The Importance of Satellite Channel Emulators in Non-Terrestrial Networks

In today's interconnected world, staying connected has become as essential as food, water, and shelter. However, despite all the technological advancements, there are still places where traditional networks are unable to reach viz. remote villages, vast oceans, or mountainous regions. Now, imagine being able to stay connected anywhere on the planet, whether one is trekking in the Himalayas, sailing across the Pacific, or living in a remote village. This vision is becoming a reality, thanks to Non-Terrestrial Networks (NTN), a ground-breaking approach to communication that extends the internet beyond the reach of traditional networks. 3GPP release 17 introduces the concept of integration of satellite components in the 5G architecture. The "Integration of satellite components in the 5G architecture" work item adds or enhances several features in 5G core architecture to support NTN for several use cases viz. Coverage extension, Internet of Things (IoT), disaster communication, and global roaming and broadcasting. The 5G NTN market is projected to account for USD 16,123 million by 2027, growing at a CAGR of 38.2% during the forecast period (2022 – 2027, Source: Secondary Research, Expert Interviews, and MarketsandMarkets Analysis). The primary factor driving the 5G NTN market growth is the rising need for service continuity in underserved areas, such as mines, remote areas, the sea, and other complex locations.

Let us start by understanding "What are Non-Terrestrial Networks?"

Present day mobile networks rely on cell towers and underground cables. Due to their higher infrastructure cost, pure terrestrial networks like 4G/5G are unable deliver connectivity to remote, rural, and underserved areas. Unlike terrestrial networks, NTN operate above the Earth, using satellites, high-altitude radio platforms (HARP) like balloons or drones, or uncrewed aerial vehicles (UAVs).

Whether it is a satellite orbiting the Earth, a drone hovering over a disaster zone, or a balloon floating in the stratosphere, NTN will provide a crucial link for seamless communication, working alongside existing terrestrial networks to ensure full coverage in the Himalayas, the Pacific, or a remote village.

NTNs rely on platforms in space or the atmosphere to relay signals between users and larger communication networks. The key such platforms in NTN are satellites, which are generally segregated in three categories:

- ***Geostationary Earth Orbit (GEO) Satellites:*** These satellites are positioned high above Earth (approx. 35786km), covering almost one third of earth area, making them perfect for broadcasting or large-scale communication.
- ***Low Earth Orbit (LEO) Satellites:*** On the other hand, sitting closer to Earth (160-2000km), LEO satellites offer faster internet with lower delays and hence ideal for real-time applications like mobile communications. Companies like Starlink and OneWeb are leading satellite service providers in this area.
- ***Medium Earth Orbit (MEO) Satellites:*** These provide a middle ground (>2000km but less than 35786km), offering both speed and wide coverage.

Further, HARP like balloons or drones can deliver localized connectivity, which is especially useful during disasters, emergencies, or temporary setups.

Integrating NTN with modern communication systems like 5G is essential, and gNodeB, the advanced base station for 5G, plays a key role. In NTN, gNodeBs are adapted to work seamlessly with satellites and airborne platforms. gNodeB acts as a bridge between 5G devices and NTN platforms, managing handovers when users move between terrestrial and non-terrestrial networks and hence, ensuring high-speed, low-latency connectivity, even in dynamic environments.

This integration allows NTNs to deliver the same high-quality experience we expect from ground-based networks, making them a vital part of the 5G ecosystem (Figure 1).

