How Are 5G Non-Terrestrial Networks Driving Satellite Link Impairment and Hardware-In-The-Loop Emulation?

2024 is seeing a continuation of the explosive expansion in the development and interest in 5G non-terrestrial network (NTN) deployment (Figure 1). The term NTN does not just refer to satellite communications but also refers to any non-terrestrial network deployments using a variety of platforms such as high-altitude platform systems (HAPS), balloons, aircraft/drones, etc. If the NTN is satellite based, it involves low-Earth orbit (LEO), medium-Earth orbit (MEO), and geostationary orbit (GEO) satellites with 5G communications platforms.

Today, devices are typically separated into those that are connected to the 3GPP terrestrial network and those connected to satellites. In other words, users need one device to connect to a terrestrial network and another device to connect to a satellite (or other non-terrestrial network). With NTN, all mobile devices will eventually be connected to both terrestrial and satellite networks as part of the 3GPP ecosystem. As the technology evolves the satellite platforms will host the 5G base stations. NTN will also provide backhaul connectivity for remote sites (high bandwidth applications).

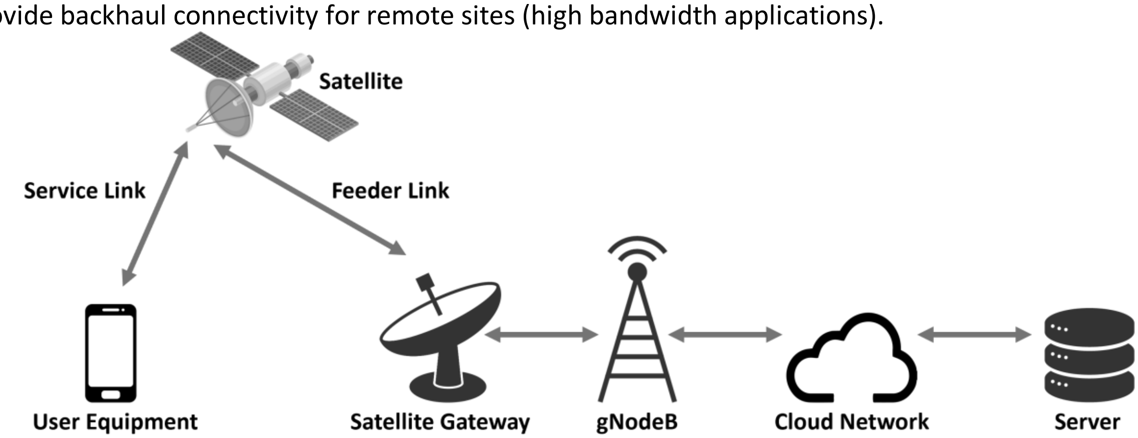

Figure 1: The architecture of a 5G NTN.

The NTN can further be divided into two sub-categories – NTN-IoT (Internet of Things) and NTN-NR (new radio). Currently, NTN-IoT has dramatically expanded the reach of IoT use cases, enabling true global coverage over land, air, and sea. It operates at both the GEO and LEO altitudes, but the vast majority of current services operate at GEO where large footprint coverage is required and latency is not a major concern. NTN-NR is becoming increasing relevant. It will directly link smartphones and other 5G devices to non-terrestrial services. Due to the major issues with latency and signal power levels, these platforms will operate at the LEO or HAPS altitude and enable low data rate services, voice and messaging, and seamless access regardless of geographical location or terrain.

5G NTN-IoT Use Cases:

We can summarize NTN-IoT use cases as:

- **Asset tracking:** Location of shipping containers, vehicles, and other valuable assets over a wide geographic footprint.

- **Agriculture/farming:** Precision farming (guidance of farm machines) and livestock monitoring.
- **Automotive:** Communications with low date rate access control and monitoring, and emergency call capabilities.
- **Disaster response:** Search and rescue, damage assessment, and provide connectivity to areas with limited or no communications due to damaged infrastructure.
- **Maritime:** Vessel tracking or environmental monitoring in open ocean or areas with very limited connectivity.
- **SOS and two-way communications:** Smartphone, wearables, and cars to allow SOS and two-way communications with no terrestrial access.

