

**SPECIAL REPORT**

# **6G, NTN, AND ADVANCED WIRELESS INFRASTRUCTURES**

*6G and its enabling technologies are transforming the mobile ecosystem, and our wireless infrastructure must keep pace.*



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*Alix Paultre, Editor-at-Large*

THE NEXT GENERATION of the cellular ecosystem will involve integrating satellite communications using low-Earth-orbit (LEO) satellites, leveraging AI in space to solve challenges of time, system reliability, data quality, and performance.



The latest development in the evolution of the mobile wireless communication infrastructure, 6G, is expected to provide more inclusive and sustainable connectivity, operating faster, handling more bandwidth, and delivering lower latencies.

The resulting enhanced connectivity could foment new applications in areas such as virtual and augmented reality, AI, connected systems, ubiquitous coverage through non-terrestrial networks, and others. These advances demand the latest in wireless communications tools to accelerate 6G system design to optimize the digital, RF, and antenna array components of 6G systems.

This eBook presents some of the trends and solutions emerging in this rapidly progressing arena.



CHAPTER 1

# NTN Device Validation Demands Dedicated Test Environments

*Because non-terrestrial networks must perform reliably to support high-speed internet, they require a dedicated test environment to ensure their operation.*

RAGHUL PREMKUMAR, Business Development/Applications Engineer, Anritsu



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Non-terrestrial network (NTN) deployment continues to ramp up to support the ever-growing need for high-speed internet, particularly by extending broadband connectivity in underserved and rural areas. These networks also serve as a level of redundancy for terrestrial networks, as they can provide immediate connectivity when terrestrial networks are damaged or out of commission. To achieve such goals, devices must reliably perform, requiring a dedicated test environment to ensure their operation.

NTNs leverage various platforms to deliver communication services, each with unique characteristics and use cases. As shown in the **table**, increased

altitude leads to broader coverage but also higher latency. These differences directly affect link performance, service continuity, and device design.

For these reasons, NTNs bring a new level of testing. While many measurements and analysis remain the same as those for terrestrial networks, the considerations change rather dramatically. Engineers need to account for these specific variables when verifying NTN chipsets, devices, and systems.

### Standards Guide the Way

One thing NTNs share with terrestrial networks is their adherence to industry standards. 3GPP Release 17 defines the first standardized NTN

Satellite	Altitude	Latency
High-Altitude Platform Stations (HAPS)	20 to 50 km	~1-20 ms 10-50 ms
Low Earth Orbit (LEO)	300 to 1,500 km	20-50 ms
Medium Earth Orbit (MEO)	7,000 to 25,000 km	~80 100-150 ms
Geostationary Earth Orbit (GEO)	36,000 km	250-300 ms

Comparison of satellites used in NTNs.

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specifications for both NB-IoT and NR:

- NTN NB-IoT extends Release-13 NB-IoT to satellite links. It supports low-data-rate messaging, asset tracking, and remote IoT connectivity where terrestrial coverage is unavailable.
- NTN NR expands 5G NR operation to satellite systems, enabling higher data rates, messaging, and emerging IoT applications. Enhanced mobility, improved Doppler compensation, and more advanced capabilities continue into 3GPP Release 18.

Spectrum allocation and regulations are also an issue in NTN design. Engineers need to account for ITU specifications, as well as regulatory bodies in different countries, since NTN transmit across boundaries.

### Design Challenges of NTN

Utilization of satellites presents different challenges when designing and manufacturing NTN devices. Among the considerations are:

#### *Delay and Doppler Shift*

One major factor is the inherent delay associated with transmitting and receiving signals because of the extreme distance between a UE and satellites, compared to terrestrial networks. Signals typically travel between 300 m to 10 km in a terrestrial network versus 20 to 36,000 km in an NTN.

Propagation distance in NTNs is significantly longer than in terrestrial networks (hundreds of meters to ~10 km terrestrially versus hundreds to tens of thousands of km in NTNs). This introduces large propagation delays and high Doppler shifts, particularly with LEO satellites moving at ~7.5 km/s (~17,000 mph).

Another major consideration is that movements by non-GEO satellites cause a Doppler shift in signal frequency due to the speed of the satellites. NTN-enabled devices must compensate for delay and Doppler shift in accordance with the 3GPP standard.

Doppler shift can be calculated from the relative speed and frequency between a satellite and a base station. It's most noticeable with LEO satellites, since their relative speed is larger than that of other orbit satellites.

To correct for Doppler shift, engineers must know the speed and position of the base station/device and the satellite. LEO Doppler can exceed  $\pm 40$  kHz at 2 GHz. NTN devices must implement the delay and Doppler compensation procedures defined in 3GPP TS 38.211, TS 38.212, and TS 38.213.

#### *Reselection and Roaming*

In terrestrial networks, devices switch from one base station to another based on signal strength. This process, called reselection, is more complex for NTNs because of the added factor of requiring precise location

information. For example, since LEO satellites travel ~17,000 miles an hour, they go around the earth in about 90 minutes.

Satellites crossing borders and switching operators from different countries also pose design considerations. Therefore, when developing NTN-enabled devices, engineers must ensure that the roaming behavior complies with 3GPP standards, as well as respective government regulatory guidelines. Factors to consider include:

- Satellites move rapidly across the sky, causing frequent cell boundary changes.
- Beam footprints can be extremely large, requiring precise timing and frequency tracking.
- Cross-border coverage introduces additional roaming and regulatory constraints.

#### *Interference*

A number of unique conditions contribute to interference in NTNs. Orbital slot allocation for satellites creates interference concerns, especially at LEO altitudes, due to all of the satellites deployed. Interference in NTNs primarily arises from dense LEO constellations, inter-beam and inter-satellite frequency reuse, and coordination between different satellite operators.

Accurate antenna measurements become more pronounced in this scenario. Some larger satellites can have 700 square feet of antennas. Testing

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**1. NTN test solutions need to support 3GPP standards, specifically NTN NB-IoT and NTN NR.**

large, phased-array antennas requires precise control and verification of each antenna element's performance. Modular VNA systems allow for effective near- to far-field transformation by minimizing measurement errors caused by long test cables through dedicated optical connections.

### Creating a Testing Environment

NTN test environments must allow for accurate simulation of these variables to achieve high-quality evaluation of NTN devices. Simulated environments create an efficient process that shortens test times and reduces cost-of-test. The environment must conduct tests that address the specific NTN challenges outlined earlier. Among the key parameters a test environment must measure include:

#### *Latency*

Because it can take 10 to 300 ms for a signal to travel from a satellite to the ground and vice versa, latency testing is critical. Propagation delays can exceed 600 ms round-trip for GEO links. Packet loss and jitter measure-

ments need to be made with a high degree of accuracy to ensure that signal transmission is optimized.

#### *RF Testing*

A 3GPP-compliant test environment with simple operation and flexible parameter settings enables the efficient implementation of RF tests. It should support simulation of NTN-specific delay and Doppler profiles, as well as NB-IoT and New Radio (NR) NTN waveforms. The environment must integrate solutions with simple upgrade paths via software and hardware modules to support future 3GPP Release standards that are currently in development.

Solutions such as those shown in **Figure 1** support 3GPP-compliant NR NTN and NB-IoT NTN RF measurements in compliance with 3GPP, as well as protocol tests. They're equipped with 5G and NR NTN pseudo base station functionality to perform RF tests from Frequency Range 1 (FR1) up to 7.125 GHz to Frequency Range 2 (FR2) (mmWave band).

NTN-integrated fixed wireless access (FWA) and customer prem-

ises equipment (CPE) solutions are emerging in regions lacking terrestrial broadband infrastructure. RF and parametric testing ensure that these devices maintain stable connectivity despite satellite dynamics.

#### *Handover Tests*

Rapid satellite motion and beam movement and footprint changes create challenging handover scenarios in an NTN environment. To compensate, the amount of overhead signaling must be reduced to ensure seamless transition from satellites, especially if there's a handover between a terrestrial base station to NTN.

Measurements of critical performance parameters, such as latency, signal strength, and throughput, must be made to evaluate the quality of handovers. This can be done through a simulated environment that creates the various real-world scenarios associated with NTN. In addition, signal-integrity testing should be done to ensure that the quality of the signal remains strong during handovers. Enhanced mobility improvements defined in 3 GPP Release 18 should

## CHAPTER 1: NTN Device Validation Demands Dedicated Test Environments



RTD + MD8430A

RTD + MT8000A

**2. Test analyzers that support NTN make it possible to create and use test cases for accurate evaluation of chipsets and devices.**

also be validated.

### *Protocol Testing*

To accurately evaluate the protocols implemented in NTN-compatible chipsets and devices, it's necessary to set up multiple test cases. Examples include:

- Testing under varying propagation delay profiles
- LEO/GEO Doppler and timing offsets
- NTN-to-terrestrial roaming
- Beam change and satellite visibility interruptions

Solutions, such as the analyzers shown in **Figure 2**, that support the rapid creation and evaluation of these test cases enable efficient develop-

ment and performance verification of chipsets and devices.

### *Conformance Testing*

To ensure the quality of NTN-compatible devices, conformance testing that complies with the latest 3GPP standards — (TS 38.521-4 (NR NTN RF) and TS 36.521-4 (NB-IoT NTN RF) — is required. The most cost-effective solutions are built on flexible platforms to create test environments that can meet today's requirements, as well provide an easy and seamless upgrade path as standards evolve. Such an approach is more time- and cost-efficient to help speed time-to-market and lower cost-of-test.

## Conclusion

NTNs are filling a valuable void in wireless connectivity, but they bring a new set of validation challenges. Engineers designing chipsets, devices, and modules for NTNs need to create test environments that efficiently address the unique measurement requirements to ensure operation in the field.

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## CHAPTER 2

# Antenna Design Must Evolve to Meet 6G NTN Needs

*6G will push antenna technology to new limits, demanding intelligent, adaptive, and multi-band systems capable of supporting emerging terrestrial*

BAHA BADRAN, Global Head of Engineering, Taoglas



images courtesy of Samtech

The 5G rollout is still some way from completion, but industry attention is already turning to the future. 6G networks may appear to be aspirational at this stage, but development in the underlying technologies is accelerating, and commercial deployment of this next-generation wireless technology is expected to begin around 2030.

In this article, we discuss the challenges that 6G will present to radio access technologies, particularly the antenna, and look at some of the work being done around the globe to address them.

## Antenna Demands in the 6G Era

The 6G vision centers on a cyber-physical continuum in which the digital and physical worlds are tightly linked. Rather than treating communication, sensing, computing, and positioning as separate capabilities, 6G brings them together in what's described as an "Intelligent Network of Everything."

This requires RF systems that not only transport data, but also cooperate with sensing, localization, and computing functions at a far deeper architectural level than today. AI will play a

major role here, enabling near-instant data transfer, sub-millisecond latency, and data rates approaching terabits per second. Coverage will also extend well beyond terrestrial networks, with non-terrestrial networks (NTNs) expected to be a native part of the 6G architecture.

The range of services under discussion includes holographic communication, brain-computer interfaces, real-time digital twins, immersive extended reality, autonomous mobility, and large-scale machine-type communications (Fig. 1).

