Testing Regenerative and Transparent 5G NTN Architectures with the ACE9600

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Introduction

The integration of Non-Terrestrial Networks (NTN) into 5G is transforming global wireless communications by enabling connectivity through satellite-based infrastructures operating alongside terrestrial networks. Introduced in 3GPP Release 17 and further expanded through Release 18 and Release 19, NTN technologies are driving new applications including direct-to-device communications, satellite backhaul, global IoT coverage, and resilient network architectures.

Unlike terrestrial networks, NTN systems operate under highly dynamic channel conditions characterized by large propagation delays, significant Doppler shifts, moving beams, and frequent handovers between satellites and gateways. As NTN architectures evolve from traditional transparent payloads toward regenerative payloads with onboard gNB functionality, validating system performance becomes increasingly complex.

This application note presents advanced methodologies for validating 5G NTN systems using the Maury Microwave ACE9600 Advanced Channel Emulator. By reproducing realistic satellite channel impairments and orbital dynamics under controlled laboratory conditions, the ACE9600 enables repeatable and realistic testing of NTN modems, user equipment (UE), gateways, and network infrastructure prior to deployment.

Challenges of 5G NTN Validation

Unlike terrestrial cellular systems, 5G NTN operate under highly dynamic propagation conditions driven by satellite movement, orbital geometry, and continuously changing link characteristics. Depending on the satellite orbit type and network architecture, NTN systems may experience large propagation delays, significant Doppler frequency shifts, rapid Doppler rate variations, moving coverage beams, and frequent handovers between satellites and gateways.

In Low Earth Orbit (LEO) constellations, satellites travel at high relative velocities with respect to the UE, generating Doppler shifts that can vary continuously throughout a satellite pass. In addition, the propagation delay and path loss evolve dynamically as the satellite position changes over time. These impairments can directly impact synchronization procedures, waveform performance, mobility management, throughput, and overall link reliability.

As shown in Figure 1, the relative velocity and distance between the satellite and the UE change continuously as the satellite moves across the sky. This causes the Doppler shift to vary from large negative to large positive values, while the propagation delay decreases to a minimum at closest approach and then increases again.

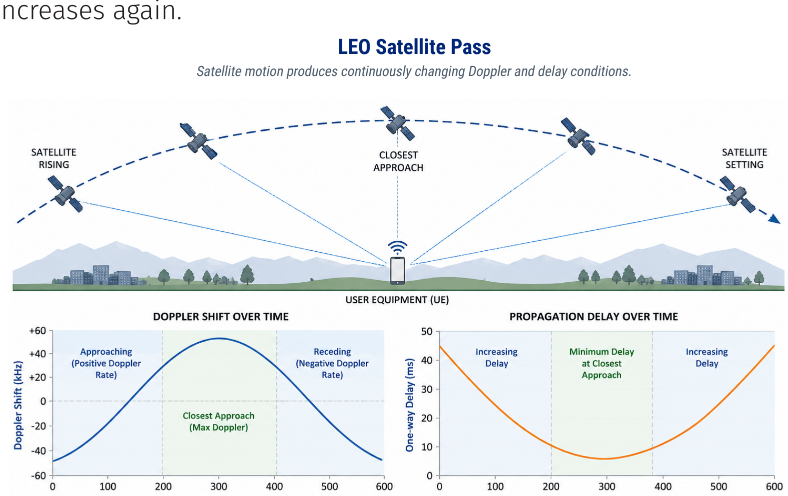

Figure 1. Example of time-varying Doppler shift and propagation delay during a LEO satellite pass.

As defined by 3GPP Release 17 and later expanded in Release 18 and Release 19, NTN architectures are also evolving from traditional transparent payload implementations toward regenerative payload architectures with onboard gNB functionality and inter-satellite networking capabilities (Figure 2). This evolution introduces additional validation challenges related to mobility management, feeder link switching, distributed routing, timing synchronization, and end-to-end system resiliency.

Traditional RF validation methods based on static attenuation, fixed delay lines, or simplified fading simulators are insufficient to accurately reproduce the continuously changing conditions experienced in real NTN deployments. Realistic NTN validation requires dynamic and repeatable emulation of orbital movement and time-varying channel impairments under controlled laboratory conditions.