5G NTN-NR Use Cases:

As NTN continues to evolve, NTN-NR will dramatically increase in importance and will provide ubiquitous continuity of 5G basic services. Seamless access to services such as mobile data, voice calls, and messaging regardless of the user's location or surrounding terrain. This growth will not only benefit individual users but also industries and businesses that rely heavily on uninterrupted connectivity currently not possible with existing terrestrial LTE/5G.

- **5G backhaul:** NTN will serve as effective backhaul solutions for terrestrial 5G networks, greatly extending network reach, improved capacity, and reliable connectivity in difficult-to-reach/remote environments.
- **Automotive connectivity:** Provide service anywhere/anytime for fleet monitoring, software updates, diagnostics, and telephony, as well as support connected and intelligent vehicles enabled by the low latency of LEO platforms.

The 3GPP Standard for NTN

3GPP has been working diligently to develop the NTN standard to permit wireless connectivity above the Earth's surface (Figure 2, Table 1). The standard addresses various scenarios, frequency bands, services, and orbits. Satellite networks operating in the Frequency Range 1 (FR1) offer direct connectivity to outdoor handheld devices and automotive or drone-mounted devices via the 5G NR standard. Satellite access networks operating in the Frequency Range 2 (FR2) and Frequency Range 3 (FR3) will provide broadband connectivity using very small aperture terminals (VSATs) installed on rooftops or Earth station in motion (ESIM) terminals on moving platforms such as trains and vessels.

Below is a summary of 3GPP NTN releases.

Release-16 featured a study of Radio Access Network (RAN) by working groups, which focused on NR solutions for non-terrestrial networks to support LEO and GEO satellites using 5G. The following premises provide a framework for standards:

- 5G-NR frequency division duplex (FDD).
- Earth-fixed tracking with the assumption the Earth is fixed and moving cells.
- User equipment (UE) with Global Navigation Satellite Systems (GNSS).

- Transparent payload is assumed.

Release-17 enabled NTN in 5G and the normative work, and can be summarized as follows:

- Mobility management with large coverage area and with moving coverage.
- Delay in satellite (due to the orbit altitudes of different types or orbits).
- QoS with satellite access and satellite backhaul.
- RAN mobility and non-geostationary regenerative based satellite access.
- Regulatory requirements for super national satellite ground stations.

Release-18 addresses NTN-IoT enhancement and NTN-NR frequencies:

- Support for half-duplex operation in FDD bands to conserve power and simply device design.
- Network verification of UE location to meet regulatory standards.
- Measurement protocols to support increased mobility.
- Expanding the RF frequency bands above 10 GHz to Ka band.

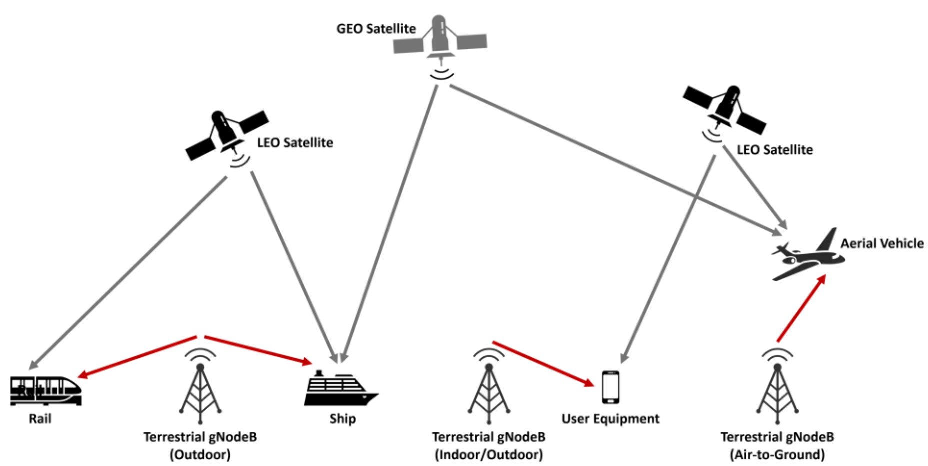

Figure 2: Connectivity between terrestrial networks and non-terrestrial networks.