This vision is still several years away from reality, but global standardization bodies such as the ITU and 3GPP are already defining initial 6G networking requirements. In laboratories and academic institutions around the globe, R&D on the technologies required to enable 6G networks is advancing rapidly, and early field trials are anticipated by the end of the current decade.

Along with advances in semiconductors, signal processing, and AI, the realization of the 6G vision depends

## CHAPTER 2: Antenna Design Must Evolve to Meet 6G NTN Needs



1. The convergence of digital and physical domains drives the need for far more capable antenna systems. (Credit: Taoglas)

heavily on the evolution of the antenna. More than a transmission and reception device, the antenna is key to the efficiency, reliability, and scalability of next-generation networks.

### The Antenna Challenges Ahead

The seamless interaction between the network and physical world, which is fundamental to the 6G vision, will be enabled by multiple arrays of embedded sensors and actuators, connected to each other and to the network.

The network gateways that will handle the massive volume of data flowing to and from these devices will require exceptional levels of resilience and reliability. At the same time, they

will push the limits of energy and spectral efficiency across both new and existing frequency ranges. These requirements highlight the challenges facing the design and topologies of the antennas of the future (Fig. 2).

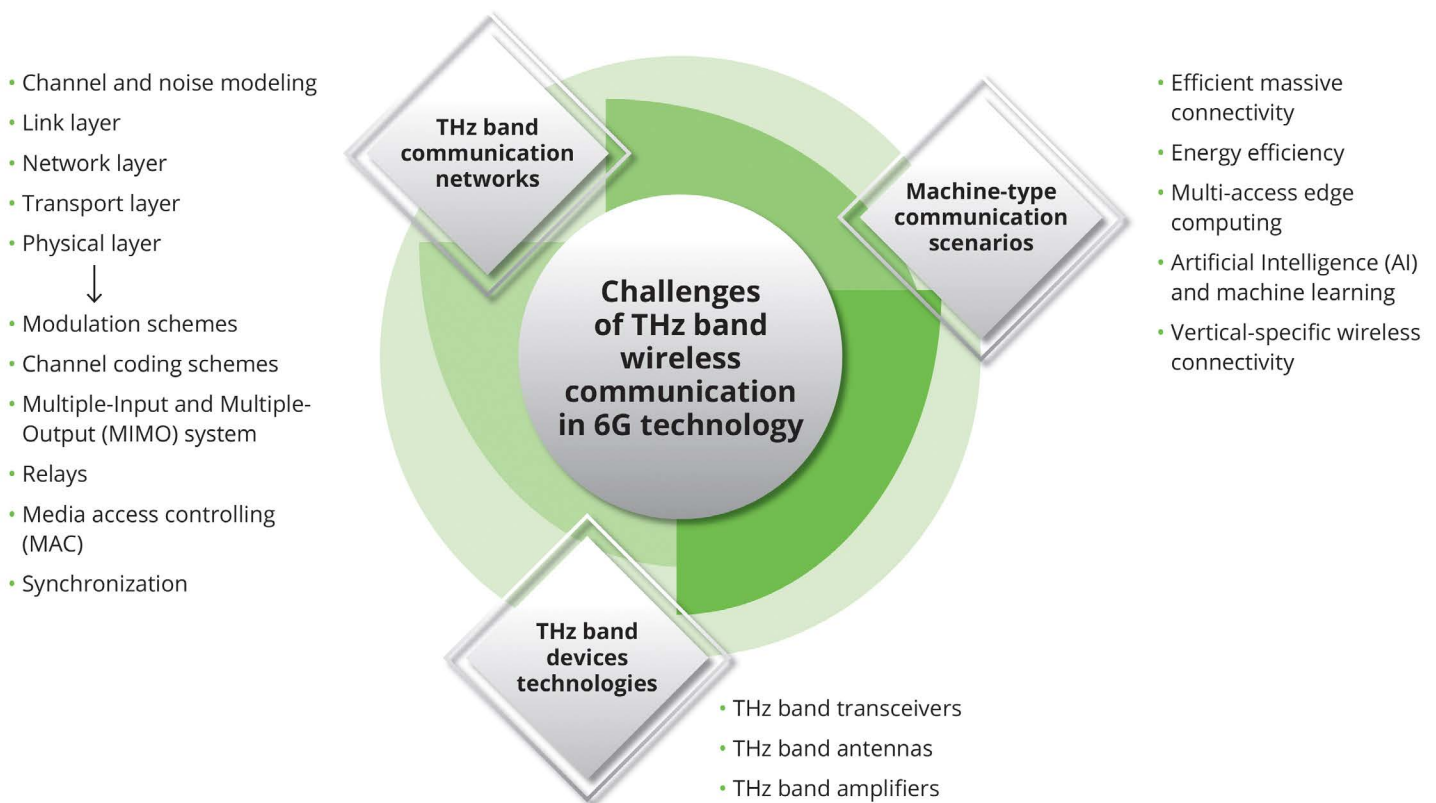
6G will be deployed across a wide range of frequency bands. These include current frequencies in the sub-1-GHz range, 3.5- to 6-GHz mid-band range, and millimeter-wave (mmWave) range, as well as new frequencies in the 7- to 15-GHz centimeter-wave (cmWave) range, and the 90- to 300-GHz sub-THz range. 6G antennas must therefore support multi-band operation across this broad frequency range.

The ongoing trend toward higher

frequencies, with shrinking propagation distances and increasing signal attenuations, will drive higher network densities. As network infrastructures become denser, antennas will need to be more tightly integrated with RF front ends and baseband circuitry, driving greater miniaturization and co-design across the entire module. And with more access points operating in smaller cells, interference management and signal coordination will be critical to maintaining stability and efficiency.

These challenges are expected to move current massive-MIMO (multiple-input, multiple-output) arrays toward more synchronized distributed MIMO architectures, with anten-

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## 2. Key technical hurdles facing next-generation antenna design. (Credit: Taoglas)

nas distributed across wider spaces to deliver the required performance.

Meeting the 6G challenge will require continual improvement in the mechanical and electrical radiation performance of the antenna, alongside energy savings and diminishing form factors. Future antennas will have to be highly flexible, operating across a wide range of frequencies and power levels, since there will be no room in future devices for multiple antennas.

Ongoing R&D work is focusing on the concept of the intelligent antenna system — highly reconfigurable, compact, and software-defined devices — that will form the backbone of the future 6G radio ecosystem.

### Emerging Research Directions and Technology Enablers

The antennas used in future 6G devices, whether in base stations, vehicles, or wearables, will not just transmit and receive signals; they will sense, adapt, and collaborate. These adaptive antennas will use real-time feedback from network conditions and user mobility to optimize beam patterns automatically, minimizing interference while maximizing link quality.

To achieve this, current research is converging around several key enabling technologies that are expected to redefine antenna performance in the 6G era, including:

Reconfigurable intelligent surfaces (RIS) are large, programmable surfaces made up of thousands of sub-wavelength elements that can manipulate electromagnetic waves in real-time. By adjusting phase, amplitude, and polarization, RIS panels can actively shape the radio environment, redirecting, focusing, or scattering signals to improve coverage and spectral efficiency. Rather than relying solely on base stations, networks will be able to use RIS as controllable reflectors, effectively turning walls, buildings, or even vehicles into part of the network infrastructure.

Metamaterials provide unprecedented control over electromagnetic behav-

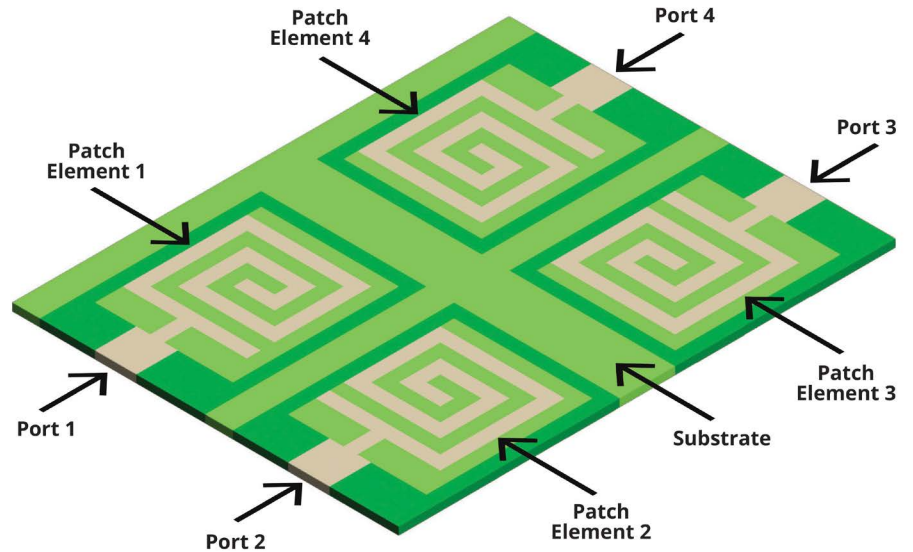
## CHAPTER 2: Antenna Design Must Evolve to Meet 6G NTN Needs

ior through engineered substructures. These materials enable ultra-compact, wideband, and steerable antennas that can operate efficiently at THz frequencies. Researchers are demonstrating tunable metasurface antennas capable of switching beam patterns and frequencies electronically, eliminating the need for bulky mechanical steering systems.

Antenna arrays that use advanced semiconductor switching, varactors, or microelectromechanical systems (MEMS) are emerging as a practical approach to agility. Electronically configurable antennas can dynamically adjust beam direction, gain, and impedance based on real-time network feedback. Such adaptability will be vital for maintaining robust links across highly variable propagation conditions, such as in mobile or dense urban environments.

New substrates such as low-loss ceramics, flexible polymers, and graphene-based conductors (Fig. 3) are under investigation for THz-band operation. Their lower dielectric loss and higher thermal conductivity support efficient operation even as antenna geometries shrink. Meanwhile, additive manufacturing and 3D printing are enabling cost-effective prototyping of complex, high-performance structures.

Machine learning is increasingly used to design, tune, and manage antennas. Algorithms can predict performance tradeoffs and automatically adjust array parameters for optimal



**3. Material innovations that support efficient THz-range antennas (Credit: Taoglas)**

beamforming or interference reduction. In future 6G networks, AI will also support self-healing and adaptive operation, enabling antennas to autonomously respond to network and environmental changes.

### The Road Ahead: From Research to Realization

Although 6G promises transformative capabilities, it's still very much at the pre-commercial research stage, with key technologies under evaluation. Industry experts expect early trials toward the end of the decade, but full-scale rollout will depend on global standardization and ecosystem readiness.

As the mobile sector continues to grapple with the challenges of monetizing and fully deploying 5G, 6G research represents both an opportunity and a test. It must deliver meaningful new capabilities while ensuring

commercial and environmental sustainability. Many of the technologies explored today, including reconfigurable surfaces, adaptive arrays, and AI-driven control, will evolve through intermediate milestones such as "5G-Advanced" and early 6G prototypes, making sure that there's a smoother transition between generations.