To properly evaluate NTN modems, UE, gateways, and network infrastructure, engineers must be able to emulate realistic scenarios including:

- Time-varying propagation delay
- Dynamic Doppler shift and Doppler rate
- Satellite and beam handovers
- Dynamic path loss
- Multipath fading conditions
- Multi-orbit satellite environments
- Feeder link transitions
- Inter-satellite connectivity scenarios

Accurate reproduction of these conditions is essential to validate system performance, improve interoperability, reduce deployment risk, and accelerate development of next-generation NTN networks.

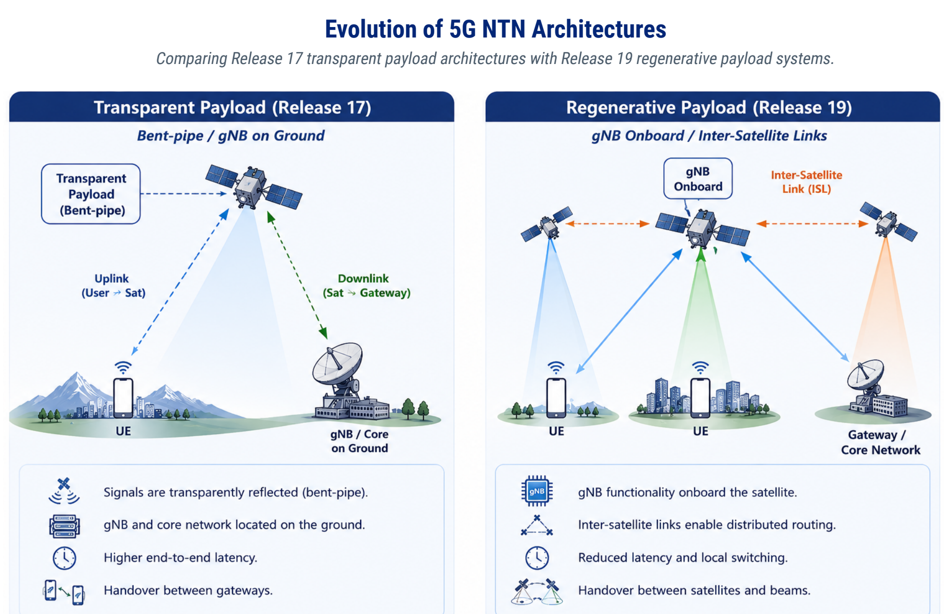

Figure 2. Evolution from transparent NTN architectures toward regenerative payload architectures with onboard gNB and inter-satellite connectivity.

Key NTN RF Channel Impairments

Unlike terrestrial cellular systems, NTN RF channels are highly dynamic and continuously change as satellites move relative to the Earth and the UE. Accurate laboratory validation therefore requires realistic emulation of time-varying RF impairments that directly affect synchronization, waveform performance, throughput, and overall link stability (Figure 3).

Layered RF Channel Impairments in NTN Link Emulation

Multiple dynamic RF effects are applied simultaneously to reproduce realistic satellite channel behavior.