Connected Device/System	Characteristics	Terrestrial Network Connectivity	Non-Terrestrial Network Connectivity
Aerial Vehicle	High-Speed	Limited and Primary	Wide and Secondary from LEO/GEO
Ship	Low-Speed, Remote Location/Open Ocean	Limited and Secondary	Good and Primary from LEO/GEO
Rail	Medium to High-Speed, Rural/Suburban Area	Good and Primary	Wide and Secondary from LEO
User Equipment	Low Speed, Rural/ Remote Area	Good and Primary	Wide and Secondary from LEO

Table 1: A breakdown of how different devices/systems connect to terrestrial and non-terrestrial networks.

Lunar NTN Communications

Not only does NTN address Earth-based non-terrestrial communications but a sub-section involves communications on the Moon. NASA with its Artemis program wants to establish a human presence on the lunar surface and provide connectivity for exploring and operating in all geographic areas, including the poles and the far side of the Moon. A constellation of satellites in lunar orbit will provide position, navigation, and timing (PNT) as well as serve as relay satellites, enabling communications from anywhere on the Moon back to Earth. The lunar Internet of Things will be a communication of networks and services with multiple provider systems from international and commercial entities. 3GPP NTN will provide the ideal solution for lunar communications and lunar surface wireless networks. Work is already underway for space-qualified 3GPP infrastructure (gNodeB base stations and UE).

5G NTN Partnerships and Broadband/Narrowband Networks

There are many commercial players involved with NTN. This market is estimated to grow dramatically over the next few decades. According to the Boston Consulting Group, it is predicted that the market size will grow to over $40 billion by 2030.

In summary we will characterize the partnerships and networks into three broad categories:

- **Broadband data networks**: These require dedicated terminals for ground station connection (Table 2).
- **IoT-NTN data networks**: This also involves emergency (SOS) connections to 5G UE or handsets (Table 3).
- **Emerging non-terrestrial cellular networks**: Typically works with commercial UE with no significant changes to their designs (Table 4).

Operator	Satellite System (Deployed)	Spectrum	Technology	Services	Operational
Starlink (SpaceX)	12,000 (6,078)	Ku-band	Proprietary	Broadband	yes
Kuiper	3,236 (2)	Ka-band	Proprietary	Broadband	TBD
Boeing	147 (1)	V-band	Proprietary	TBD	TBD
Echostar	10 GEO (10)	Ku, Ka, S-bands	Proprietary	Broadband	yes
GalaxySpace	1,000 (8)	Q, V spectrum	Proprietary	Broadband	TBD
Hughesnet	3 GEO (2)	Ka-band	Proprietary	Broadband	yes
Inmarsat	14 GEO (14)	TBD	Proprietary	Broadband to IoT	TBD
OneWeb	648 (648)	Ku-band	Proprietary	Broadband	TBD
Telesat	198 (2)	C, Ku, Ka-band	Proprietary	Broadband	TBD
Viasat	4 GEO (4)	Ka band	Proprietary	Broadband	yes

Table 2: NTN broadband data networks.

Operator	Satellite System (Deployed)	Spectrum	Technology	Services	Operational
AST SpaceMobile	243 LEO (2)	MNO spectrum	Pre-Rel 17 3GPP	messaging/voice/boardband	2024
Globalstar	48 LEO	L/S-band	Proprietary	Asset tracking	yes
Iridium	66 LEO	L-band	Proprietary	LDR/messaging	yes
Ligado	1 GEO	L-band	Rel 17 NB-IoT	Asset tracking	TBD
Lynk	5,000 LEO (3)	MNO spectrum	Pre-Rel 17 3GPP	low date rate messaging	yes
OrbComm	24 LEO	137-150 MHz	Proprietary	Asset tracking	yes
Sateliot	250 LEO (5)	2GHz MSS	Rel-17 NB-IoT	NB-IoT	TBD
SpaceX	2,016 LEO (0)	MNA spectrum 2GHz MSS	Pre-Rel 17 3GPP	messaging/voice/boardband	2024

Table 3: IoT-NTN data networks.

