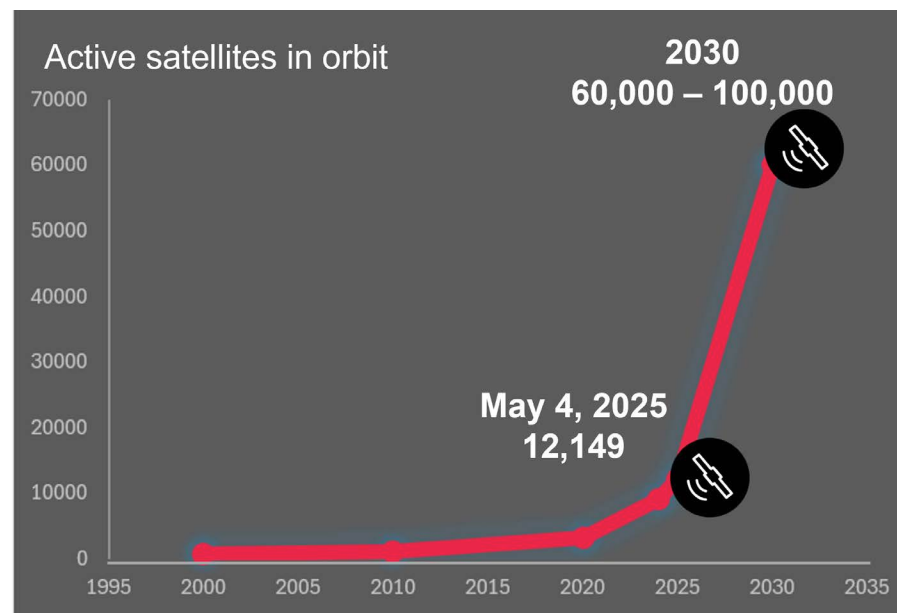


Figure 1. Exponential growth in the satellite market.

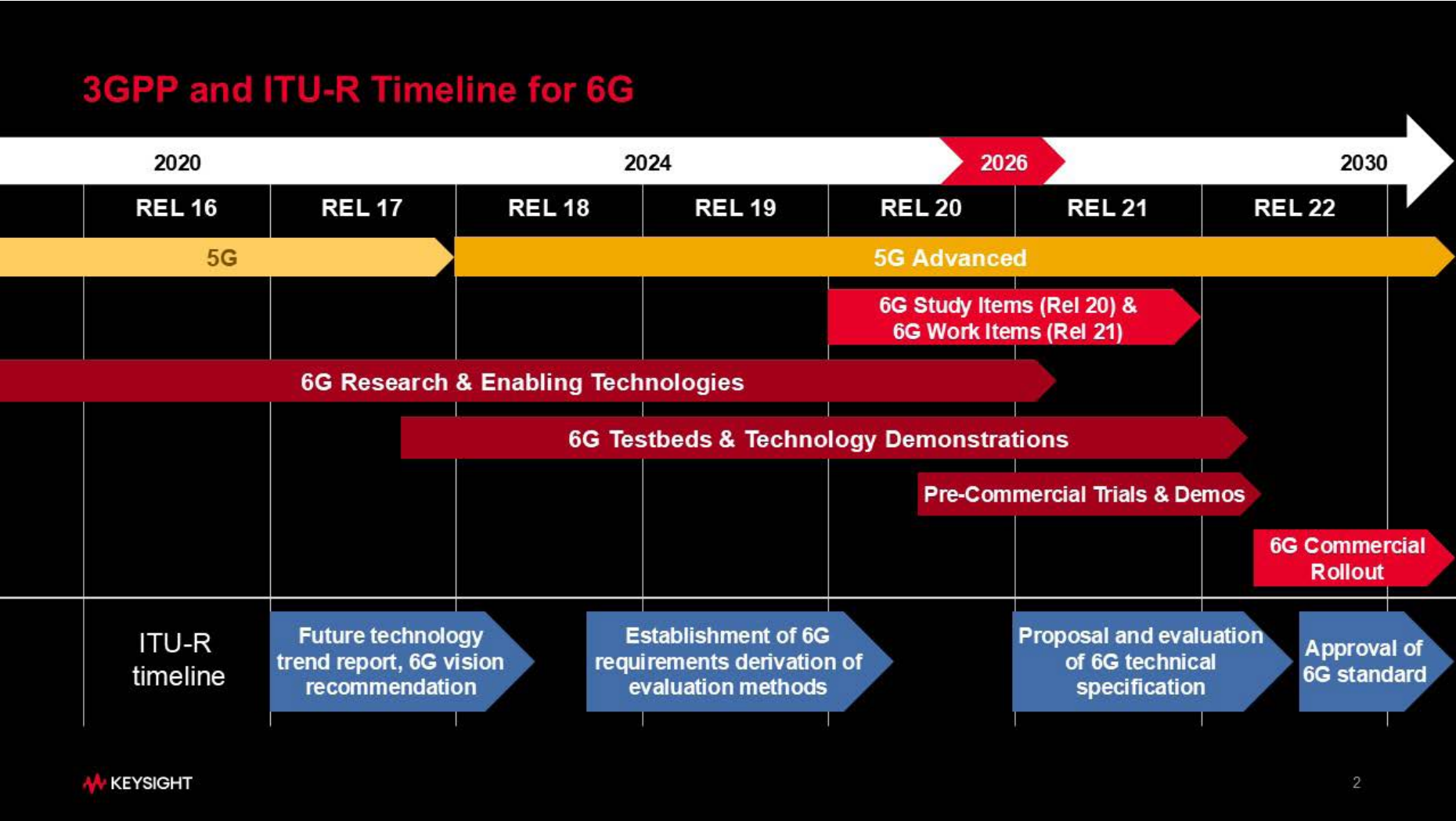


Figure 2. Working alongside 3GPP, the International Telecommunication Union Radiocommunication Sector (ITU-R) is developing the IMT-2030 framework by defining technology requirements, evaluation criteria, and global spectrum policies for 6G NTN.