The consensus among industry researchers is clear: Antennas will be at the heart of 6G innovation. Their ability to dynamically shape, sense, and control the wireless environment will define how 6G delivers on its promise of a seamlessly connected, intelligent world.

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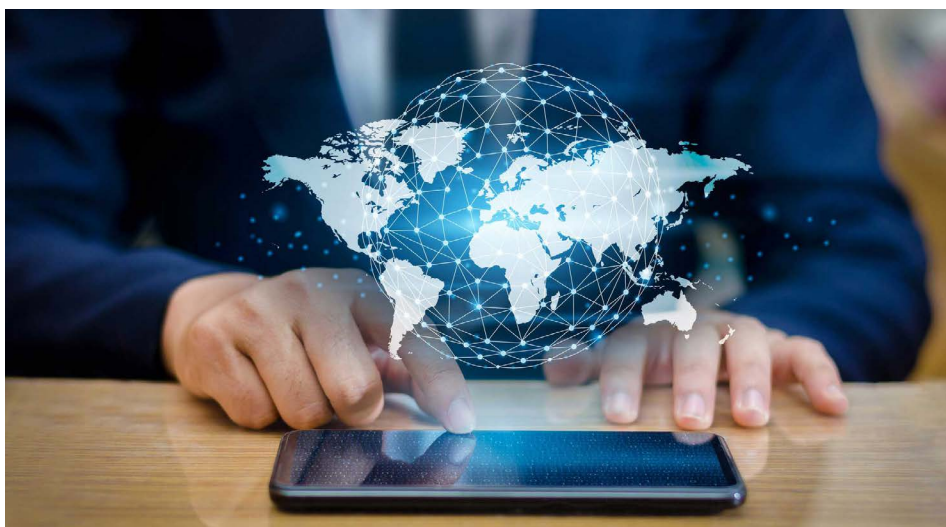
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## CHAPTER 3

## Next-Gen RF Transceivers Deliver Seamless Earth-to-Space Connectivity

*Terrestrial networks have evolved from the low-data-rate voice-centric connectivity of 2G, to support for mobile data and multimedia services with 3G and 4G, to enabling enhanced mobile broadband, massive machine-type communication, and URLLC with 5G NR.*

JENNY YU, Systems Engineer, and SANJAY PITHADIA, Marketing and Applications Manager,  
Wireless Infrastructure, Texas Instruments



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The vision of 6G non-terrestrial networks (NTNs) is truly fascinating. They aim to seamlessly integrate satellites, high-altitude platform stations, unmanned aerial systems, and terrestrial networks into a unified global system. Ultimately, NTNs intend to provide uninterrupted, high-speed connectivity and mobility anywhere on Earth, from dense cities to rural areas, to remote oceans, and even deep space.

On the other hand, satellite communication is not something new. Since the first geostationary orbit (GEO) satellites of the 1960s proved that space-based relays could deliver global coverage, legacy satellites have been mostly GEO- or medium-Earth-orbit (MEO)-based, using proprietary technologies and providing narrowband voice and data services.

Today, the satellite communications industry is undergoing its most sig-

nificant transition. This shift includes low-Earth-orbit (LEO) satellite constellations that offer dramatic cost savings, software-defined payloads, and electronically steerable antenna terminals. The industry is also adopting direct-to-device (D2D) connectivity and Third Generation Partnership Project (3GPP) NTN standardization.

These innovations are transforming satellite communications from a niche solution into scalable broadband infrastructure that complements and extends terrestrial networks worldwide.

This article examines the fundamental system design factors, challenges, trends, and solutions for satellite communications systems from the perspective of integrated radio-frequency (RF) transceivers, an essential component to bridge the real and digital worlds.

### Integrated RF Transceivers

Before diving into the satellite communication system, let's begin with

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a primer about integrated RF transceivers, which serve two main functions: converting signals between baseband and RF, and converting signals between the digital and analog domains. High-speed analog-to-digital and digital-to-analog converters (ADCs and DACs), typically sampling data at gigasamples per second, are at the core of the integrated RF transceivers used in communication infrastructures.

There are two types of integrated RF transceiver architectures. In the direct RF sampling architecture, conversion between the baseband and RF occurs in the digital domain (Fig. 1a). In a zero-intermediate frequency (ZIF) architecture, the conversion between

the baseband and RF takes place in the analog domain (Fig. 1b).

A satellite communications system (Fig. 2) consists of three types of components: the satellite payload, user terminal, and the gateway, also known as the ground station. The satellite payload communicates with the user terminals on the ground through the service link.

Depending on the design, the satellite payload may be transparent (providing no onboard processing and simply “repeating” with filtering and amplification) or regenerative (incorporating onboard processing capabilities such as coding and decoding, modulation and demodulation, switching, and routing). The satellite payload connects to the

gateway through a feeder link, and the gateway interfaces with the back-end data network.

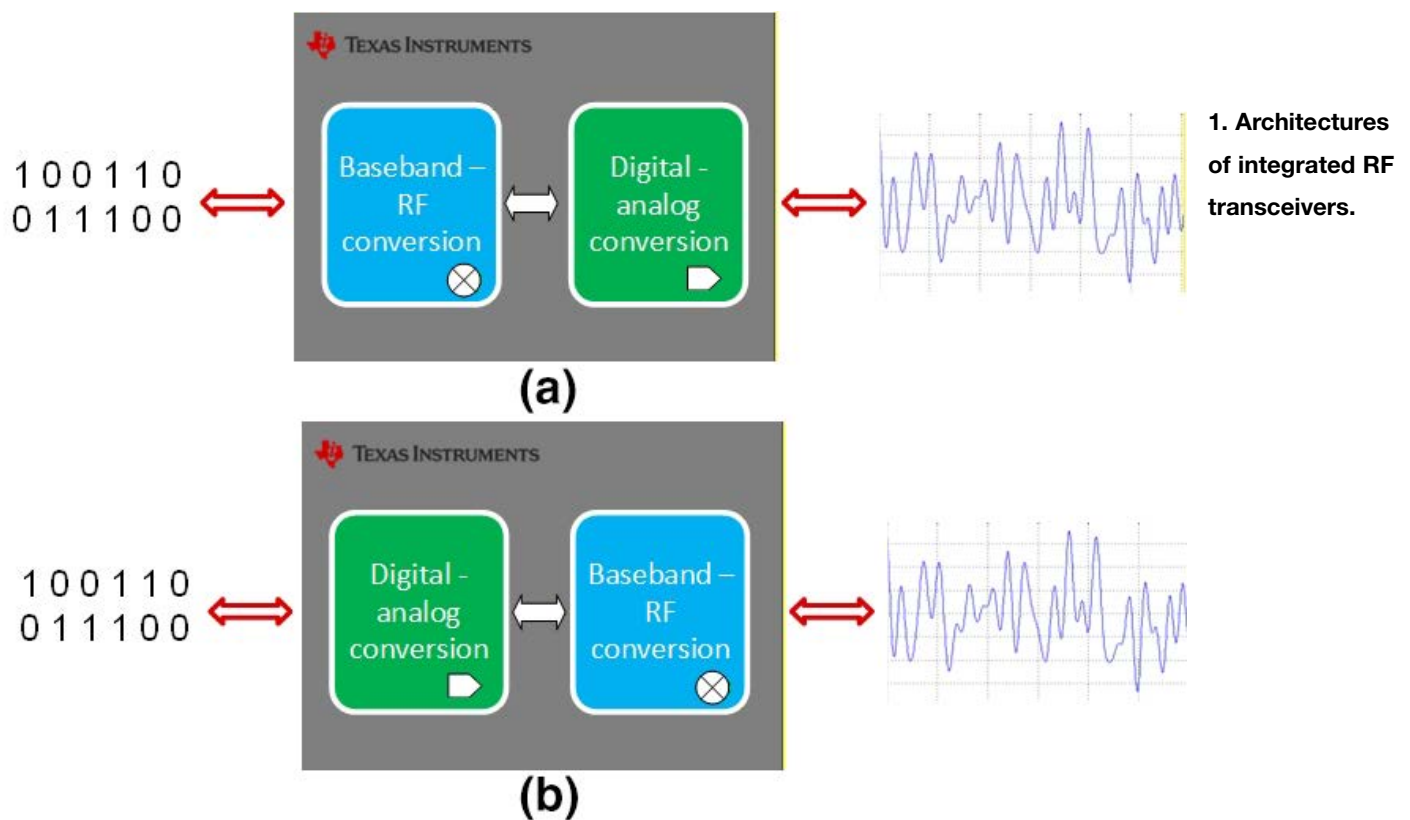
Like many other applications, these building blocks have different functions and constraints, driving different design requirements.

**Fundamental Satellite Communication System Design Factors**

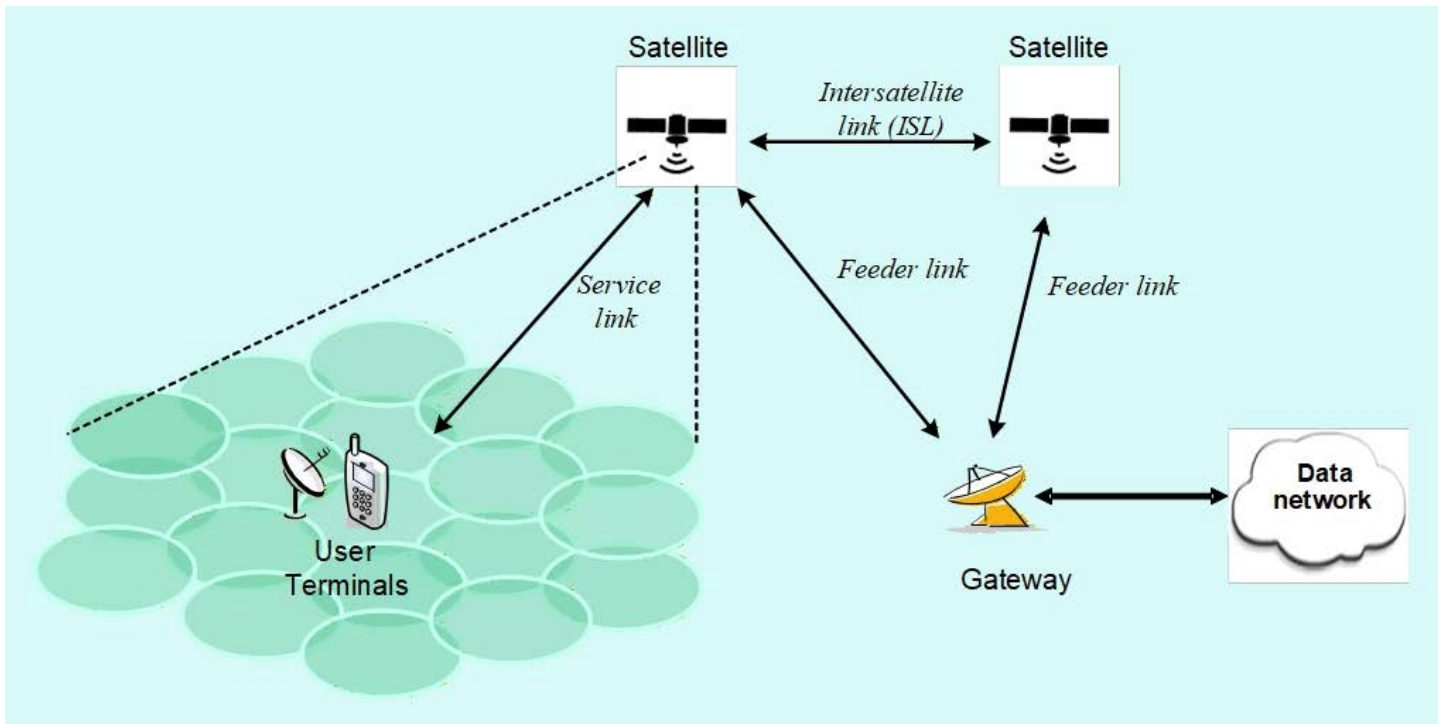
There are several considerations when designing satellite communication systems that are related to, but still differ from, terrestrial networks:

**The RF spectrum and signal bandwidth**

The legacy mobile satellite service (MSS) spectrum, including the



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2. Satellite communication networks. (Source: 3GPP technical report specification 38.821)

L-band and S-band, remain in use for both GEO and LEO systems. Recent 3GPP work standardized operation in the MSS bands under the NTN framework, enabling both traditional MSS operators and emerging LEO constellations to support 5G devices directly.