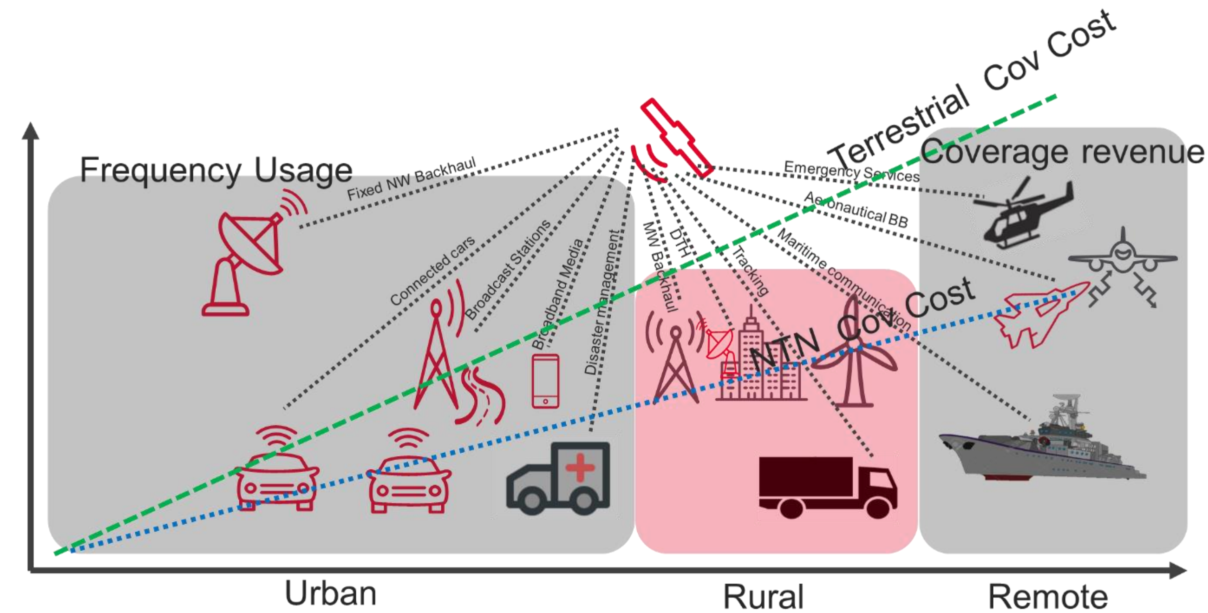

Figure 1: Coverage/cost comparison of terrestrial and NTN across urban, rural and remote regions.

Traditional satellites work in bent pipe configuration, bouncing signals back to Earth for processing. Modern regenerative payloads change the game by processing data directly onboard the satellite. Regenerative payloads enable faster communication by reducing the need for signals to return to Earth as well as cut down latency. It enables efficient bandwidth to use further enabling optimization of how data is transmitted, reducing bottlenecks. It facilitates advanced features such as performing tasks like error correction and beamforming, making them more flexible and efficient for modern communication systems. With regenerative payloads, satellites become smarter and more autonomous, enabling faster and more reliable NTN systems.

Testing satellite communication systems under realistic environmental conditions is essential to ensure their reliability. Key considerations include:

- ***Orbital Parameters**:* High-velocity satellites and High-Altitude Pseudo-Satellites (HAPS) operating in long-distance and inter-satellite links.
- ***Signal Buffers for Delays**:* Traditional methods simulate link distances but do not fully address bidirectional communication complexities.
- ***Simulating Sliding Delays**:* Accurately replicating satellite kinematics by modelling dynamic delays to reflect satellite and platform movement.

Errors identified in operational satellite communication systems can incur significant costs—up to 1000 times higher than detecting the same error during the specification phase.

Historically, satellite link modelling focused on unidirectional links, addressing one link at a time. However, modern communication systems integrate terrestrial networks and satellite links to create end-to-end signalling chains. To address these evolving challenges, modern testing platforms must adapt to meet the demands of contemporary SATCOM systems.

The transfer function of the radio channel encompasses all the modifications a transmitted signal undergoes as observed from the receiver's perspective.