Partnership	Satellite System (Deployed)	Spectrum	Technology	Services	Operational
Apple/Globalstar	48 LEO	L,S-band	Proprietary	SOS messaging	yes
AT&T/AST	243 LEO (2)	MNO spectrum	Rel 12 3GPP	messaging/voice/video	yes
MediaTek/Skylo/Bullitt	6 GEO (Inmarsat)	L-band	3GPP-NTN	messaging	yes
Qualcomm/Iridium	66 LEO	L-band	Proprietary	messaging	yes
Skylo/Ligado/Viasat	1 LEO (Ligado)	L-band	3GPP-NTN	NB-IoT, Messaging, LDR	yes
T-Mobile/SpaceX	2,016 LEO (0)	MNO spectrum	Rel 12 3GPP	messaging/voice/video/Data	TBD
Verizon/AST	243 LEO (2)	MNO spectrum	Rel 12 3GPP	messaging/voice/video	yes
Verizon/Kuiper	3,236 (90)	Ka-band	Proprietary	Backhaul LTE & 5G	TBD

Table 4: Emerging non-terrestrial cellular networks.

Channel Emulators

A channel emulator is used to emulate the impairments that are typically added to an RF signal as it's being transmitted between a transmitter and receiver, when one or both antennas are moving relative to each other. In NTN applications, at least one of the antennas is on a satellite or other high-altitude platform and the other may be part of a UE. With terrestrial-based networks, a multipath fading emulator is typically used to emulate the RF link. However, existing terrestrial multipath fading emulators are not suitable/capable of testing NTNs before deployment, and unlike ground-based (terrestrial) infrastructure, failure is not an option. Servicing/repairing the NTN asset is not possible/practical or is cost prohibitive requiring extensive testing/modeling before deployment to identify any potential failure. Therefore, there has been a big push to repurpose or enhance existing satellite link (channel) emulators to address this new testing requirement. Non-terrestrial infrastructure testing typically requires much larger times delays (MEO/GEO orbits), Doppler shifts (MEO/LEO orbit speeds), atmospheric scintillation modeling, and greater path delays when implementing multipath modeling. Typically for a satellite link communicating with a mobile UE, the number of reflective paths are less (typically between 3 and 12), especially when compared to terrestrial massive MIMO implementation, but the individual path delays and relative Dopplers can be higher.

Required Time Delays

The typical round trip delays (excluding onboard payload processing delay) for satellite orbits are shown in Table 5.

Satellite	Altitude	Round Trip Time Delay	Antenna Speed	Typical Beam Footprint Size
LEO	500 - 1200 km	3 - 8 ms	10 minute fast tracking	100 - 1,000 km
MEO	5000 - 20,000 km	33 - 133 ms	1 hour slow tracking	100 - 1,000 Km
GEO	35,786 km	239 ms	stationary	200 - 3,500 km

Table 5: LEO, MEO, and GEO round trip time delays.

In additional to the above orbits, trans-lunar orbit is typically 2.4 to 2.7 seconds round trip; however, the bandwidth requirements are typically lower than Earth satellite orbits.

With all satellite orbits except GEO, the signal path time delay between the satellite and a point on the surface of the Earth will vary with elapsed time and the emulator must vary the delay matching a specific orbit in a phase continuous manner. The changing time delay cannot be implemented by dropping/adding signal samples but must use a resampling technique to ensure fully phase continuous time delay with frequency dependent signal Doppler (Figure 3).

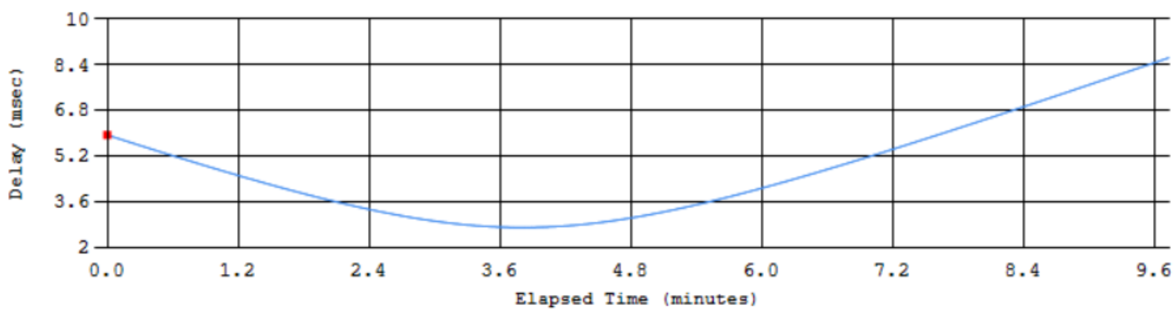

Figure 3: Example of the varying delay over time for a LEO (Starlink satellite) communicating with a UE.