Regulatory developments, such as those from the Federal Communications Commission in the United States, permit satellites to operate within the terrestrial mobile service spectrum to provide supplemental coverage from space (SCS), subject to certain restrictions. Current SCS allocations reside below 3 GHz.

Direct-to-device (D2D) and Internet of Things services typically use the MSS and SCS bands because lower frequencies provide better propaga-

tion characteristics for communicating with small, low-gain user devices such as smartphones. The signal bandwidth is often only a few or tens of megahertz.

Broadband satellite services generally use the Ku- and Ka-bands because of their larger available bandwidth, typically hundreds of megahertz.

The feeder links connect the satellite payload and the gateway. Because the gateway serves as the primary aggregation point for all user traffic entering and leaving the satellite network — and needs to handle network functionalities such as rapid handovers — the gateway must be able to support ultrawide gigahertz bandwidths. It typically operates in the Ku-band, Ka-band, Q-band, or V-band.

### Noise and interference

Terrestrial networks require base stations to detect weak signals in the presence of strong blockers (interferers). In macro base-station deployments, blockers may exceed the preferred signal by  $\geq 50$  dB, necessitating low receiver noise figures, high linearity, and large spurious-free dynamic range.

In satellite systems, propagation distances on the order of hundreds to thousands of kilometers introduce significant propagation losses. These include free-space losses, atmospheric attenuation, and shadowing. Consequently, the received signal at the satellite antenna is typically below the noise floor, and large phased antenna arrays provide the necessary

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directivity gain for signal-to-noise recovery.

As a result, NTN systems are primarily noise-limited, whereas terrestrial networks are generally interference-limited.

### **Phased-array antenna size**

In satellite communication systems, because of the long propagation distance, satellite links require highly directive antennas to overcome path losses and minimize unwanted emissions. Large phased-array antennas with advanced beamforming enable the generation of numerous high-gain spot beams and provide null-steering capability for interference suppression.

Terrestrial systems also employ massive multiple-input multiple-output (MIMO) technology. However, arrays typically consist of only tens of elements in the FR1 bands and a few hundred elements in the FR2 bands. In contrast, satellite payload arrays may include several thousand elements, with even larger arrays used at ground stations.

### **Beamforming architecture**

Beamforming is essential in satellite communication networks. The scale of satellite phased-array antennas requires careful optimization of the beamforming architecture, based on the system requirements of cost, power consumption, beamsteering flexibility, and pointing accuracy.

Satellite payloads and gateways frequently adopt hybrid and digital beamforming solutions, whereas

user terminals employ analog beamforming solutions, mostly because of the cost and small number of beams required.

In comparison, terrestrial FR1 systems often utilize fully digital beamforming, enabled by smaller array sizes and more favorable power budgets.

### **Size, weight, and power**

Satellite payloads face stringent power constraints. As a result, power efficiency and a low-power-dissipation RF architecture are more important considerations than in terrestrial base stations, which have access to stable and abundant power sources.

While size and weight are important for terrestrial base stations, they're even more important for satellite payloads, because they directly affect nearly every aspect of spacecraft performance and cost.

Launch vehicles impose strict mass and volume limits. The launch cost is directly proportional to the payload weight. Larger or heavier structures require stronger mechanical reinforcement to withstand vibration and shock during launch, which further adds mass.

Once in orbit, increased size and weight raise the satellite's moment of inertia, demanding larger attitude-control hardware and more propellant, which can reduce mission lifetimes. Thermal and power management also become more challenging.

Collectively, these factors make compact, lightweight payload designs

essential for achieving goals related to cost, endurance, and operational lifetimes in satellite systems.

### **Reliability in space**

Satellite systems must meet strict reliability requirements because it's not possible to perform in-orbit maintenance. Depending on mission objectives, designs may incorporate space-grade components, radiation-hardened devices, or redundant commercial-grade electronics to achieve a target lifetime and reliability.

## **Technology Trends**

I see these trends developing in integrated RF receivers for satellite communications:

- **The direct RF-sampling architecture:** Compared to a zero-IF architecture, direct RF sampling-based RF transceivers offer many advantages. For example, they're highly configurable and flexible with multiband support; support fast frequency hopping; and require no in-phase-quadrature mismatch, local oscillator leakage, or DC offset calibration. Since satellites are most likely not restricted to one particular country or region while orbiting around the earth, it's necessary for the same satellite to be able to support multiple different frequency bands and quickly hop over multiple frequencies. A direct RF-sampling architecture is a perfect fit.
- **High channel density:** With the large size of a phased-array anten-

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na, especially when using digital or hybrid beamforming, each satellite payload needs numerous transceiver channels. RF transceivers with high channel density can significantly reduce size and weight, enabling a compact and lightweight design. For example, TI's [AFE8190](#), the industry's first 16-channel RF transceiver, integrates 16 transmitters, 16 receivers, and four additional ultrawideband transceivers for digital-predistortion feedback observation in one device.

- **Low power consumption and high power efficiency:** Two equally important aspects ensure that every watt matters in satellite communication design, especially for satellite payloads. First, design innovations and process minimization help reduce the active device-level power consumption. Second, system-level features can be implemented to improve the overall system power efficiency. Integrating digital predistortion within the RF transceiver, such as TI's [AFE7769D](#), makes it possible to drive power amplifiers harder toward the saturation region for better system power efficiency, or adopt high-efficiency power amplifiers with gallium nitride. It's also beneficial to include and enable power-saving features when the satellite travels over low- or no-traffic regions.
- **Ultrawideband (gigahertz) support for feeder links:** With the increase in satellite constellations and service

subscribers, it's inevitable that the gateways need to support growing capacity, demanding more bandwidth. Direct RF-sampling-based transceivers are well positioned to support the ultra-wide bandwidth, enabled by the high-speed data-converter core.

- **Beamforming integration:** For many reasons, beamforming technology has gradually moved from analog to digital or hybrid (especially for payloads and gateways), including true multibeam per aperture, finer precision, wide-beam bandwidth support, fast adaptive beam-tracking, and better spectral agility. Integrating digital beamforming into an analog front end offloads the field-programmable gate array computational and memory resources, reduces the data throughput, and provides overall power dissipation optimization.
- **Space reliability:** Space reliability also includes giving options to meet the various space radiation tolerance requirements and being clever on how to introduce space redundancy. For example, TI's [AFE7950](#) and [AFE7950-SP](#) are pin-compatible devices offering different radiation tolerance.

### Conclusion

As NTN's move from vision to reality, satellite communications are entering an exciting period. For RF transceiver vendors, NTN offers opportunities to

shape the foundation of next-generation communication networks.

Higher integration, better power efficiency, smarter beamforming, and more flexible RF architectures will be essential enablers of global, resilient, and seamless NTN coverage. Integrated RF transceivers like the [AFE8190](#) and [AFE8030](#) can help solve these challenges with a high level of integration and ease of design for small-form-factor payload radios.

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## CHAPTER 4

# Testing Challenges in Non-Terrestrial Networks and Future Wireless Systems

*Non-terrestrial networks, combined with early 6G research, demand test equipment capable of handling extreme parameters and complex multichannel scenarios, requiring significant shifts in RF and physical-layer validation.*

JOHAN NILSSON, Product Manager, Signal and Spectrum Analyzers, Rohde & Schwarz



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**5**G non-terrestrial networks (NTNs) extend cellular connectivity through satellites and high-altitude platform stations. Released in 3GPP Release 17, NTN specifications enable standard smartphones to connect directly to satellites, addressing a critical gap: While terrestrial 5G reaches over 80% of the world's population, it covers less than 40% of Earth's landmass.

The technical challenges differ fundamentally from terrestrial deployments. Propagation delays reach 540 ms for geostationary satellites and 25

to 50 ms for low-Earth-orbit (LEO) constellations, dwarfing the sub-millisecond timing typical in terrestrial networks. Doppler shifts from fast-moving satellites reach  $\pm 50$  to 100 kHz at S-band frequencies. **Figure 1** shows how the round-trip time (RTT) is calculated, influenced by various parameters.

These characteristics forced significant architectural modifications. Hybrid automatic repeat request (HARQ) processes had to be reconsidered: For GEO satellites, RTT exceeds practical acknowledgment limits,

leading to HARQ-disabled modes or increased process counts from 16 to 32. Timing advance values extended dramatically, with mandatory GNSS positioning for all NTN devices enabling UE-specific corrections.