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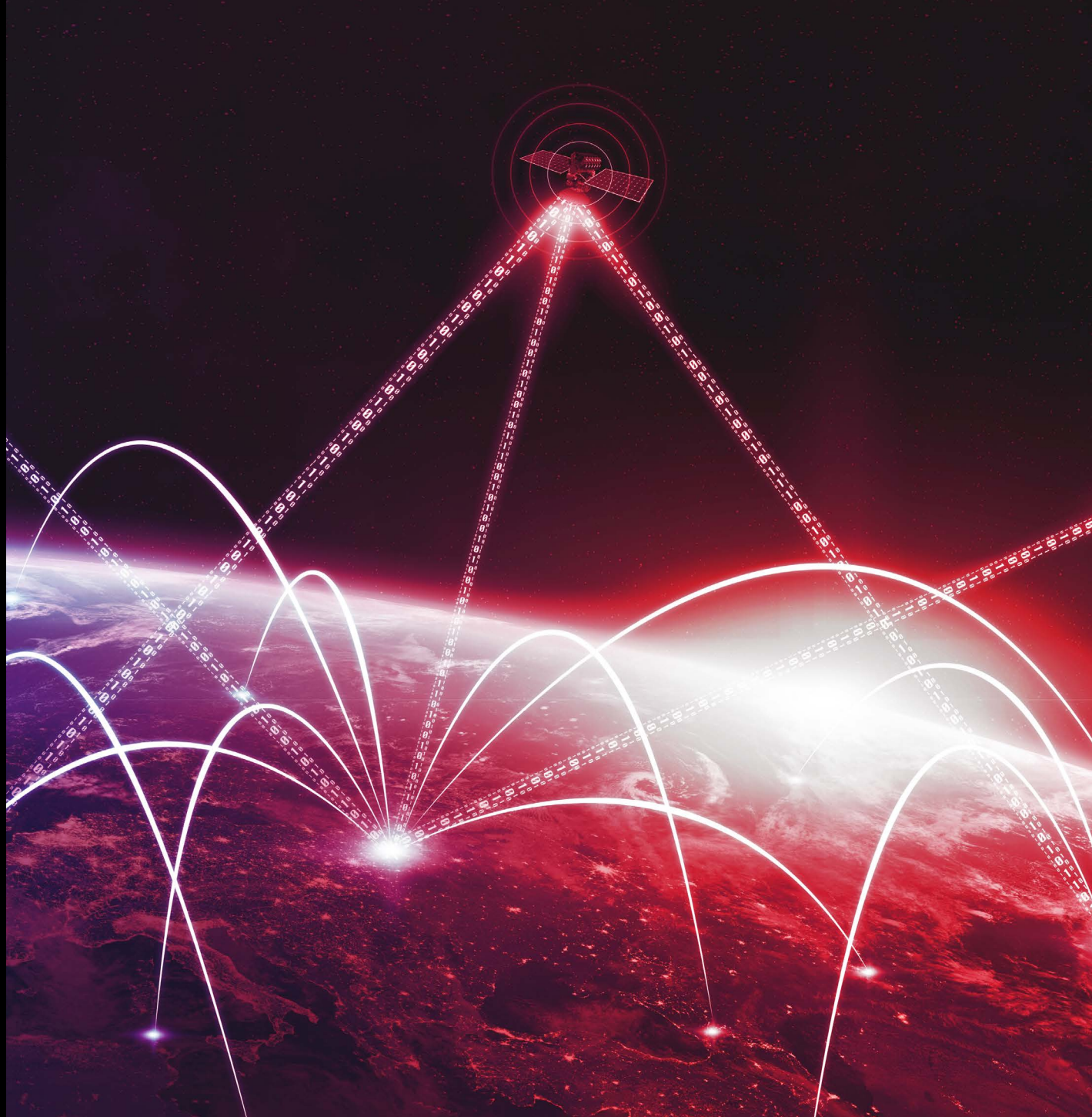
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CHAPTER 1

The 5G to 6G NTN Evolution



The 5G to 6G NTN Evolution

The evolution from 5G to 6G marks a significant transition in the role and architecture of NTNs. In 5G, NTN was introduced as a supplemental capability, primarily through transparent satellite payloads acting as radio repeaters. These systems extended coverage to underserved areas but relied heavily on terrestrial infrastructure for core network functions. Integration was also incremental, with NTN support added in later releases (starting from 3GPP Release 17), and focused on specific use cases like IoT-NTN and NR-NTN (see Figure 3).

In contrast, 6G NTN is envisioned as a “Day 1 native” component, designed from the ground up to be an integral part of the overall network architecture. This enables seamless convergence between terrestrial and non-terrestrial domains, allowing for unified control, resource management, and service delivery. The native integration of NTN into 6G supports direct-to-device connectivity, dynamic spectrum sharing, and AI-driven orchestration across space and ground.

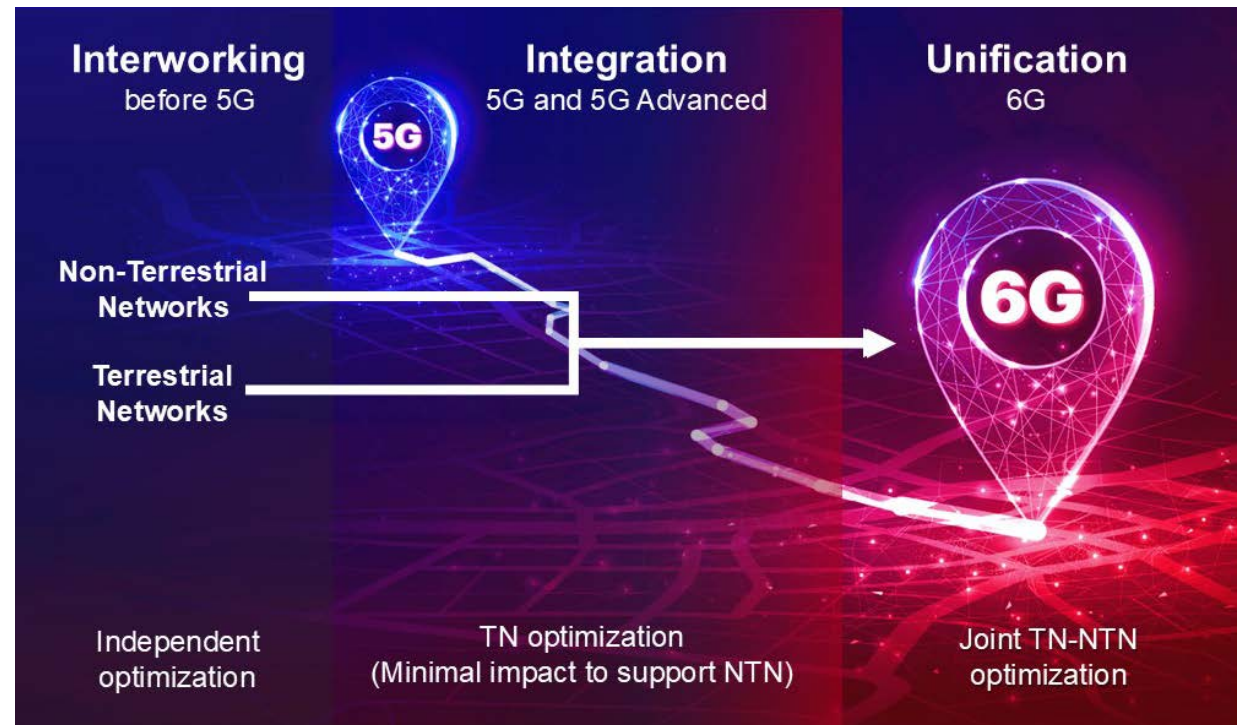


Figure 3. The convergence of terrestrial and non-terrestrial networks towards an optimized 6G network.

3D Network Architecture and Multi-Orbit Support

A defining feature of 6G NTN is its 3D network architecture, which spans terrestrial, aerial, and space layers. This multi-layered design incorporates low earth orbit or LEO, medium earth orbit (MEO), and geostationary orbit (GEO) satellites, along with high-altitude platforms (HAPs), and unmanned aerial vehicles (UAVs), as illustrated in Figure 4.