Doppler Shift

Due to the speed of a satellite orbit, especially for LEO orbits, significant Doppler shifts will be imposed on the received signal. Since most channel link emulators operate at baseband or IF, this Doppler can be broken down into its two constituent components – (a) signal Doppler and (b) carrier Doppler. Because of the relative motion between the transmitting and receiving antennas, the signal Doppler will be frequency dependent and will result in expansion/compression of the passband with associated chip rate variations to the signal. This can only be implemented by changing the delay with resampling of the passband signal. In addition to the signal Doppler, a frequency offset to emulate the carrier Doppler has to be added by shifting the complete signal passband. This shift can be in the order of 100's kHz to 1-3 MHz range, especially as some NTN operate at higher (Ka band) frequencies.

Signal Bandwidths

While the 3GPP standard uses carrier aggregation to increase the bandwidth of the NTN links, especially for backhaul applications, most test applications do require the capability for emulators to process large contiguous signal bandwidths. While UE may only use 5 MHz bandwidth, backhaul and high-capacity satellite transponders can use bandwidths in excess of 500 MHz.

Signal Path Losses and Atmospheric Scintillation

The signal power loss between a satellite and a receiver in an NTN can be very high (90 to 120 dB). Emulators are typically used to only add the variation in signal path loss due to orbit movement and the overall signal is typically “padded” down externally to the emulator to bring the signal power to levels expected by the receiver. Since the signal communicating with a satellite can travel significant distances through the atmosphere with associated rain cloud and other signal scattering, atmospheric scintillation with phase shift and signal amplitude variation over time becomes necessary to accurately model the link. In addition, additive white Gaussian noise (AWGN) is often used to simulate receiver thermal noise, background radiation from space, and other impairments that can impact the link budget and received signal errors.

Hardware-in-the-Loop (HITL) Impairments

While channel (or link) emulators are used to emulate the link impairments between a satellite and a UE, the industry is moving towards not only emulating the link but also the impairments that the hardware in the communications link may inadvertently add to the signal. As mentioned earlier, NTN assets (especially spaceborne) cannot afford to fail and therefore every possible hardware degradation influence that is practical to test for may want to be emulated to see the impact on signal data rates/performance. Also, due to different country regulatory requirements, certain portions of the frequency spectrum may be off limits and therefore that portion of the signal spectrum might need to be “notched out.” Typical HITL impairments are:

- Passband IMUX/OMUX shaping/slope/notching
- Amplifier compression/distortion (AM/AM & AM/PM)
- Programmable phase noise of LOs, etc.

ACE9600 Advanced Channel Emulator (ACE)

The Maury Microwave Advanced Channel Emulator model ACE9600 of the dBm product line (Figure 4) is one of the most advanced channel emulators on the market today. The emulator is signal agnostic, simplifying test set up. The ACE9600 can accommodate up to four independent channels per chassis with up to four chassis fully synchronized for a total of sixteen synchronized channels. The ACE9600 can be configured with:

- Bandwidths of 72, 125, 300, or 600 MHz per channel (no need for carrier aggregation)
- Programmable delay, attenuation, phase shift and signal/carrier Doppler
- Optional internal RF converters
- Optional AWGN
- Optional multipath (12 paths per channel, Rayleigh, Rician, CW, etc.)

* Optional hardware-in-the-loop impairments, IMOX/OMUX, amplifier compression (AM/AM & AM/PM), and programmable phase noise

Figure 4: Maury Microwave Advanced Channel Emulator model ACE9600 of the dBm product line.

Figure 5 depicts the type of impairments that typically occur with an NTN satellite link and can be easily implemented using the ACE9600.