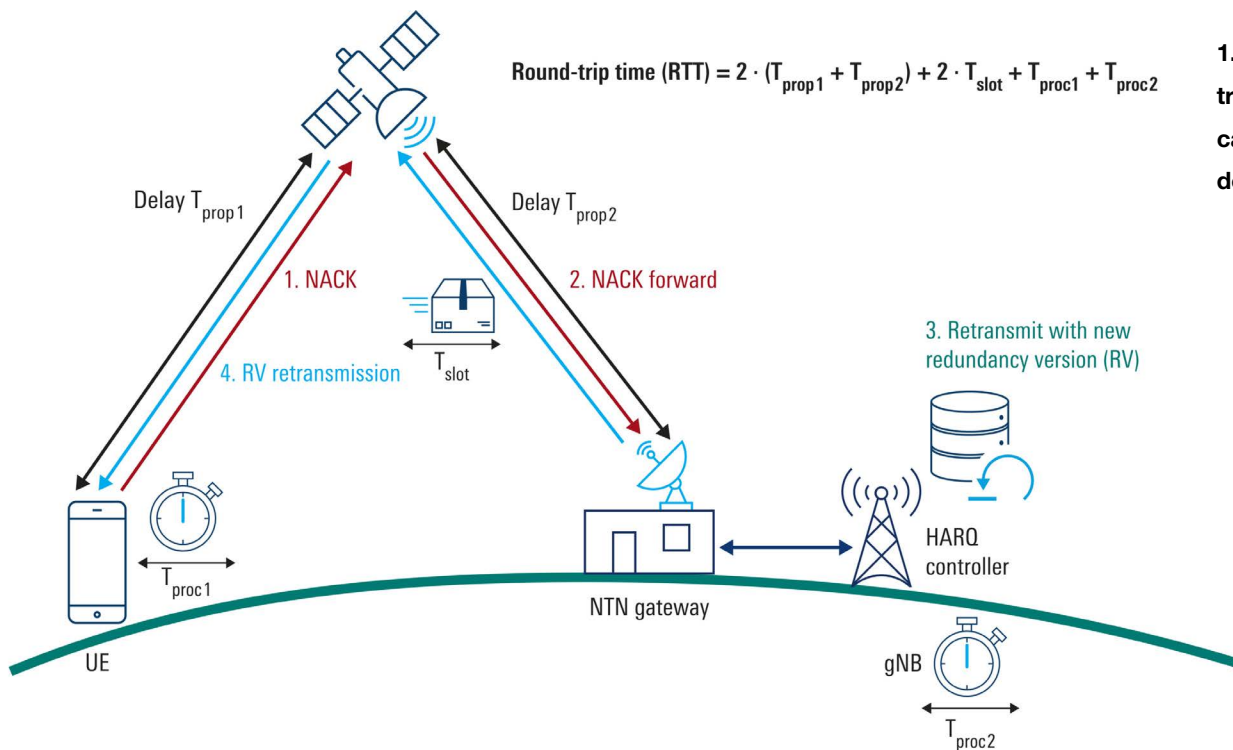
Current NTN deployments operate primarily in FR1 spectrum, specifically in S-band and L-band (n255, n256, n254). Typical channel bandwidths are limited to 10 to 30 MHz due to power constraints and spectrum coordination challenges.

Real-world deployments accelerated between the years 2024 and 2025, with SpaceX's Starlink Direct-to-Cell service launching SMS capabilities with T-Mobile, AST SpaceMobile demonstrating 5G broadband from space to unmodified smartphones, and multiple IoT-NTN services going commercial using 3GPP-standardized connectivity.

## Testing Complexity in NTN Scenarios

Validating NTN equipment presents unique measurement challenges. Satellite access nodes must han-

## CHAPTER 4: Testing Challenges in Non-Terrestrial Networks and Future Wireless Systems



1. How round-trip time is calculated in NTN deployments.

due to time-variant propagation delays, differential delays across large beam footprints, and continuously changing frequency offsets. These are impairments that terrestrial equipment rarely ever encounters.

Consequently, test setups must emulate dynamic conditions accurately: channel emulators modeling geometric relationships between moving satellites, beam patterns sweeping Earth's surface, and three-dimensional orbital velocity vectors. Component testing requires characterization under conditions outside terrestrial specifications: extreme timing offsets, rapid frequency variations, and power control optimized for ~190- to 210-dB path loss.

The verification of phased-array antennas, critical for both ground stations and airborne platforms, requires

phase-coherent multichannel measurements. Traditional approaches involve multiple synchronized instruments, complex cabling arrangements, and careful calibration procedures. Each additional connection point introduces potential phase errors and amplitude imbalances that can obscure the actual device performance.

### The 6G Vision: Addressing 5G Limitations

While 5G NTN deployment continues, 6G research addresses fundamental limitations. Expected around 2030, 6G aims to tackle the challenges that 5G couldn't fully solve.

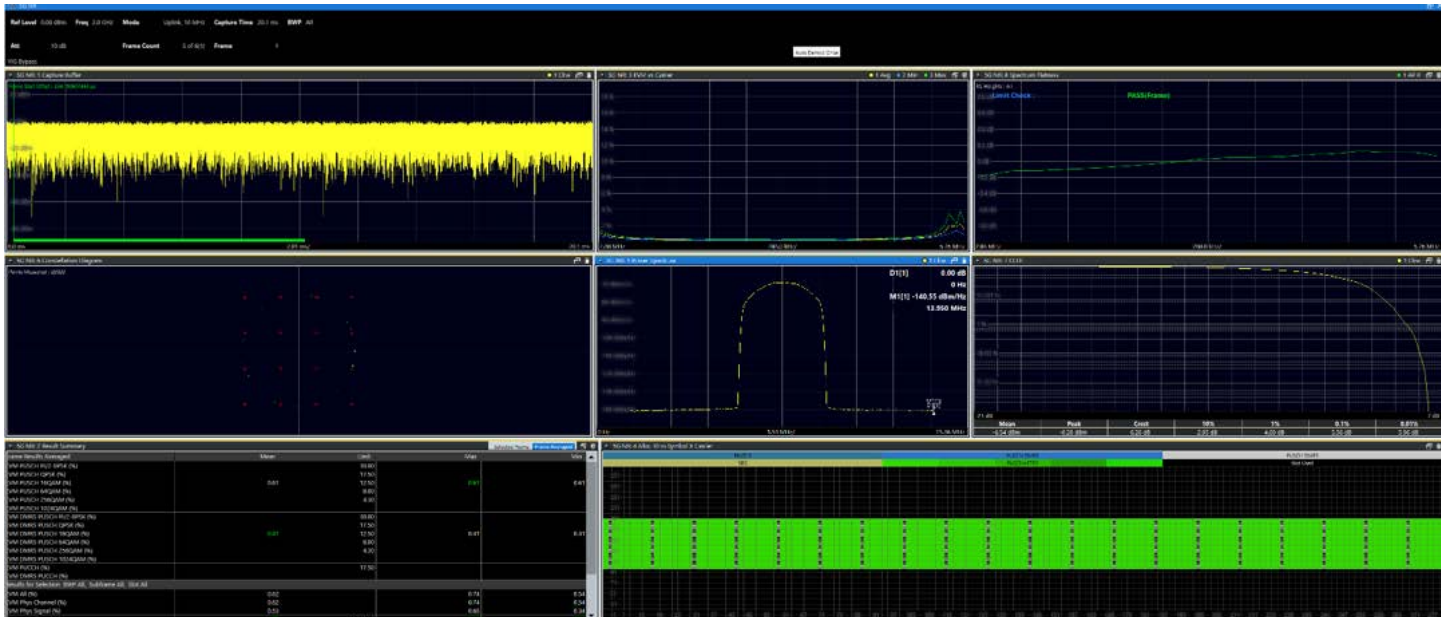
Coverage and capacity remain primary concerns. Current satellite direct-to-handset services achieve around 20 Mb/s, serving basic con-

nectivity but far below terrestrial performance. 6G aims for dramatic terrestrial improvements targeting peak rates approaching 1 Tb/s, while also advancing NTN capabilities through higher frequency bands, regenerative satellite payloads, and AI-optimized beam management.

Energy efficiency emerges as critical. 5G networks consume significant power, especially in dense mmWave deployments. 6G focuses on sustainability from the ground up through AI-driven resource allocation and intelligent sleep modes.

Most significantly, 6G embraces AI as native infrastructure rather than an enhancement. This manifests in three stages: AI optimizing operations (neural receivers, resource allocation, beamforming, etc.), networks

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## 2. Demodulation of a 3GPP signal modified to include a signal showing a crest factor of 6 dB.

designed for AI workloads (semantic communication, federated learning), and AI as a billable service (on-demand inference, intent-driven communication).

For NTN specifically, 6G evolution includes regenerative satellite payloads with full base-station functionality on board. Combined with inter-satellite links, this enables direct routing between satellites rather than requiring each transmission to bounce through ground stations. Such a constellation-level architecture reduces the number of hops for certain traffic patterns and improves overall network flexibility and resilience.

### Beyond-5G Research: The Parameter Challenge

The 5G to 6G transition presents a fundamental challenge: testing technologies without established stan-

dards. Researchers must experiment with parameters far outside current specifications.

Consider modulation formats. Though 5G standardizes up to 256-QAM, researchers investigate 4096-QAM and even 16384-QAM for specialized scenarios. These extreme modulation orders demand unprecedented signal-to-noise ratios and introduce measurement challenges that push traditional test equipment to its limits.

The question isn't whether these orders will appear in consumer devices (they likely will not), but rather how they influence the design of adaptive modulation schemes and AI-driven signal processing.

Channel bandwidths provide another example. 5G specifies bandwidths up to 100 MHz in FR1 and 400 MHz in FR2. Early 6G research requires testing sig-

nals spanning multiple gigahertz continuously, exploring wideband channel effects not addressed with current standards. Researchers need the ability to generate, transmit, and analyze these ultrawideband signals to understand propagation characteristics and develop appropriate channel models. In initial 6G deployments, these wideband scenarios seem unlikely.

Frequency domain spectrum shaping (FDSS) represents a promising technique for improving power efficiency in uplink-constrained scenarios. These are particularly relevant for IoT and satellite communications.

By applying frequency-domain filtering to DFT-spread-OFDM waveforms, FDSS reduces peak-to-average power ratio and out-of-band emissions. This allows transmitters to operate closer to saturation, improving link budgets by 4 to 5 dB, which

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### 3. Screenshot of probabilistic distribution.

is critical when every decibel determines whether a connection succeeds or fails over satellite distances. **Figure 2** shows a demodulation with all relevant parameters of an FDSS signal.

Digital post-distortion (DPoD) offers another avenue for improving system efficiency. Traditional digital predistortion (DPD) in transmitters compensates for power amplifier nonlinearities but adds complexity and power consumption to user devices. DPoD shifts this compensation to the receiver, typically at the base station where processing power is abundant.

Early implementations, including testbeds developed jointly by Nokia Bell Labs and Rohde & Schwarz, show substantial coverage improvements for 6G uplink scenarios. However, validating these AI-based receivers requires the ability to precisely characterize both linear and nonlinear

impairments across multiple signal paths simultaneously.

Neural receivers and custom modulation formats push testing requirements even further. Rather than using predetermined constellations like QPSK or QAM, AI/ML-trained systems optimize constellation shapes jointly with receiver processing, taking channel characteristics into account. These “learned constellations” may eventually enable pilotless communication, dramatically reducing signaling overhead.

Testing such systems requires equipment that can handle arbitrary constellation definitions and accurately measure performance metrics like error vector magnitude, even when the modulation format itself is unconventional. **Figure 3** shows the implementation of a probabilistic distribution as recently discussed in 3GPP.

### The Multichannel Testing Imperative

These research challenges share a requirement: sophisticated multichannel analysis. Beamforming systems for 6G require precise phase and amplitude relationships across dozens or hundreds of antenna elements, demanding phase-coherent measurements across multiple ports.

Traditional approaches create complexity, which include multiple synchronized spectrum analyzers, precision reference clocks, and elaborate matched cable networks. Each connection introduces uncertainty. Calibration becomes time-consuming and must be repeated frequently. Individual analyzer noise floors limit the detection of weak signals or small impairments.

For amplifier characterization, fundamental to any wireless system and

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particularly critical for satellite payloads, engineers need to observe both input and output signals simultane-

ously across wide bandwidths. This reveals nonlinear behavior, spectral regrowth, AM-AM and AM-PM conversion characteristics, and memory effects. Traditional setups require sep-

arate signal generators, analyzers, and careful synchronization.