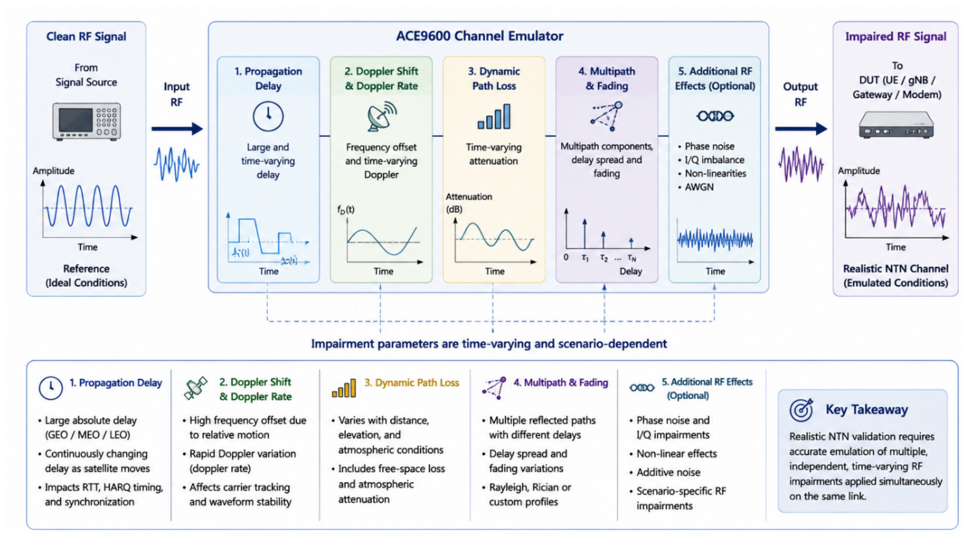

Figure 3. Example of multiple dynamic RF impairments applied simultaneously during NTN channel emulation.

Propagation Delay

One of the primary characteristics of NTN systems is the large propagation delay introduced by satellite communications. Depending on the orbit type, propagation delay may vary from a few milliseconds in LEO systems to several hundred milliseconds in Geostationary Earth Orbit (GEO) deployments.

As satellites move across the sky, the distance between the satellite and the UE continuously changes, resulting in dynamic propagation delay variations throughout the satellite pass.

Doppler Shift and Doppler Rate

The high relative velocity between LEO satellites and ground terminals generates significant Doppler frequency shifts that continuously evolve during the satellite pass. Depending on the carrier frequency and orbital geometry, these frequency offsets can become substantial and may directly impact carrier synchronization and waveform stability.

In addition to the Doppler shift itself, NTN systems also experience rapidly changing Doppler rates, requiring accurate emulation of time-varying frequency behavior.

Dynamic Path Loss

As the satellite position changes over time, the RF path loss between the satellite and the UE also varies continuously. These variations are influenced by orbital geometry, satellite elevation angle, atmospheric absorption, and environmental conditions.

Dynamic attenuation profiles are essential for evaluating receiver sensitivity, adaptive coding and modulation behavior, and overall link robustness under realistic operating conditions.

Multipath and Fading

Although many NTN links are dominated by line-of-sight propagation, multipath and fading effects may still occur in mobile, urban, maritime, or aeronautical environments. Reflections from surrounding objects may introduce additional signal paths and fading conditions that impact overall link quality.

Depending on the application scenario, NTN validation may therefore require realistic emulation of Rayleigh, Rician, or custom multipath fading profiles.

Dynamic Multi-Channel Scenarios

Modern NTN systems may involve multiple simultaneous RF links, beams, or satellite paths operating under independent dynamic conditions. Accurate validation therefore requires synchronized multi-channel emulation capable of reproducing independent delay, Doppler, attenuation, and fading profiles across multiple RF channels simultaneously.

These dynamic RF impairments are essential for realistic laboratory validation of NTN modems, user equipment, gateways, and satellite communication infrastructure.

Table 1 highlights the RF impairments typically encountered in 5G NTN systems and their impact on performance.

Impairment	Typical NTN Impact
Propagation Delay	Increased RTT and synchronization challenges
Doppler Shift	Carrier frequency offset
Doppler Rate	Rapid tracking variations
Dynamic Path Loss	Signal level fluctuations
Multipath/Fading	Link degradation

Table 1. Summary of key RF channel impairments in 5G NTN systems.

ACE9600 Architecture for NTN Emulation

Accurate NTN validation requires realistic reproduction of multiple RF impairments under controlled laboratory conditions. The ACE9600 Advanced Channel Emulator supports both traditional static RF testing and advanced dynamic channel emulation for satellite communication applications.

For conventional RF validation, the ACE9600 can apply static propagation delay, Doppler offset, attenuation, and fading conditions. In addition, the system supports continuously evolving channel behavior representative of real satellite movement and orbital dynamics through dynamic time-varying impairment profiles.