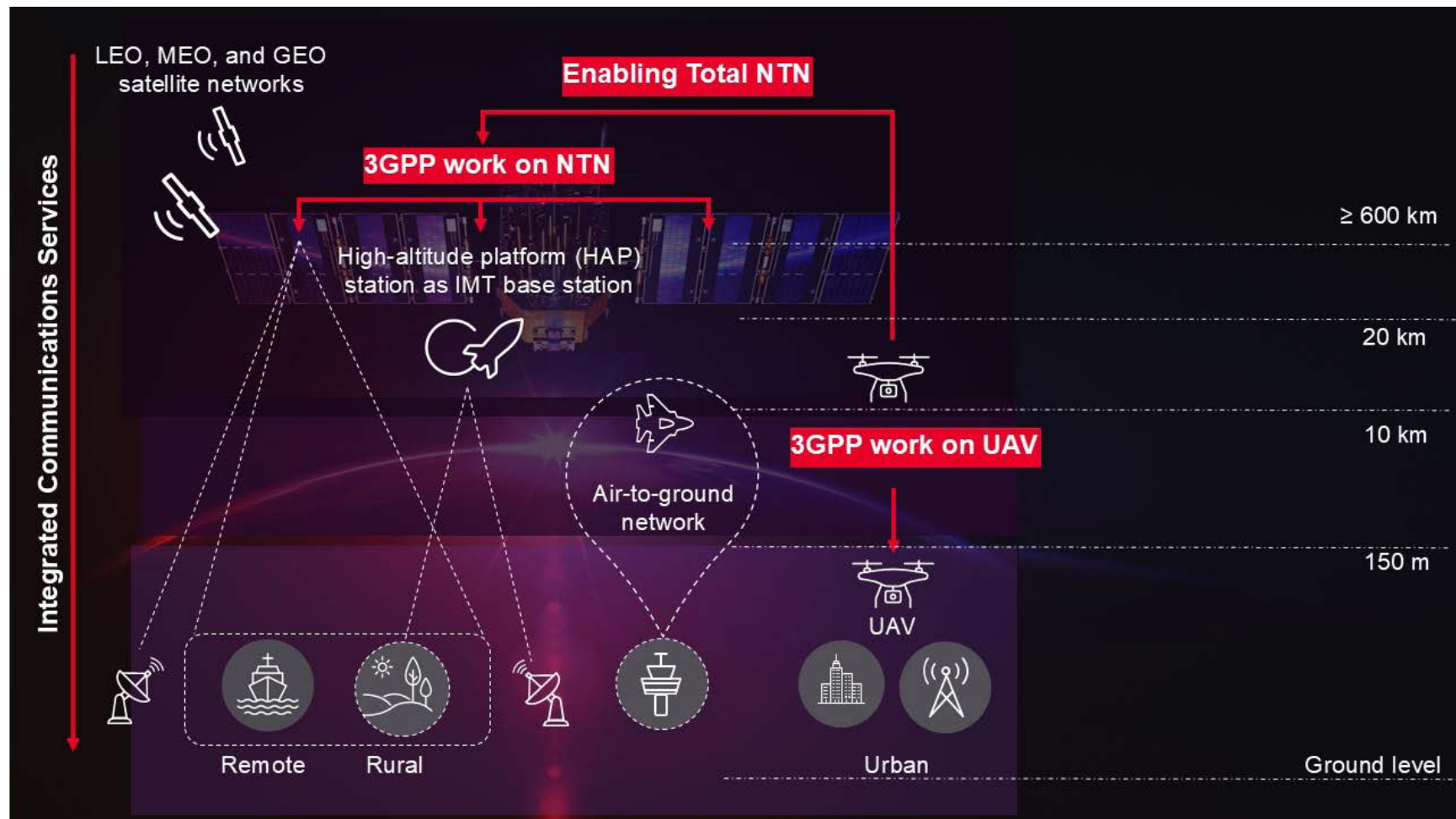


Figure 4. The 3D architecture of 6G terrestrial-NTN framework enables multi-connectivity and seamless handover across layers, ensuring robust and ubiquitous coverage. It also supports advanced use cases such as autonomous mobility, maritime and aerial communications, and emergency response in remote areas.

IMT-2020 vs IMT-2030: Evolution and Innovation

The transition from 5G under IMT-2020 to 6G under IMT-2030 reflects both evolutionary enhancements and some revolutionary innovations. IMT-2020 focused on three core scenarios: enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC). Explorations are underway to extend these capabilities in IMT-2030 through eMBB+, URLLC+, and mMTC+, offering improved performance, reliability, and coverage (see the purple segments of the palette diagram in Figure 5).

IMT-2030 also introduces new scenarios that redefine the role of 6G NTN in global connectivity. These include integrated sensing and communication (ISAC), AI-native networks, precise positioning, and immersive extended reality (XR). The ITU's IMT-2030 framework emphasizes NTN as a key enabler for ubiquitous coverage, especially in underserved regions. The vision includes multi-orbit satellite constellations, direct-to-device services, and dynamic spectrum harmonization across terrestrial and non-terrestrial domains (see the orange segments of the palette diagram in Figure 5).

Together, these advancements position 6G NTN as a cornerstone of the future digital ecosystem to deliver intelligent, sustainable, and globally inclusive connectivity.

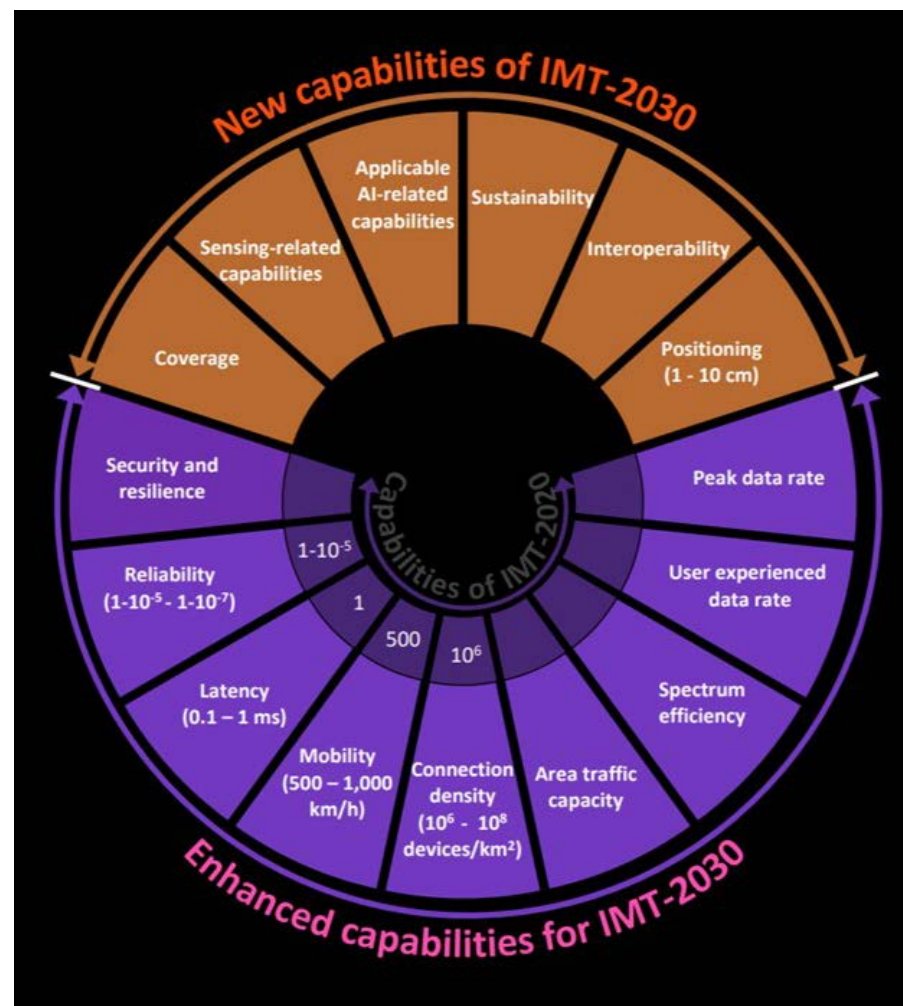


Figure 5. The wireless communications industry recognizes that 6G is more of an evolutionary progression than a complete revolution towards IMT-2030 from IMT-2020. (Note: The range of values given for capabilities are estimated targets for research and investigation of IMT-2030).



CHAPTER 2

6G NTN Market Drivers



6G NTN Market Drivers

Monetizable applications and services are important for the viability and success of new technologies. By 2035, NTN services alone will account for \$15 billion of the total revenue for the global NTN and D2C services market, driven by applications in internet of things (IoT), emergency communications, and rural broadband (see Figure 6). Direct-to-cell (D2C) applications enabling satellite-to-smart devices are estimated to generate \$10 billion by 2035 as 3GPP Releases mature.