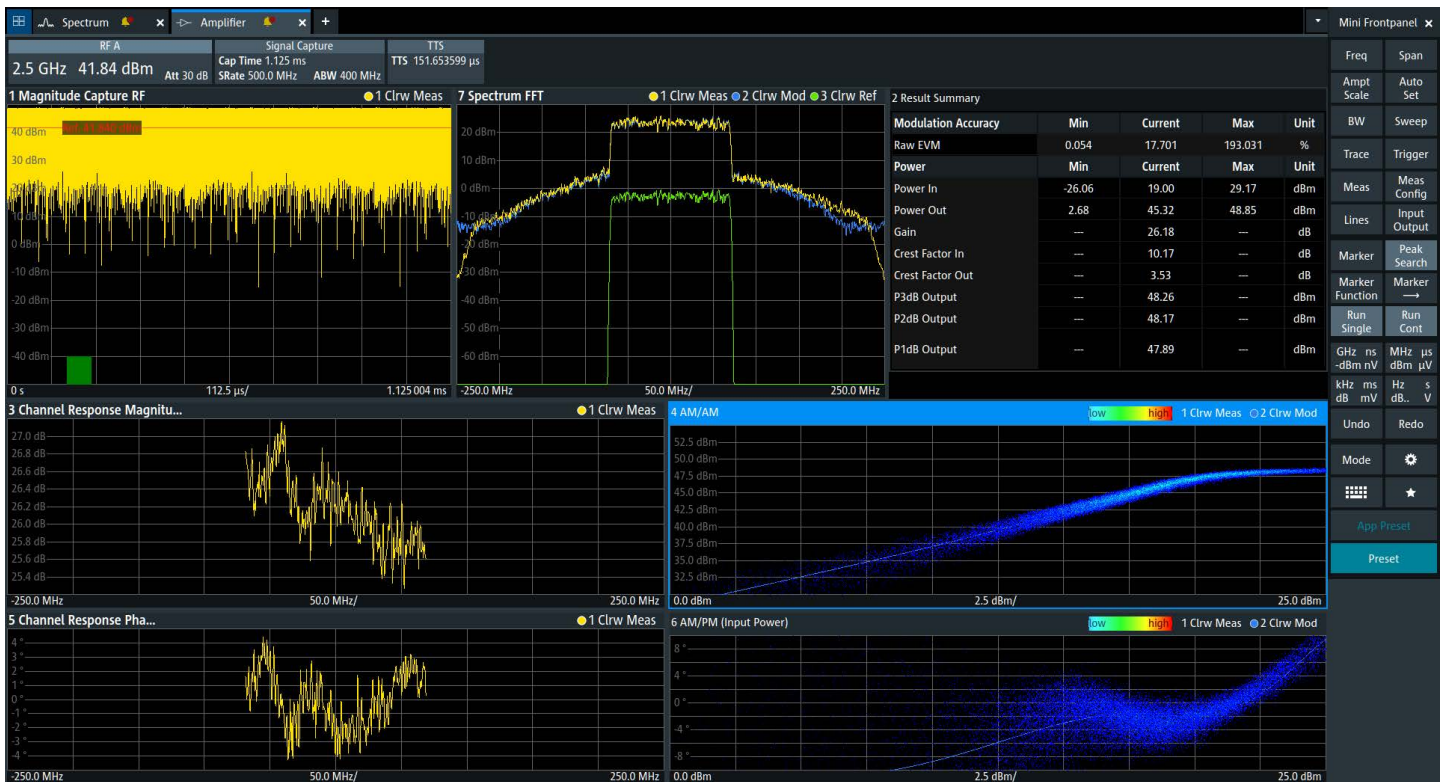
The challenge intensifies when researchers investigate cross-layer effects or mutual interference between different signals at different frequencies. Understanding how a high-power radar signal might impact co-located 5G equipment requires simultaneous capture and analysis of both signals, potentially separated by gigahertz in frequency but sharing the same physical space and interference environment.



4. The FSWX signal and spectrum analyzer overcomes the limits of traditional analysis methods with its novel architecture.

**Architectural Solutions:  
The Multiport Approach**

Recent analyzer architecture advances address these challeng-



5. Amplifier characterization with simultaneous input/output signal measurement and spectral regrowth, featuring a view of both frequency- and time-domain data.

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es through fundamental redesign. Multiport architectures with phase-coherent internal signal paths enable scenarios that previously required multiple instruments.

For example, Rohde & Schwarz's FSWX signal and spectrum analyzer has an innovative dual-port architecture (Fig. 4). Two independent receive paths, each with 4-GHz analysis bandwidth up to 44 GHz, operate simultaneously and phase-coherently. This configuration directly enables several critical measurement scenarios.

For amplifier or frequency converter characterization, connecting input and output signals to separate ports allows for instantaneous comparison (Fig. 5). The analyzer captures both signals simultaneously, revealing frequency-domain characteristics like spectral regrowth and time-domain behavior like AM-AM conversion, all within a single measurement. This eliminates synchronization challenges and reduces calibration requirements.

Phased-array testing becomes dramatically simpler. The phase-coherent architecture enables direct measurement of phase relationships between antenna elements or signal paths. For beamforming research, where the relative phase between channels determines beam direction and sidelobe levels, it provides immediate validation without external synchronization hardware.

The dual-path architecture also opens the door to an innovative cross-correlation mode. A single input signal splits internally into two independent paths, each with its own local oscillator and analog-to-digital converter.

By processing these two paths together using cross-correlation algorithms, the analyzer can suppress its own noise floor by approximately 15 to 20 dB. This extends dynamic range significantly, revealing weak signals, small spurs, or subtle impairments that would otherwise hide in the instrument's inherent noise.

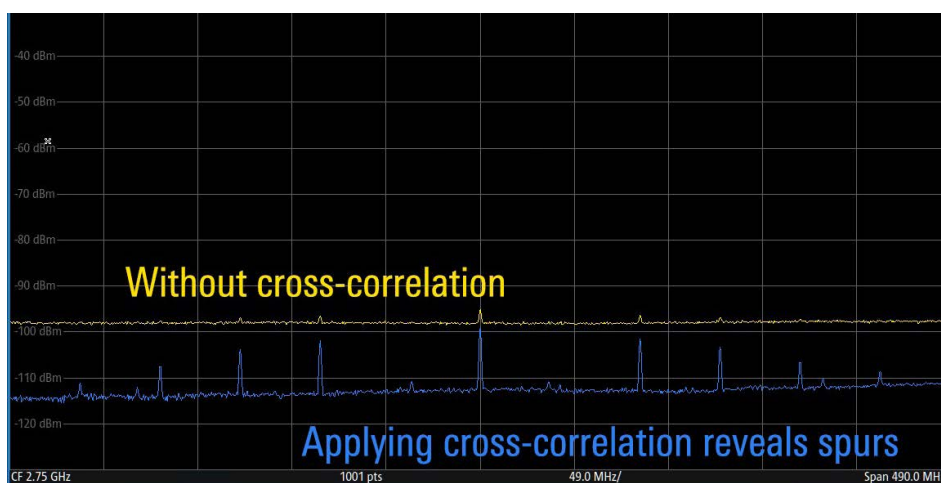
As Figure 6 illustrates, the cross-correlation technique of the FSWX can lower the test noise floor with only a slight increase in measurement time. The blue trace with applied cross-correlation reveals spurs hidden in the yellow trace without cross-correlation.

The cross-correlation capability proves particularly valuable for error-vector-magnitude (EVM) measurements at low signal powers, which are common in research scenarios where signals have undergone significant attenuation or where researchers deliberately test extreme conditions. The improved noise floor extends the usable measurement range of the EVM bathtub curve (Fig. 7), providing accurate results even when traditional analyzers struggle.

The architecture's advanced filter banks offer another advantage. Rather than relying on YIG filters, which introduce frequency-response variations and uncertainty in wideband measurements, switched filter banks across the entire operating range provide consistent preselection. This eliminates image frequency ambiguity and improves measurement accuracy, especially above 8 GHz, where traditional architectures face increasing challenges.

### Enabling Beyond-5G Experimentation

These architectural capabilities directly address Beyond-5G research requirements. When investigating custom modulation formats or learned



6. Cross-correlation technique lowers the test noise floor.

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constellations, researchers need to accurately measure performance without being limited by test equipment impairments. Cross-correlation mode reduces analyzer contributions to EVM measurements, allowing focus on actual device or algorithm performance.

For DPoD research, simultaneous input/output capture across wide bandwidths reveals how receiver-side processing compensates for transmitter nonlinearities. The phase-coherent architecture ensures accurate characterization of both magnitude and phase distortions that AI-based receivers must correct.

FDSS validation requires measuring subtle spectrum-shaping effects and precisely quantifying peak-to-aver-

age power ratio improvements. Wide instantaneous bandwidth capture ensures that no transient effects are missed, while low noise floors reveal spectral detail even at reduced power levels.

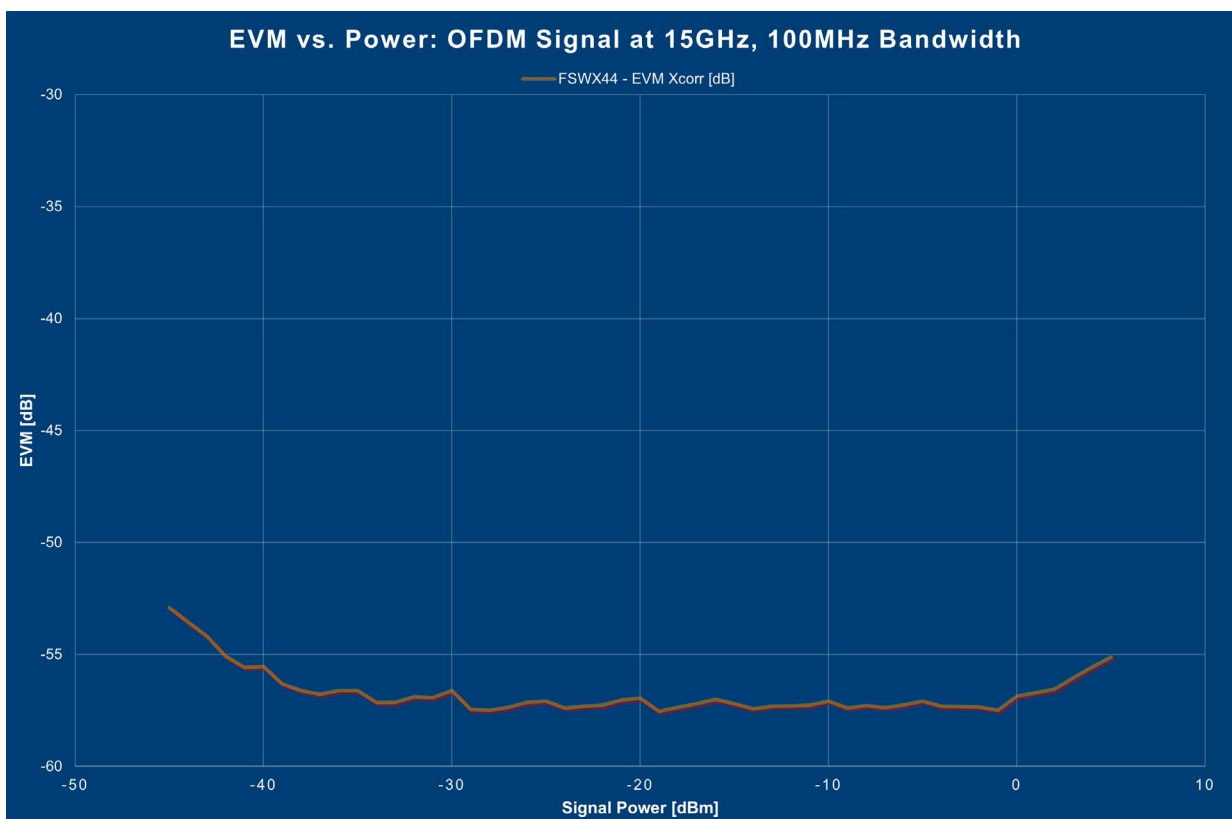
Multi-antenna research scenarios benefit from the ability to simultaneously analyze multiple signal paths with guaranteed phase coherence. Whether investigating multiple-input, multiple-output (MIMO) channel estimation, spatial multiplexing techniques, or advanced beamforming algorithms, having phase-locked measurements eliminates a major source of uncertainty.