There are primarily four key domains of freedom:

- ***Time**:* Signals arriving at the receiver at different times suggest transmitter movement, resulting in Doppler spread. The Doppler effect is frequency-dependent, with the overall spread typically centred around the carrier frequency.
- ***Space**:* Signals arriving from various angles create spatial spreading.
- ***Frequency**:* Different components of the received signal exhibit variations across frequencies.
- ***Polarization**:* Polarization can shift, such as when signals reflect off specific surfaces. Transmitters equipped with multiple antenna systems for different polarization layers can transmit distinct signals that share the same physical properties (e.g., location, delay, and frequency).

To ensure NTNs work reliably, engineers use RF channel emulators, a specialized tools that replicate real-world conditions to test and optimize satellite links in the lab environments. A satellite link emulator is a specialized tool that replicates the behaviour of satellite communication links under controlled conditions. It simulates the physical and operational characteristics of a satellite network, allowing engineers to test devices, systems, and protocols without needing access to an actual satellite in orbit. These emulators simulate real-world scenarios like:

- ***Propagation Delays and Interference:*** Accounting for signal travel times over vast distances.
- ***Doppler Effects:*** How signals shift when satellites move relative to Earth creating frequency shifts caused by LEO and MEO satellite movement.
- ***Signal Degradation:*** Atmospheric disturbances, rain fade, or noise interference.
- ***Handover Events:*** Simulating transitions between satellites in LEO or MEO.

Payload Configuration	Round Trip Delay	Orbit	Typical delay
Bent Pipe	$2 * \frac{d_{GW-Sat}(\vartheta_{GW}) + d_{Sat-Rx}(\vartheta_{Rx})}{c}$	GEO	272ms
		LEO	14ms
Regenerative	$2 * \frac{d_{Sat-Rx}(\vartheta_{Rx})}{c}$	GEO	135ms
		LEO	6ms

From a propagation modelling perspective, terrestrial channels in satellite communication systems are largely like those in traditional terrestrial systems, with multipath propagation caused by objects near the user. In satellite communication, signal behaviour diverges from terrestrial systems due to unique characteristics:

- ***Minimal Angular Spread***: Satellite systems often operate with point-like transceivers, resulting in negligible angular spread compared to terrestrial links.
- ***Line-of-Sight Dominance****:* Radio channels in satellite communication predominantly rely on line-of-sight links, limiting the role of reflected signal paths.
- ***Spatial Separation****:* Multi-channel transmission in satellite systems requires alternative spatial separation methods, as conventional reliance on reflected signals, typical in cellular systems, is not applicable.
- ***Plane Wave Characteristics****:* In practice, the signal behaves like a plane wave until it reaches reflection points.

From a modelling perspective, the angular spread can be approximated as nearly zero, simplifying certain aspects of propagation analysis. And hence, modern satellite communication systems demand tailored approaches to address these distinctive challenges effectively.

Satellite link emulators play a critical role in the development, testing, and optimization of NTN. As NTN integrates satellites, high-altitude platforms, and drones with terrestrial networks, ensuring robust and reliable communication becomes vital. This is where satellite link emulators step in.

Satellite link emulators support NTN development by testing network under realistic conditions. Satellite link emulators recreate real-world conditions to validate system performance. This ensures that NTN components—like user terminals, gNodeBs, and satellites can operate seamlessly under challenging circumstances, such as high latency in GEO satellite links, frequent handovers in LEO satellite constellations, or dynamic weather impacts on signal quality, therefore accelerating development. Engineers can test and refine NTN solutions on the ground before deployment. This saves time and cost compared to testing with live satellites. For example, engineers can fine-tune regenerative payload functionalities or validating protocols for seamless integration between terrestrial and NTN. Engineers can optimize system performance by replicating different environmental and operational factors. Satellite link emulators help identify potential bottlenecks or failures in NTN systems, such as packet loss during signal fade or data rate fluctuations due to satellite movement, hence ensuring interoperability by involving multiple technologies and stakeholders viz. LEO, MEO, and GEO satellites; ground stations; and end-user devices. Satellite link emulators ensure these components work harmoniously by simulating cross-domain interactions. Further, operators can use satellite link emulators for training and troubleshooting purposes, learning to manage complex NTN setups without requiring a live environment. These emulators also aid in diagnosing and troubleshooting issues which may arise post-deployment.