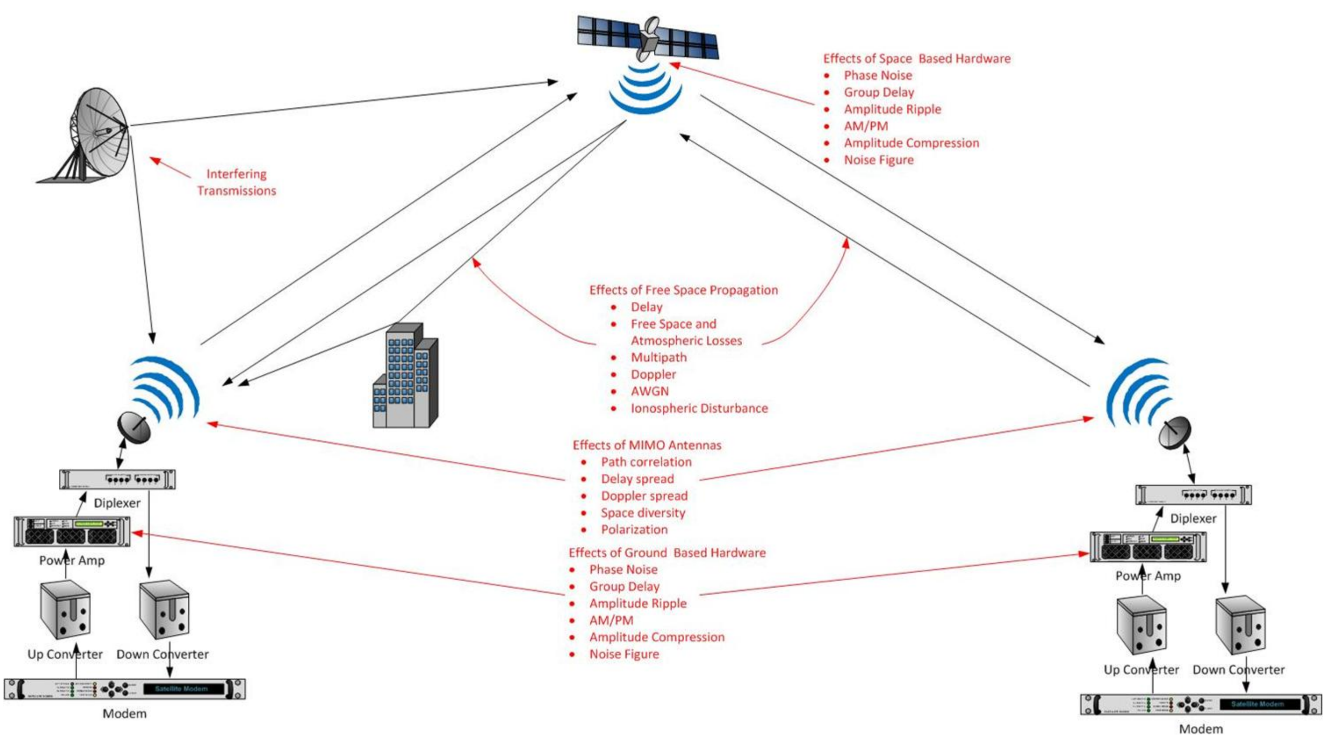

Figure 5: RF link and hardware-generated impairments available with the ACE9600.

Sophisticated modeling and control software is provided with the channel emulator as an optional accessory to permit realistic scenarios to be easily created using ephemeris models. The SATGEN-RTE (real-time emulation) software allows users to generate test setups in which satellite orbit profiles, ground station locations, uplink and downlink frequencies, and atmospheric modeling/losses are easily defined by the user. The software will automatically generate the impairment parameters and upload them to the emulator for test development execution. In addition to SATGEN-RTE, the link emulator product line supports the Satellite Tool Kit (STK©) package from Ansys/Analytical Graphics.

The graphical user interface provided with the ACE9600 permits hardware-in-the-loop impairments to be easily specified/generated. Figure 6 is an example using one of the payload suite wizards to define a "notch" in the passband response, generate the necessary FIR coefficients, and upload to the ACE9600. This is typically used to "notch" out part of the spectrum that may be denied to the communications system based on the regulatory spectrum requirements of national authorities.