The Beyond-5G option extends standard cellular analysis capabilities to support parameters outside current

specifications. Researchers can configure arbitrary channel bandwidths, custom modulation formats, and non-standard resource block configurations. This flexibility enables exploration of the parameter space that will eventually inform 6G standardization decisions.

### Looking Ahead: Test Infrastructure for the Transition

The path from 5G NTN to 6G isn't a single technology leap, but rather an evolutionary process where researchers build understanding through experimentation. Test infrastructure must support both validation of current standards and exploration of future possibilities.



**7. Residual error vector magnitude over a power sweep with cross correlation.**

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For NTN evolution, this means equipment capable of emulating increasingly complex scenarios: regenerative payloads with on-board processing, inter-satellite links with dynamic routing, and integrated sensing/communication where signals serve multiple purposes simultaneously. As NTN frequency bands expand to Ka-band and beyond, test equipment must maintain performance at these higher frequencies while handling wider instantaneous bandwidths.

For terrestrial 6G development, terahertz spectrum exploration requires new approaches to signal generation and analysis. Though initial 6G deployments may not utilize THz bands (predictions of widespread terahertz communication have repeatedly proven premature), research must continue to understand propagation, device physics, and channel modeling at these frequencies.

The integration of AI throughout the wireless stack creates new validation requirements. How do you verify that an AI-optimized network makes correct decisions? How do you test neural receivers against the infinite variety of possible channel conditions? How do you measure the performance of semantic communication systems where traditional metrics like bit error rate may not apply? These questions demand test approaches that blend traditional RF measurement with data science techniques.

### Conclusion

The evolution beyond 5G presents testing challenges paralleling the technological advances themselves. From NTN's extreme delays and Doppler shifts, through 6G's terabit speeds and microsecond latencies, to AI-native communication systems, each advance requires corresponding measurement capability.

Modern test equipment addresses these through architectural innovation: multi-port phase-coherent designs, cross-correlation techniques, and flexible analysis frameworks. As researchers explore technologies that won't standardize for years, test infrastructure must support both current validation and future exploration.

The goal isn't easier measurements, though simplified setups help, but making previously impossible measurements achievable. Accurate characterization of neural receivers, validation of digital post-distortion across wide bandwidths, and multi-antenna analysis with confident phase relationships let researchers focus on advancing technology rather than wrestle with test limitations.

As wireless technology evolves, the partnership between innovation and validation remains essential. The ability to test what we imagine today determines what we deploy tomorrow.

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## CHAPTER 5

# Seamless Connectivity Everywhere: How NTN Will Transform 6G

*In the 6G era, non-terrestrial networks promise not only coverage, but resilience and inclusivity.*

JESSY CAVAZOS, 6G Solutions Lead, Keysight Technologies



Keysight Technologies

**N**on-terrestrial networks (NTNs) have long been pitched as the answer to connectivity gaps, including remote communities, disaster zones, and industries operating beyond terrestrial reach. In the 6G era, NTNs promise to deliver not just coverage, but resilience and inclusivity.

What's changed? They're no longer theoretical. Direct-to-device connectivity is moving from concept to reality, with multiple players launching services that extend mobile coverage

beyond terrestrial limits. Dead zones are no longer the end of the conversation. Phones can keep messaging, pulling weather information, and performing signaling to help when towers disappear.

### From Orbit to Everywhere

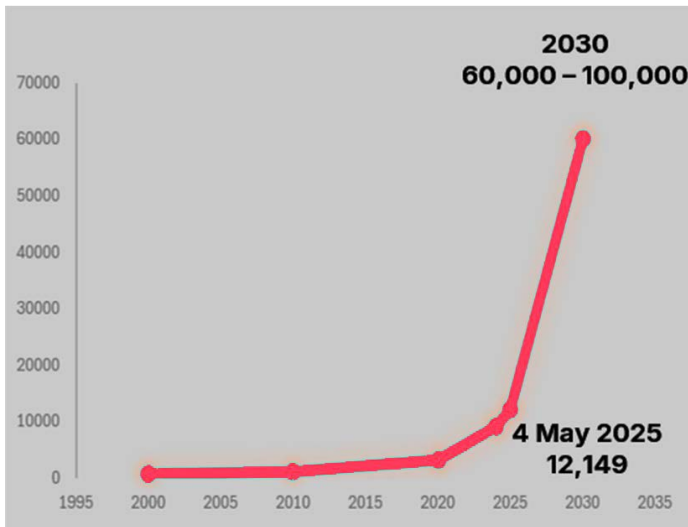
The journey from a single satellite in 1957 to thousands in orbit today sets the stage for the rise of NTNs. Current projections show tens of thousands of active satellites (Fig. 1), many in low Earth orbit (LEO), creating a dense

mesh for global connectivity.

Industry momentum is accelerating: SpaceX has demonstrated direct-to-cell messaging, AST SpaceMobile is partnering with AT&T and Verizon for global coverage, and Apple's Globalstar integration offers emergency messaging on iPhones. By late 2024 and throughout 2025, carriers began rolling out real offers such as nationwide texting in New Zealand, Canada-wide trials, curated data apps in Japan, and U.S. expansion with mainstream apps like WhatsApp and Google Maps integrated into OS-level SAT mode.

This tipping point combines policy clarity under the Federal Communications Commission's (FCC) Supplemental Coverage from Space (SCS) framework with international spectrum harmonization led by the International Telecommunication Union (ITU) and ongoing 3rd Generation Partnership Project (3GPP) standardization. In addition, technical advances now allow satellites to act as roaming cell sites for ordinary handsets.

## CHAPTER 5: Seamless Connectivity Everywhere: How NTN's Will Transform 6G



1. **Active satellites in orbit from 2000 to 2030.**

why operators are integrating satellite access as roaming, ensuring continuity without user intervention.

### The Enabling Stack for NTN-Driven 6G

Delivering seamless NTN-TN integration requires a portfolio of technologies:

- **Frequency Range 3 (FR3) spectrum:** The sweet spot for 6G, balancing coverage and capacity better than millimeter-wave (mmWave) frequencies while offering more bandwidth than sub-6-GHz.
- **Extreme MIMO (xMIMO):** Thousands of antennas forming ultra-narrow beams to maximize spectral efficiency and reduce interference.
- **Reconfigurable intelligent surfaces (RIS):** Smart reflectors that redirect signals around obstacles, mounted on buildings or even satellites.
- **Integrated sensing and communication (ISAC):** Networks that sense and communicate simultaneously, enabling cooperative navigation and environmental awareness.
- **AI-native radio access network (RAN):** Networks that learn and adapt, optimizing spectrum, predicting handovers, and balancing energy in real-time.

Together, these technologies form the backbone of an intelligent, adap-

### 3D Network Architecture: The Backbone of 6G NTN

Unlike 5G, where NTN was an add-on, 6G envisions NTN as a Day 1 native component of a unified 3D network architecture spanning terrestrial, aerial, and space layers. This multilayered design integrates:

- LEO, medium Earth orbit (MEO), and geosynchronous orbit (GEO) satellites
- High-altitude platforms (HAPs)
- Unmanned aerial vehicles (UAVs)

The result would be seamless handover across layers, enabling robust coverage and advanced use cases such as autonomous mobility, maritime communications, and emergency response. This architecture supports multiconnectivity, dynamic spectrum sharing, and AI-driven orchestration across all domains.

### Transformational Applications

#### Direct-to-Device Connectivity

Imagine pulling out your phone in a desert or on a ship and having the same coverage you expect downtown. This becomes possible in 6G. Early deployments support messaging and essential apps, with voice and richer data on the horizon as spectrum and satellite density scale.

#### Autonomous Mobility and Drones

NTNs will enable drones to inspect pipelines across remote terrain and vehicles to navigate safely in areas without terrestrial towers. Reliable NTN links will support precision agriculture and urban air mobility, where machines depend on continuous data streams.

#### Disaster Relief and Public Safety

When terrestrial networks fail during hurricanes or wildfires, NTNs can activate instantly, providing life-saving communications for first responders. This resilience is

CHAPTER 5: Seamless Connectivity Everywhere: How NTN's Will Transform 6G

tive NTN-enabled 6G ecosystem, but each technology provides unique advantages and challenges, as highlighted in the **table**.

Industry experts caution that these technologies demand rigorous validation under real-world conditions, including Doppler effects, latency, and synchronization challenges unique to NTN's.