The ACE9600 is capable of applying:

> Static or dynamic propagation delay

> Static or dynamic Doppler shift and Doppler rate

> Static or time-varying attenuation profiles

> Multipath and fading emulation

> Multi-channel synchronized operation

> Independent impairments per RF channel

> Wide instantaneous bandwidth operation

Dynamic NTN scenarios may be generated using SATGEN II, a proprietary satellite orbit modeling software from Maury specifically designed for the ACE platform. SATGEN II generates time-varying channel parameter files formatted for the ACE9600 Advanced Channel Emulator, including Doppler shift, propagation delay, and path loss profiles derived from realistic orbital trajectories.

The software supports multiple entity types including fixed ground stations, moving land vehicles, ships, aircraft, and configurable satellite orbits. SATGEN II can generate dynamic scenarios for up to eight entities per channel and up to four synchronized RF channels simultaneously, enabling realistic multi-link NTN emulation.

In addition to SATGEN II, the ACE platform also supports integration with Ansys Systems Tool Kit (STK) through the ACE STK plug-in interface. The plug-in provides real-time synchronization between STK-generated orbital dynamics and the ACE hardware, allowing dynamic channel parameters generated by STK to be applied directly to the emulator in real time.

When operating in dynamic mode, the ACE and STK environments remain synchronized while orbital movement and time-varying RF impairments are graphically displayed through the STK interface. This enables highly realistic and repeatable NTN scenario generation using advanced orbital simulation environments.

The ACE9600 architecture supports up to four simplex RF channels per chassis and can be synchronized across multiple chassis for larger multi-channel NTN emulation scenarios. Each channel may operate with independent impairment profiles, enabling realistic emulation of multi-beam, multi-link, or multi-satellite environments.

By combining traditional RF impairment testing with advanced dynamic satellite channel emulation, the ACE9600 enables realistic NTN validation aligned with evolving 5G NTN requirements introduced in 3GPP Release 17, Release 18, and Release 19 (Figure 4).

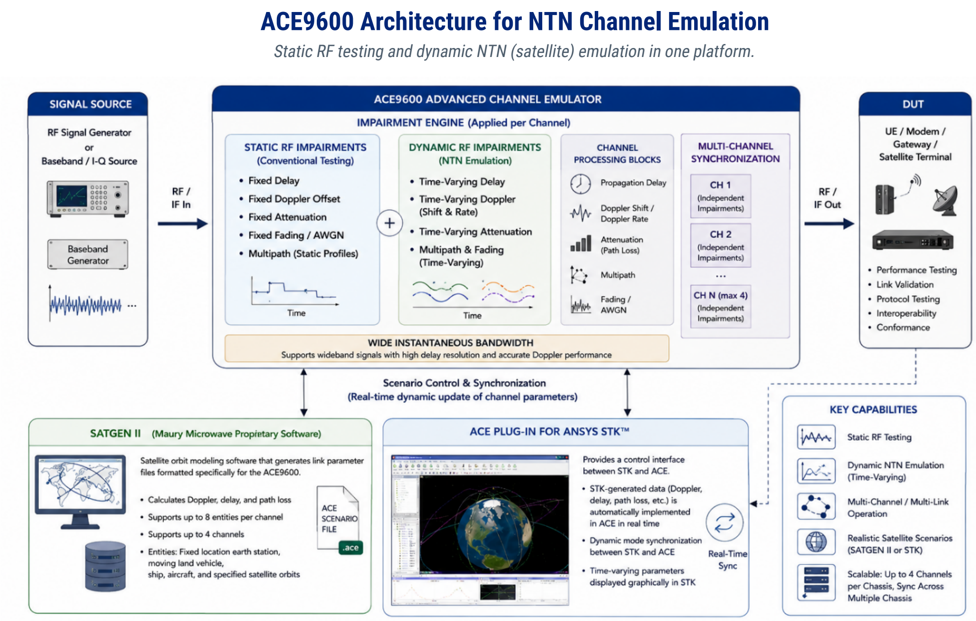

Figure 4. ACE9600 architecture for static RF impairment testing and dynamic NTN channel emulation using scenario generation with SATGEN II or STK.

Example NTN Validation Scenarios

The ACE9600 enables repeatable laboratory validation of realistic NTN operating conditions by reproducing dynamic RF impairments associated with satellite movement and orbital geometry. By combining multi-channel operation with dynamic scenario replay, the platform can emulate a wide range of NTN RF environments under controlled laboratory conditions.