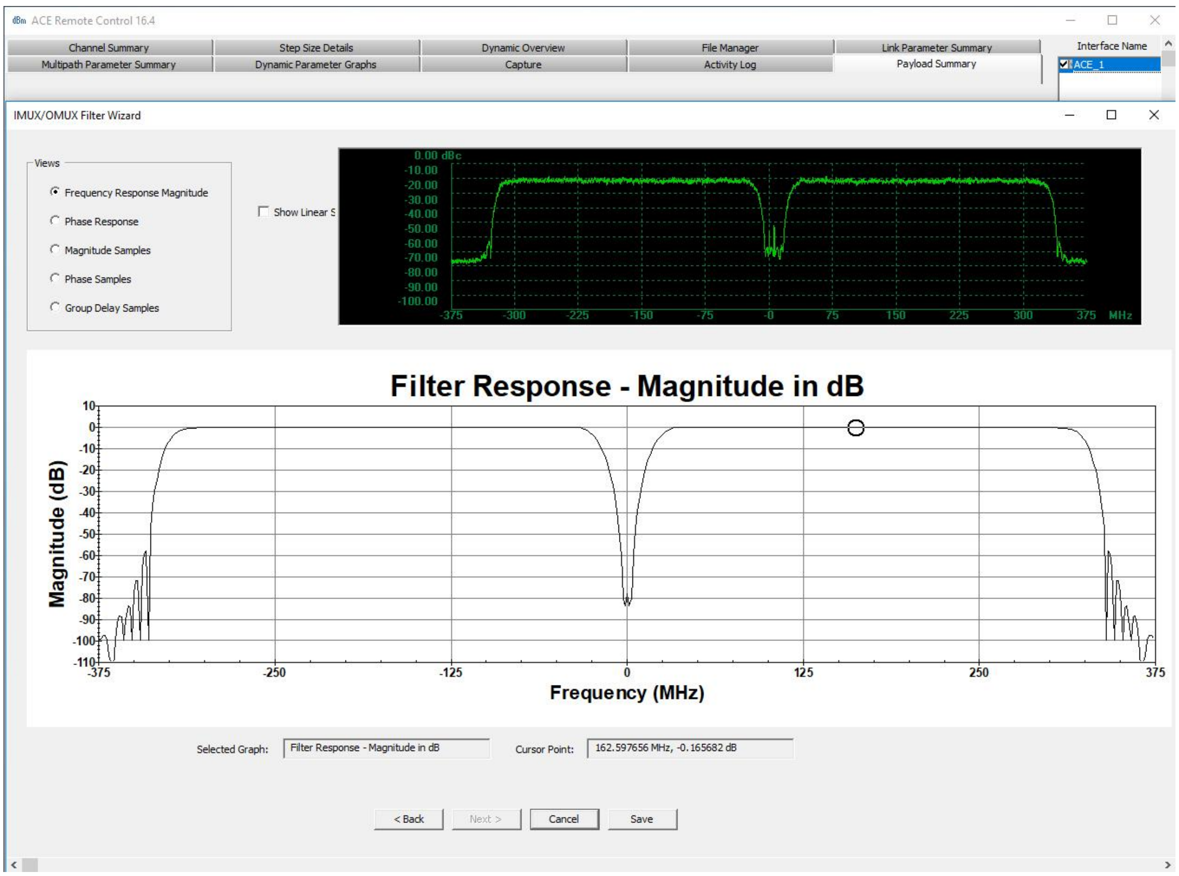

Figure 6: ACE9600 graphical user interface during hardware-in-the-loop testing for satellite payloads.

Enabling 5G NTN Advancements with Channel Emulators

As 5G NTN continue to advance, develop, and expand into emerging applications, thorough testing ensures the highest performance possible and compliance with regulatory requirements. Channel emulators, such as the ACE9600, play a critical role in 5G NTN testing through emulating link and HITL impairments. With the ACE9600, 5G NTN designers can properly evaluate electromagnetic and environmental effects and hardware-generated impairments on the signal path, enabling insight into real-world operational performance before deployment.

9 Entin Road, Suite 101, Parsippany, NJ 07054, USA
+1 973 386 9696 +1 973 386 9191 maury@maurymw.com www.maurymw.com