From a bottoms-up perspective, this new era of NTN-D2C convergence spurs many market opportunities. For example, while satellite broadband is already providing digital learning platforms from Kenya to India, adoption is limited by lags due to latency, bandwidth, and data caps, as well as costs and scalability. With ubiquitous connectivity built-in from Day 1, 6G can foster wider adoption and service for under-served communities. For time-critical emergency response scenarios, 6G NTN can use AI to prioritize emergency communications automatically, with high-capacity backhaul, and integrated sensing and communication (ISAC) to expedite communications. These may override the current 5G limitations, which include coverage, deployment, and interoperability issues.

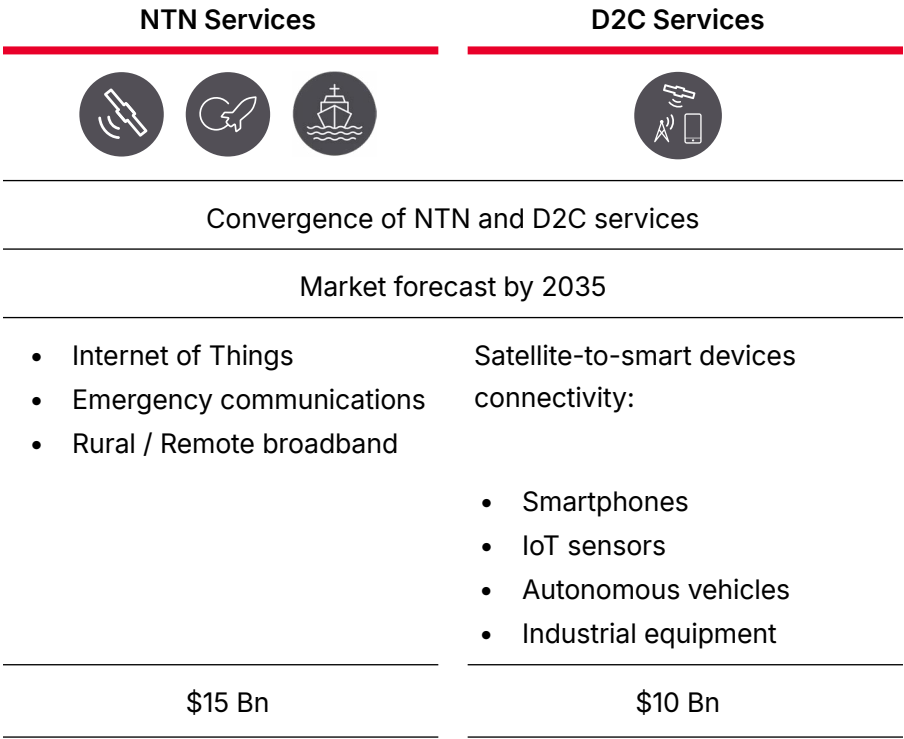


Figure 6. Convergence of NTN and D2C will drive market growth in the decade ahead. (Source: TMT Market Research and Analysis)

From chip to infrastructure on one hand, to services and applications on the other, 6G NTN is opening up many business opportunities across various industries (see Figure 7).

While the market potential of 6G NTN is significant, its realization hinges on the advancement of several foundational technologies.

Meeting the IMT-2030 objectives will require breakthroughs that transcend incremental improvements in connectivity. Researchers are already working on innovative technologies, including AI-native networks, integrated sensing and communication (ISAC), advanced spectrum and orbital resource management, and secure-by-design architectures.

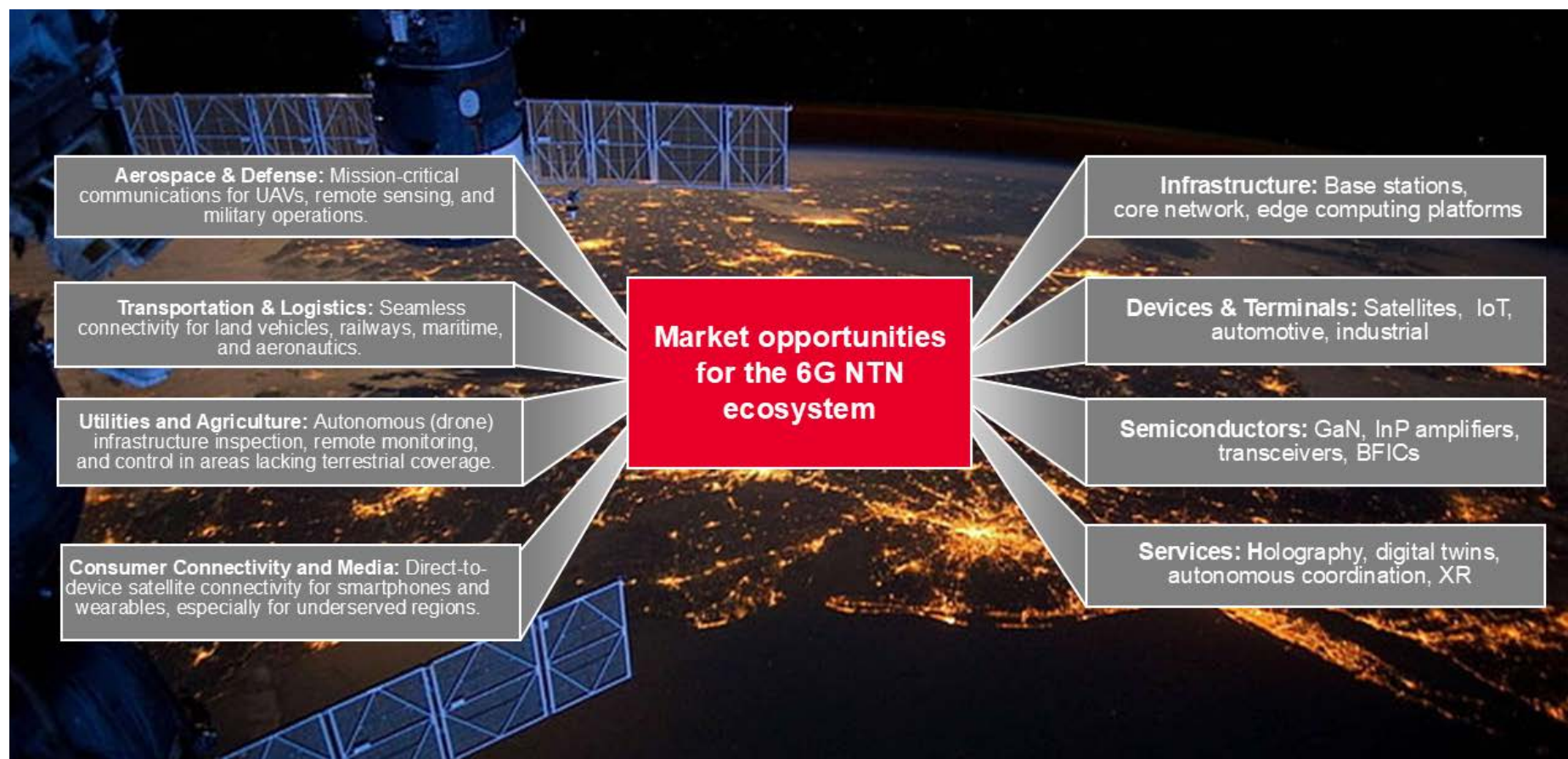
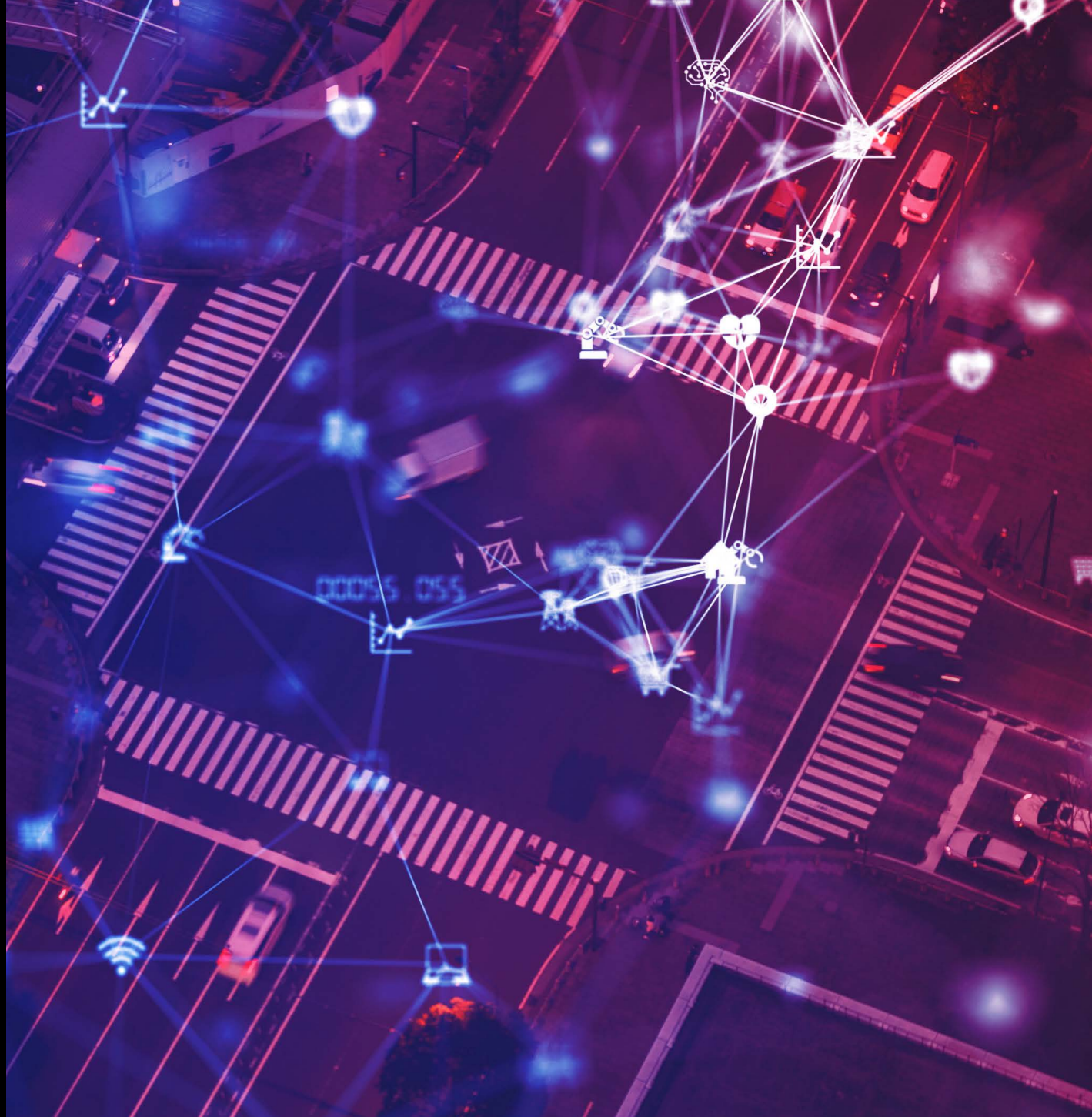