Doppler and Delay Stress Testing

One of the primary applications of NTN channel emulation is the validation of modem and receiver performance under dynamic Doppler and propagation delay conditions. Using SATGEN II or Ansys STK-generated orbital scenarios, the ACE9600 can reproduce continuously varying Doppler shift, Doppler rate, and propagation delay profiles representative of real satellite passes.

These scenarios allow engineers to evaluate:

> Carrier synchronization robustness

> Frequency tracking performance

> Waveform stability

> Timing behavior under dynamic conditions

> Receiver performance during rapid Doppler transitions

Beam Transition and Dynamic Attenuation Validation

As LEO satellites move relative to the Earth, user terminals may experience continuous transitions between satellite beams or coverage regions. The ACE9600 can emulate the RF channel conditions associated with these transitions through time-varying attenuation, delay, and Doppler profiles.

This enables realistic validation of:

> Link continuity during beam transitions

> Signal degradation at beam edges

> Dynamic attenuation behavior

> Synchronization stability during channel transitions

Multi-Channel NTN Emulation

Modern NTN systems may involve multiple simultaneous RF links operating under independent dynamic conditions. The ACE9600 supports multi-channel operation with independent impairment profiles applied per RF channel.

This capability enables emulation of:

> Multi-beam satellite scenarios

> Independent uplink and downlink conditions

> Multi-link NTN environments

> Simultaneous satellite paths with different orbital dynamics

By applying independent dynamic impairments across multiple RF channels, the ACE9600 enables realistic reproduction of complex NTN RF environments.

Multipath and Fading Scenarios

Although many NTN deployments are dominated by line-of-sight propagation, mobile and urban environments may still introduce multipath and fading effects. The ACE9600 supports multipath and fading emulation for NTN validation scenarios including urban mobility, maritime communications, and aeronautical applications.

These scenarios enable evaluation of:

> Receiver robustness under fading conditions
> Link stability in mobile environments
> Performance under dynamic multipath conditions
> Signal quality degradation caused by reflections and scattering

By reproducing realistic dynamic RF conditions under controlled laboratory environments, the ACE9600 enables repeatable validation of NTN modems, UE, gateways, and satellite communication infrastructure prior to deployment (Figure 5).

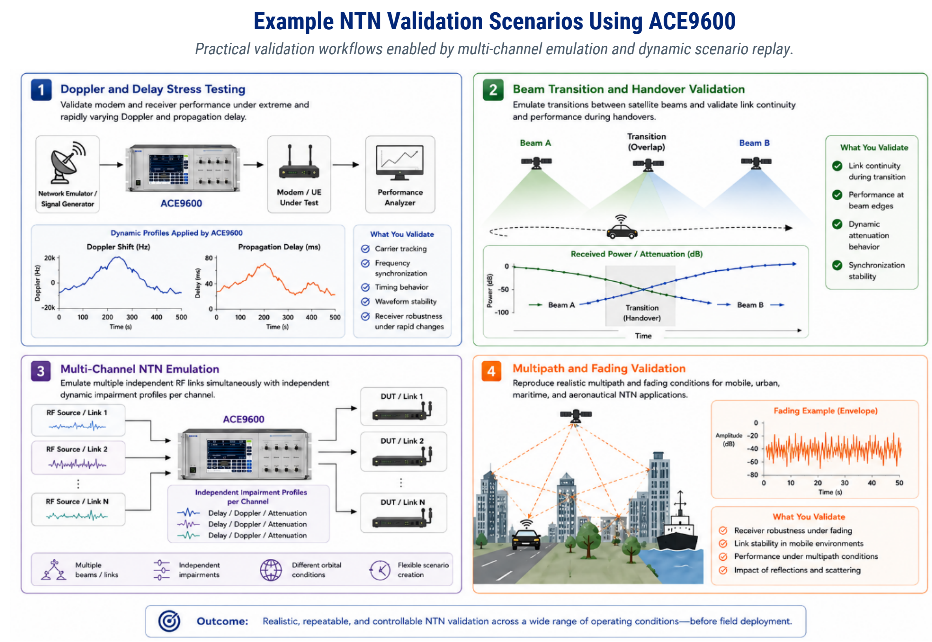

Figure 5. Example NTN validation scenarios with the ACE9600, including Doppler and delay stress testing, beam transition and handover validation, multi-channel NTN emulation, and multipath and fading analysis.