Satellite link emulators are pivotal in several key NTN applications like 5G integration, ensuring that NTN-based gNodeBs handle the high speeds and low latencies expected in 5G communication or IoT by validating satellite connections for IoT devices in remote or mobile scenarios, like maritime or agricultural monitoring. In aerospace and defence applications, these instruments can test secure, low-latency communication for defence operations, disaster response, or autonomous systems, ensuring reliable satellite links for autonomous vehicles or drones operating in isolated areas.

While satellite link emulators are indispensable, they also face challenges in terms of complexity, cost, and evolving wireless standards. Simulating the dynamic behaviour of large satellite constellations with thousands of moving elements could be complex. High-precision emulators can be expensive, limiting access for smaller organizations.

The Maury Microwave Advanced Channel Emulator (ACE) is a state-of-the-art solution tailored for the precise and complex requirements of NTN satellite link emulation (Figure 2). It plays a crucial role in simulating satellite communication links, enabling reliable design, testing, and optimization of NTN systems.

Figure 2: The Maury Microwave ACE9600.

Its key features include but are not limited to high-fidelity link emulation, scalability, flexibility, and advanced modelling capabilities. The ACE9600 can simulate propagation delays, Doppler shifts, fading, and interference and hence accurately replicates real-world satellite communication scenarios. It supports LEO, MEO, and GEO constellations with customizable parameters. The ACE9600 can handle multiple channels simultaneously (4 independent in single box scalable up to 16 independent channels by cascading 4 boxes), making it ideal for testing large satellite constellations or complex NTN architectures. This solution can also model environmental impacts like rain fade, multipath reflections, and atmospheric disruptions and supports dynamic scenarios such as satellite handovers and fast-moving terminals. This platform is adaptable to evolving NTN standards, including 5G NTN integration. The ACE9600 channel emulator permits the following impairments to be added to any signal:

Phase continuous changing delay	0.1ps/sec to 2ms/sec
Signal and carrier Doppler	up to +/- 6MHz
Signal attenuation	0 to 70 dB
Phase shift	0 to 359.9 0
Interference & Noise	Additive White Gaussian noise
Fading profiles	Multipath (Rayleigh, Rician)
Hardware-in-the-loop impairments	Amplifier compression, AM/AM and AM/PM, Programmable phase noise
Filter shapes	IMUX/OMUX filter shapes, passband ripple and signal notching

NTN is not just about technology, it is about breaking barriers and creating opportunities by reaching remote areas, powering innovation, disaster relief, and promoting equality. NTN will ensure no place is too far or too isolated for connectivity, bringing internet access to underserved communities, therefore creating a more inclusive world, giving everyone access to education, healthcare, and economic opportunities, by bridging the digital divide. Hence, in emergencies like earthquakes or hurricanes, NTN can restore communication quickly, providing a lifeline for rescue efforts. Furthermore, NTN support modern technologies like 5G and IoT, connecting devices and systems in even the most challenging environments.

The future of NTN is exciting and full of potential. As we move toward 6G, NTN will play a central role in creating a truly global, seamless communication network. Innovations like reusable rockets are making satellite launches cheaper, while AI is making NTN systems smarter and more efficient. NTN are more than just a technological advancement, they are a symbol of human ingenuity and a step toward a more connected and equitable world. With tools like RF channel emulators, advanced gNodeBs, and regenerative payloads, NTN is overcoming challenges and opening doors to limitless possibilities.

The sky is no longer the limit, it is the pathway to a brighter, more connected future for everyone and the Maury Microwave ACE9600 stands out as a critical enabler for NTN innovation, driving the development of robust, efficient, and future-proof satellite communication systems.