**Industry Acceleration: Key Players**

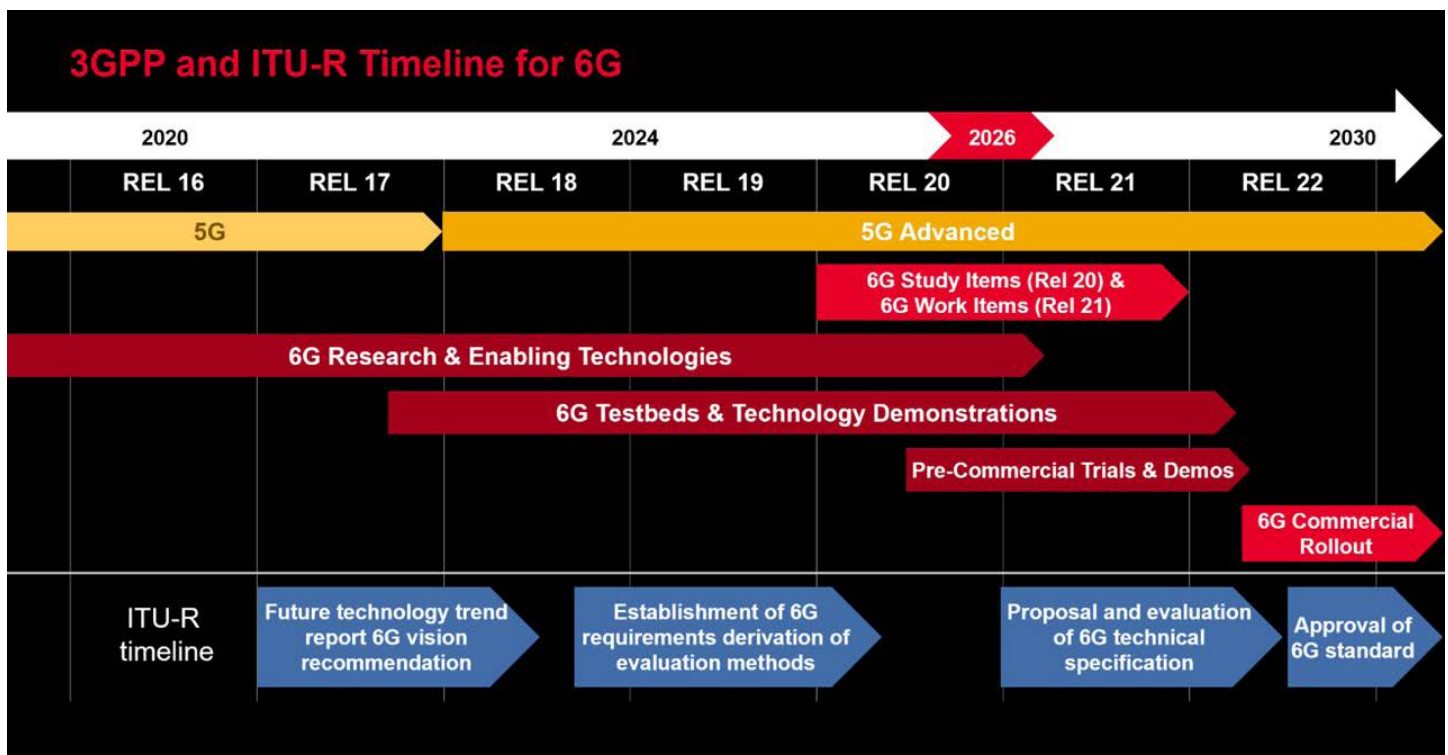
SpaceX, AST SpaceMobile, and Apple illustrate different strategies shaping the NTN's future.

- **SpaceX** focuses on mobile satellite service (MSS) spectrum acquisitions and constellation density for global scalability.

ENABLING 6G NTN TECHNOLOGIES: BENEFITS AND CHALLENGES		
Technology	Benefits	Challenges
FR3	Balances coverage and capacity; enables ultra-massive MIMO	Requires advanced channel models; hardware maturity
xMIMO	High throughput and spatial multiplexing	Hardware complexity and energy consumption
RIS	Redirects signals; improves coverage	Dynamic geometry and control overhead in NTN's
ISAC	Combines sensing and data transmission	Balancing the demands between communications and sensing
AI-native RAN	Predictive handovers; energy optimization	Limited training data; interoperability across vendors

- **AST SpaceMobile** leverages partnerships with major carriers and aims for high-capacity direct-to-device links.
- **Apple** integrates NTN's for emergency messaging, prioritizing user experience over high data rates.

Alignment with 3GPP standards, which started in Release 17 for NTN basics and evolved further in Release 18/19 for mobility and regenerative payloads, ensures interoperability and allows satellites to function as part of



2. Standards timeline for 6G.

## CHAPTER 5: Seamless Connectivity Everywhere: How NTN's Will Transform 6G

the radio access network (RAN) rather than a bolt-on.

### **Standards Roadmap: Looking Ahead to Release 20 and 21**

While Releases 17 and 18 laid the foundation, 3GPP Releases 20 and 21 will advance NTN integration further:

- **Release 20 (2025–2026):** Study phase for multi-orbit architectures, AI-native air interfaces, and advanced spectrum sharing.
- **Release 21 (2027–2028):** Normative specifications for regenerative payloads, seamless NTN-TN convergence, and IMT-2030 compliance.

These releases align with the ITU's IMT-2030 timeline, targeting commercial 6G deployments by 2030 (Fig. 2).

### **NTN Challenges Ahead**

Despite progress, NTN faces hurdles:

- **Spectrum harmonization:** Coordinating satellite and terrestrial operators across FR3 bands is complex, akin to managing air traffic at dozens of airports.
- **Standardization:** Multi-vendor interoperability is critical; without common interfaces, NTN risks fragmentation.
- **Hardware constraints:** Satellites operate under tight power and thermal budgets, making efficiency paramount.
- **Business models:** Constellations cost billions. Success depends on

proving value across consumer, enterprise, and public safety markets.

### **Design and Modeling for Success**

Lessons from 5G underscore the need for practicality. For NTN in 6G, that means:

- **Energy efficiency:** Networks that “sleep” during low traffic and satellites that dynamically adjust beams.
- **Zero-trust security:** Continuous authentication and encryption across borders and industries.
- **Digital twins:** High-fidelity virtual models to test real-world conditions before expensive launches, simulating interference, weather, and cyberattacks.

Validating NTN performance for 6G requires more than traditional link testing. Advanced modulation schemes combined with high-fidelity digital twins allow engineers to emulate complex orbital dynamics, Doppler shifts, and multilayer interference before hardware deployment.

These virtual environments replicate real-world conditions, enabling optimization of waveform design, power efficiency, and latency. By integrating AI technology into these simulations, developers can predict performance tradeoffs and accelerate innovation while reducing costly trial-and-error in orbit.

### **Orbit to Opportunity**

NTNs aren't just about satellites, they're about equity, industry, and resilience:

- **Equity:** Extending digital services to underserved communities.
- **Industry:** Enabling efficiencies in agriculture, logistics, and manufacturing.
- **Resilience:** Keeping societies connected during disasters.

With multiple players driving innovation and global standards shaping interoperability, NTNs are poised to become a baseline expectation for connectivity in the 6G era. For engineers, the mandate is clear: Design systems that are visionary yet grounded, meaning efficient, secure, and interoperable from day one.

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## CHAPTER 6

## A World Without mmWave?

*The use of high-frequency RF in our modern digital world is essential today, and it will become even more central in the future.*

DAN RHODES, Business Development Director, Filtronic



Filtronic

Without high-frequency mmWave radio-frequency (RF) technology, the modern world would be dramatically different. This change would reverberate across various sectors, shaping a world devoid of essential technologies that we often take for granted. Let's explore how the absence of mmWave technologies would impact key advances not only in daily life, but across essential sectors, too.

Use of high-frequency RF in today's digital world is essential, and it will become even more central in the future. It expands the data capacity that we consume and satisfies our

voracious appetite for more. Without the critical components and subsystems of the mmWave spectrum, the technologies of the future would continue as the stuff of science fiction.

Thankfully, mmWave technology is helping to expand possibilities and push performance boundaries ever higher. mmWave refers to radio frequencies in the electromagnetic spectrum ranging from 30 to 300 GHz, further characterized by their short wavelengths — 1 to 10 mm — allowing them to carry large amounts of data.

Without it, network capacity would be significantly limited, affecting our ability to use data-intensive applica-

tions, things we take for granted today. Think crowded areas, where many people are accessing services like video streaming, as we move into an era of even higher data consumption and connectivity demands.

### Industry Limitations

The processing power and computing capabilities driving the network depend on high-frequency connections provided by mmWave technology. If these connections aren't available, data transfer becomes slower due to narrower data pipes. This impacts not only which architecture can be configured, but also what can be achieved on the networks for business and commercial use.

For instance, in satellite communications, mmWave technology is essential for deploying large networks, particularly in low Earth orbit. These networks rely on high frequencies to establish substantial data links, known as feeder or gateway links, between satellites and ground stations.

The bandwidth would be insufficient if only lower microwave frequencies were used, leading to limited speed and capacity. In short, this would hinder the

## CHAPTER 6: A World Without mmWave?

ability to provide high-speed internet to users in remote locations.

Meanwhile, the telecommunications sector also requires mmWave for areas where fiber-optic cables either aren't available or too expensive to deploy. Fiber can't always be laid, for example, across rivers, motorways, mountainous regions, or in densely populated urban areas without significant disruption. In such cases, wireless links between base stations and the core network are necessary, especially when implementing 5G services.

For radar systems in defense, higher frequencies are needed to accurately detect and track small objects, as well as establish secure communication channels with narrow beams that are difficult to detect. Similarly, missile seekers use high frequencies to lock onto targets with precision, relying on directed mmWave beams to reduce detection and interception chances. In these applications, the absence of mmWave would limit the effectiveness of military systems, making it a crucial component in defense.

### Requirements for Future Advances

It's not just sector-specific applications that need higher frequencies. To support advances in fields like AI, autonomous vehicles, and the Internet of Things (IoT), mmWave is used, for instance, in sensors for gesture control systems. These rely on higher frequencies to detect motion with precision

over both long and short distances.

Plus, secure private networks benefit from such technology because these applications demand low-latency and high-frequency options to operate effectively. Companies like Filtronic actively work on integrating mmWave technology to meet these requirements.

In fact, a significant development in Filtronic's mmWave technology involves the use of high-power, solid-state amplifiers (SSPAs). Traditionally, the compound semiconductor gallium arsenide (GaAs) has been used within mmWave SSPAs due to its long history and established performance. However, even at higher frequencies, such as those above 40 GHz, gallium nitride (GaN) is now becoming more prevalent.

GaN offers better power density and efficiency, allowing for more power output from the same surface area. It helps make devices more compact and extends the range of signal transmission.

This move comes as the goals for the next phase of 5G and future 6G include achieving wireless xHaul data rates of 100 Gb/s. Currently, the highest capacity xHaul links operate at around 25 Gb/s.

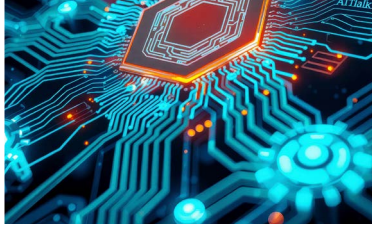
Reaching 100 Gb/s requires multiple mmWave channels. Here, we'll likely see the aggregation of different frequency bands, such as E-band, W-band, D-band, and beyond, to achieve the needed bandwidth.

Achieving these goals is challenging and requires meticulous management of manufacturing processes, as well as vertical integration of design, manufacturing, and testing.

Technology is becoming more complex, and industries are increasingly dependent on data, so it's essential to maintain reliability as well as performance when we move toward higher frequencies for applications that we might just take for granted.

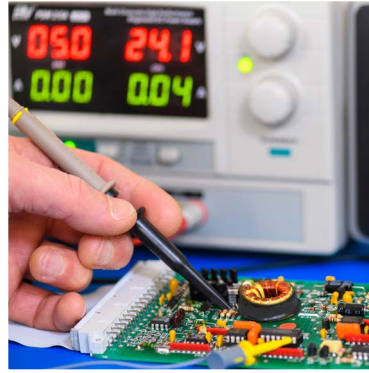
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