Conclusion

5G NTN introduce highly dynamic RF channel conditions that cannot be accurately reproduced using traditional static RF validation methods. Large propagation delays, time-varying Doppler shifts, dynamic attenuation, multipath fading, and multi-channel satellite scenarios require realistic and repeatable laboratory emulation environments.

The ACE9600 Advanced Channel Emulator enables accurate reproduction of these dynamic RF impairments through independent multi-channel operation and time-varying channel emulation capabilities. Each RF channel can operate with independent propagation delay, Doppler, attenuation, and fading profiles, enabling realistic emulation of multi-beam, multi-link, and multi-satellite environments.

The ACE9600 platform also provides significant flexibility for emulating a wide range of satellite constellations and orbital configurations without requiring dedicated hardware changes or constellation-specific licenses. Different propagation environments corresponding to LEO, Medium Earth Orbit (MEO), GEO, multi-orbit, or custom satellite scenarios may be reproduced through configurable dynamic channel profiles and scenario generation tools, allowing engineers to adapt the emulator to evolving NTN architectures and test requirements.

In addition, the ACE9600 is signal agnostic and may be used with virtually any RF waveform or communication standard operating within the supported frequency range and bandwidth configuration. Although this application note focuses on 5G NTN validation, the platform may also be applied to SATCOM, defense communications, aerospace systems, navigation signals, custom modem development, and other advanced RF communication applications.

By enabling controlled and repeatable emulation of realistic satellite RF environments, the ACE9600 helps accelerate development, improve interoperability, reduce field testing complexity, and validate satellite communication infrastructure prior to deployment.

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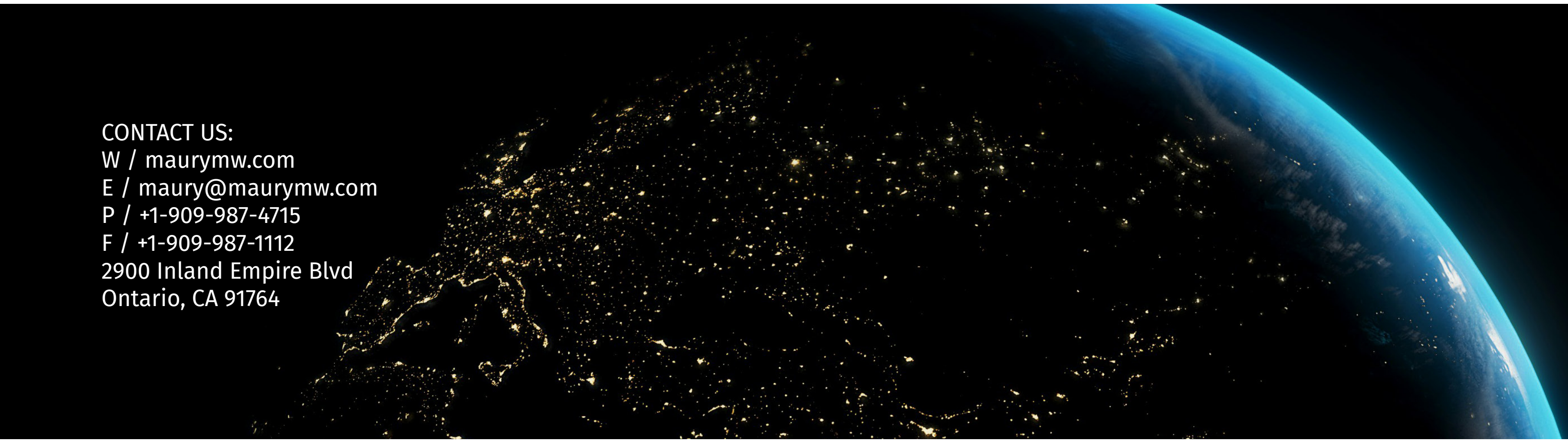

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