Figure 7. 6G NTN potentially expands market opportunities through new use cases for consumer, enterprise, and vertical markets. (References: [Vision on Non-Terrestrial Networks in 6G system \(or IMT-2030\)](#); [The Global 6G Market Report 2026-2036](#))



CHAPTER 3

Technology Candidates for 6G NTN



Technology Candidates for 6G NTN

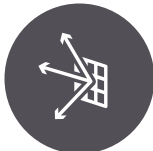
The evolution toward a unified 3D network in 6G demands resilient technology that can meet expected key performance indicators (KPIs) within standardization and interoperability frameworks, as well as governance models. Candidate technologies that have gained interest from the 6G community must tackle the challenges mentioned in Table 1.

While these technology candidates hold great potential to enable a robust 3D 6G NTN network, extensive research and development is needed to further characterize their behaviors under different scenarios and use cases. To translate these promising technologies into practical applications, targeted investigations are essential to uncover their operational boundaries and performance trade-offs.

For instance, ISAC must balance dual-function efficiency, RIS faces challenges in dynamic reconfigurability, FR3 suffers from increased path loss and limited coverage, while AI-RAN and O-RAN require robust data governance and seamless orchestration across heterogeneous networks. xMIMO, though powerful, demands scalable antenna design and real-time beamforming precision. Addressing these limitations calls for innovative mitigation strategies such as hybrid sensing-communication protocols, intelligent RIS control algorithms, advanced channel modeling for FR3, and federated learning frameworks for AI-RAN.

Early design validation and testing leveraging emulation platforms, hardware-in-the-loop setups, and AI-driven simulation environments are critical to de-risking investments and ensuring alignment with emerging IMT-2030 performance benchmarks. These efforts collectively accelerate the maturity of 6G NTN technologies, fostering a resilient and adaptive network architecture for future global connectivity.

Table 1. Key 6G NTN technology enablers and challenges engineers need to address for implementation.

6G NTN Technology Enabler	Potential Benefits		Challenges
Integrated Sensing and Communication (ISAC)			
	Converges environmental sensing and wireless data transmission into one coordinated network function.	• Usage of existing 5G and planned 6G antennas, transceivers, and power amplifiers for both transmission and environmental sensing. • ISAC waveforms can maximize spectral efficiency and adapt to channel and hardware imperfections, while enabling real-time environmental awareness.	• Communication systems prioritize throughput and latency, while sensing demands high resolution and accuracy. • Need to manage peak-to-average power ratio (PAPR) levels to balance detection accuracy and transmission power efficiency.
Reconfigurable Intelligent Surfaces (RIS)			
	Enables multi-beam shaping by using the same surface to reflect signals toward multiple users or regions simultaneously, boosting coverage.	• Adjustable phase shifts of RIS create destructive interference vs unwanted directions (null steering). This reduces interference between users or beams, critical in dense NTN scenarios. • Better spatial multiplexing – more users can share the same frequency resources without degrading performance.	• Severe path loss and dynamic geometry in NTN; need to find optimal RIS placement / orientation on aerial / space platforms. • The NTN system must estimate and update RIS configurations rapidly despite high mobility and latency, without overwhelming the control channel.
Frequency Range 3 (FR3)			
	Introduces the midband spectrum (7-24 GHz), balancing coverage and capacity for NTN.	• FR3 balances coverage and throughput by enabling better outdoor-to-indoor penetration than millimeter-wave (mmWave) while supporting wider bandwidth than sub-6 GHz. • FR3's intermediate wavelength allows packing more antennas into constrained NTN nodes like satellites or UAVs, empowering ultra-massive MIMO and precise beamforming.	• FR3 propagation requires advanced unified channel models that capture line-of-sight, non-line-of-sight, blockage, and angular characteristics accurately across terrestrial and NTN environments. • Power amplifiers, mixers, and tunable filters capable of wideband FR3 operation are not yet commercially mature.

6G NTN Technology Enabler	Potential Benefits	Challenges
AI-Enabled Radio Access Networks (AI-RAN)		
 Embeds intelligence into network management, optimizing resources, traffic, and services autonomously.	- Adaptive resource management for NTN-specific challenges such as long propagation delays and satellite mobility. - Predictive maintenance, traffic steering, and interference mitigation for robust connectivity and smooth handover between terrestrial and NTN components.	- There is limited training data for designing AI models that can process diverse and rapidly changing NTN scenarios. - Ensuring AI-RAN scalability and interoperability across heterogeneous NTN platforms and multi-vendor equipment under complex standardization environments.
Open RAN / O-RAN		
 Supports open, flexible RAN infrastructures encouraging multi-vendor ecosystems and rapid feature innovations for 6G NTN.	- Open architecture enables flexible, programmable control and multi-vendor interoperability for adapting NTN deployments quickly to both mission and network requirements. - RAN intelligent controllers (RICs) in O-RAN dynamically optimize resource management and interference mitigation for NTN environments, enhancing efficiency and reliability.	- Integrating NTN elements (e.g., feeder links, satellite parameters) with O-RAN's architecture, to ensure timely and accurate information exchange between NTN components and RICs. - RICs and service management functions demand rigorous testing, standardization, and synchronization under NTN's unique latency and mobility conditions.
Extreme MIMO (xMIMO)		
 Leverages massive antenna arrays for substantial spatial multiplexing gains, boosting throughput and spectral efficiency.	- Spatial multiplexing of numerous users enables coverage extension and high throughput. - Enhanced spatial resolution and accuracy for localization and beamforming, critical for UAVs, satellites, and NTN-enabled IoT applications.	- High hardware complexity and energy consumption due to large-scale antenna arrays, numerous RF chains, and advanced power amplifiers. - Signal processing difficulties in handling channel impairments, e.g.: multipath, Doppler shifts, and non-line-of-sight scenarios.



CHAPTER 4

Solving Outer Space Issues in the Lab



Solving Outer Space Issues in the Lab

As the potential of 6G NTN pushes the boundaries of connectivity into outer space, replicating the complexities of orbital dynamics, atmospheric conditions, and multi-layered network interactions becomes a critical challenge. Key entities and components of the 6G NTN ecosystem must undergo rigorous testing (see Figure 8).

Advanced simulation and emulation environments are emerging as indispensable research and development tools for validating system behavior under realistic space-like conditions, without leaving the lab. These platforms enable researchers to model satellite constellations, test inter-satellite links, emulate ground-to-space interfaces, and assess the performance of enabling technologies.

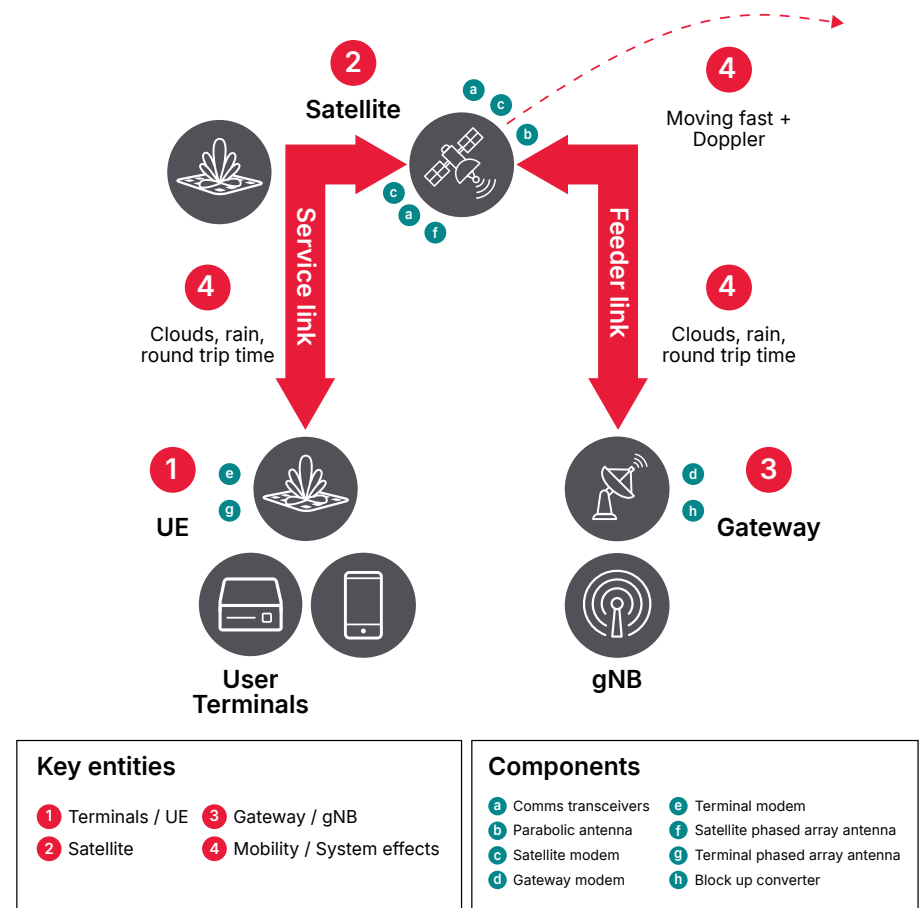


Figure 8. An illustration of the key entities and components in the 6G NTN ecosystem that require design validation and testing.

6G NTN Use Cases

Use case

Integrating AI for Channel Estimation and Feedback in 6G NTN

Testing 6G NTN RF performance relies on capturing metrics like error vector magnitude (EVM) and channel state information (CSI) to assess signal quality. AI-driven design improves channel estimation by simulating realistic channel behavior, enabling dynamic adaptation to real-time channel variations. AI models are trained using learning techniques to recognize impairments such as fading and interference, simulating complex transmission scenarios. Once trained, the AI predicts and corrects signal distortions in real time, enhancing testing efficiency for ultra-massive MIMO and advanced 6G NTN technologies.

[Watch video](#)

Solution

[Explore further](#)

Learn how to create the framework to generate data to train your AI model and assess its performance.

Optimizing 6G NTN signal performance and channel estimation demands simulation tools that reflect real-world complexity. Keysight's System Design (SystemVue) solution enhances CSI feedback and refines estimation accuracy. This flexibility allows engineers to emulate advanced NTN scenarios, assess signal quality, and optimize AI-driven estimators to counter impairments. Real-time feedback and system-level validation further ensure simulation fidelity.

Use case

Emulating FR3 channels for complex RF scenarios

Testing FR3 systems for 6G NTN applications requires phase and time-coherent multichannel emulation using semi-deterministic and deterministic channel models. Key performance metrics for FR3 testing include beamforming gain, beam width, and sidelobe levels from the physical layer (PHY) to the application layer.

[Watch video](#)



See how to perform upper-midband (FR3) end-to-end testing in the lab.

Solution



[Explore further](#)

Testing 6G FR3 requires phase and time-coherent multichannel emulation using semi-deterministic and deterministic channel models. The Keysight 6G FR3 system test solution includes a channel emulator, channel emulation software, and an MXG signal generator. The MXG signal generator provides the signal input to the FR3-capable channel emulator. The channel emulator also provides artificial intelligence (AI) enhancements to support digital twin development, photo-realistic visualizations of scenarios, and integrated sensing and communication (ISAC) capabilities for detecting and tracking objects.

Use case

Simulating satellite radio links to optimize TN-NTN networks

Simulating satellite radio links to test connectivity between terrestrial and NTN networks requires simulating operational environments to anticipate potential integration issues such as signal strength, frequency errors, and delays caused by satellite movement. Simulation provides a controlled environment to test and validate various aspects of TN-NTN connectivity. Channel modeling tools aid in creating standard and user-defined channel models, crucial for system testing. The central components include a channel emulator with cellular and satellite network models and a physical and protocol decoding analyzer.

[Watch video](#)

Watch how a digital twin simulator helps emulate real-world NTN scenarios and validate seamless handovers between terrestrial and satellite-based networks.

Solution

[Explore further](#)

Recreating satellite radio links to test NTN performance requires simulating operational environments to anticipate potential integration issues. The Keysight Satellite and Aerospace Channel Emulation Toolset and PROPSIM 16-channel emulator can be used for connecting a real base station and cell phone. Alternatively, use the Keysight UXM wireless test platform to emulate the functionality of a full cellular base station. Keysight Channel Studio provides ready-to-run test simulation models, and the Keysight WaveJudge physical and protocol analyzer decodes signals to troubleshoot communication between the phones and the network.

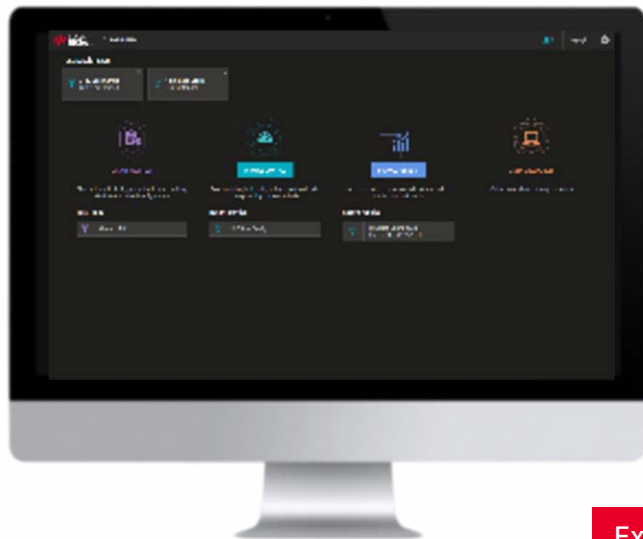
Use case

Validating Open RAN RIC functionality

Validating O-RAN RIC performance requires testing near-real-time and non-real-time scenarios, including NTN integration. It ensures compliance, interoperability, and scalability while covering AI/ML-driven optimization, realistic traffic and mobility conditions, and closed-loop use cases like traffic steering and energy efficiency. NTN adds unique latency and coverage challenges, making RIC validation critical for seamless orchestration across terrestrial and non-terrestrial networks.

[Watch video](#)

Solution



[Explore further](#)



Watch how Aalyria's Spacetime RIC performs in emulated, high-speed, and dynamic satellite environments using Keysight's RICtest solution.

Engineers testing a near-real-time RIC and xApps need UE and RAN components connected to an evolved packet core or 5G core network. The Keysight RIC test solution emulates all E2 node types standardized by the O-RAN ALLIANCE's Work Group 3 for testing RIC functionalities at any scale. This cloud solution supports thousands of E2 connections and is suitable for network vendors that need to test the scalability of their RIC architectures.

Use case

Testing NTN-direct-to-device communication

Narrow-band-IoT devices and systems require rigorous testing to ensure reliability and avoid unexpected failures. Verifying that NTN meets service provider and user expectations necessitates global and test specifications and certification programs to prove compliance. Parameters for NTN test cases depend on the distance to the satellite and orbital mode — Doppler, delay, and path loss. To perform the conformance and carrier acceptance test, engineers must configure the values with a toolset that enables them to make changes as desired.

[Watch video](#)

Solution



[Explore further](#)



Learn how to accelerate non-terrestrial networks device testing.

NB-IoT devices and systems require rigorous testing to ensure reliability. The Keysight wireless test platform combines 5G New Radio and NB-IoT NTN signaling with real-world channel emulation hardware and software. The result is an end-to-end, mixed terrestrial and space communication testbed. The lab-based platform realistically simulates a wide range of orbit trajectories, including LEO and GEO. It addresses technical challenges, optimizes UE designs, and validates UE implementations prior to network deployment.

By bridging the gap between theoretical design and real-world deployment, simulation and emulation accelerate innovation cycles and ensure that 6G NTN solutions are robust, scalable, and aligned with IMT-2030 goals.

Whether you are working on new spectrum technologies, AI/ML networks and devices, or new network topologies for your next 6G NTN innovation, Keysight's 6G solutions provide the performance, precision, and stability you need to tackle the most challenging measurements.

[Explore more use cases here](#)





CHAPTER 5

Towards Harmonization and Standardization



Towards Harmonization and Standardization

According to the ITU's [Framework and Overall Objectives of the Future Development of IMT for 2030 and Beyond](#), IMT-2030 aims to build an inclusive information society that supports the United Nations Sustainable Development Goals. Central to this effort, IMT-2030 seeks to provide ubiquitous connectivity, together with other goals shown in Figure 9.

Harmonization and standardization are essential for achieving IMT-2030 goals in 6G NTN, which have added complexity of satellite and UAV mobility beyond airspace. Harmonization to align regulations and policies across different jurisdictions will reduce conflicts and create a consistent environment for cross-border cooperation, while enabling seamless service continuity and compliance.

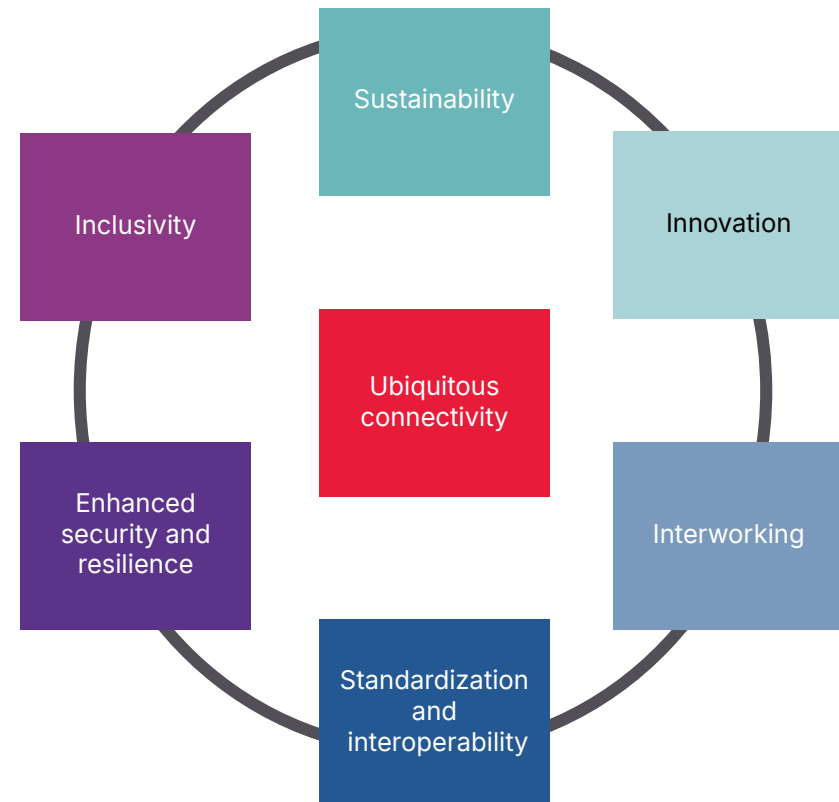


Figure 9. The building blocks of an inclusive information society, according to ITU's [Recommendation ITU-R M.2160-0](#).

Standardization through the much-anticipated 3GPP releases goes further by creating a uniform standard adopted industry-wide to enable interoperability and consistent performance. Release 20 started in 2025 and focuses on study and foundational work, including analysis of technology options, while Release 21 will handle the normative specifications, aiming for completion by late 2028 (see Figure 10). These releases align with the ITU timeline for submitting 6G technology proposals for IMT-2030 designation by 2029, enabling commercial 6G deployments by the target year of 2030.

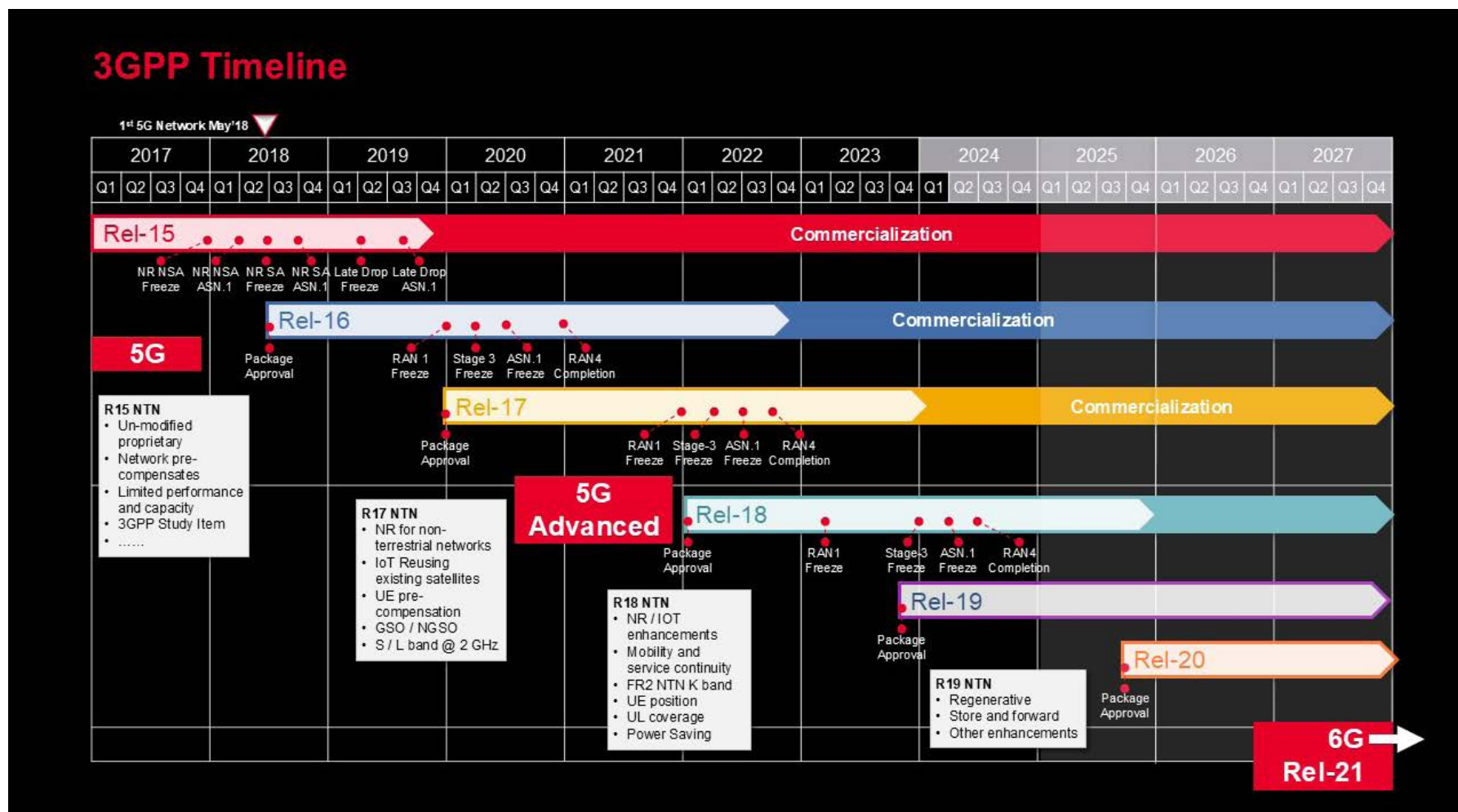
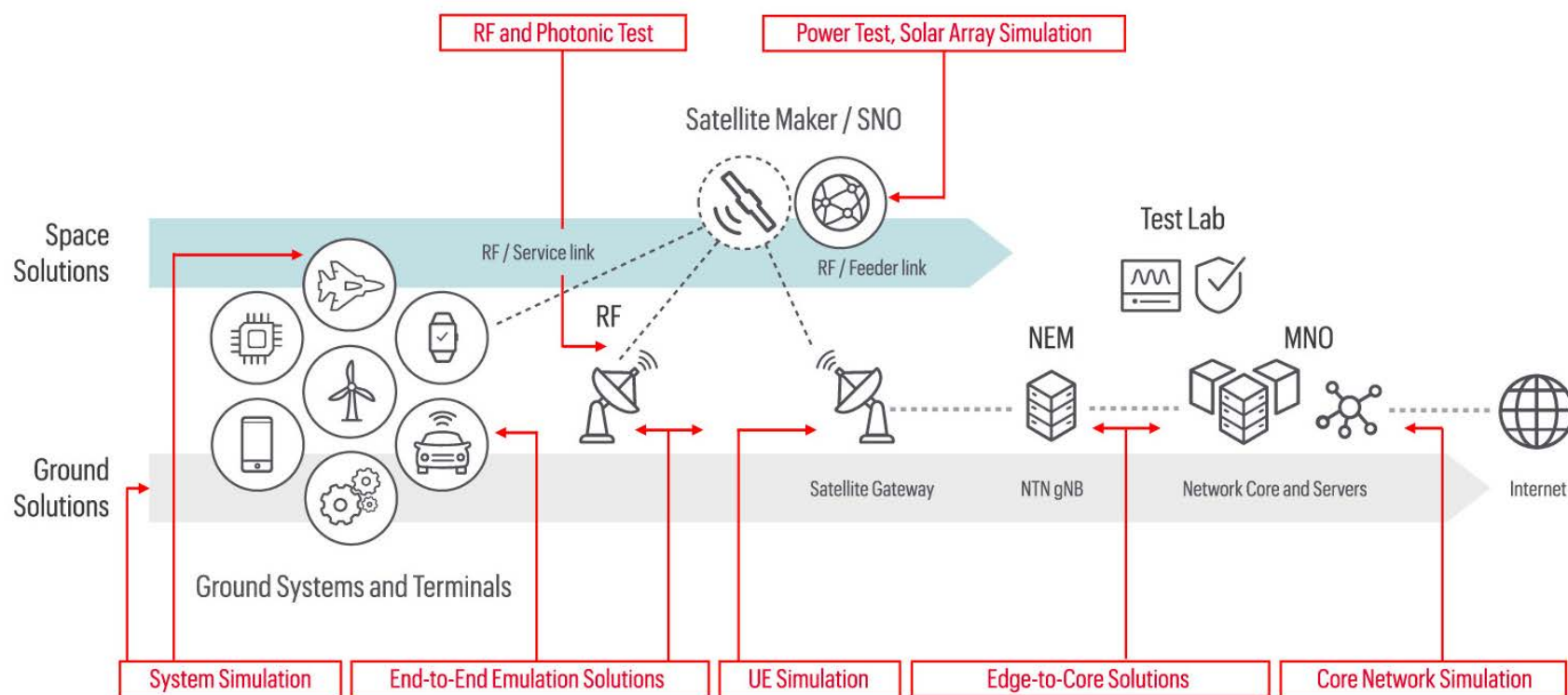


Figure 10. 3GPP driving 5G Advanced and 6G standards to support vertical markets. A common set of standards will facilitate interoperability and roaming agreements for a competitive market model.

The 6G community has already begun evaluating candidate technologies and performance KPIs through rigorous design validation and testing against real-world scenarios via simulation and emulation methodologies.

We are committed to helping you accelerate your research and innovation to create an efficient, safe, and secure 6G NTN ecosystem, with the end-goal of better connectivity for all. Explore [Keysight 6G Solutions](#), or [reach out to us](#).

Keysight NTN Solutions





Keysight enables innovators to push the boundaries of engineering by quickly solving design, emulation, and test challenges to create the best product experiences. Start your innovation journey at www.keysight.com.

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