

Realistic Simulation of 5G/6G NTN RF Systems and Transmission Channels

Introduction

Commercial 5G deployments began in 2018, with steady expansion of terrestrial networks across urban and suburban regions. Despite this progress, large geographic areas — particularly rural, remote, maritime, and airborne environments — remain underserved by terrestrial infrastructure. This persistent coverage gap has accelerated interest in extending 5G through Non-Terrestrial Networks (NTN), positioning NTN as a critical enabler of truly global connectivity. NTN is especially well suited for enhanced mobile broadband, massive IoT, and direct-to-device services beyond the reach of traditional cellular networks.

NTN has evolved into an umbrella term encompassing multiple network types that rely on non-terrestrial platforms. These include satellite communication networks, High-Altitude Platform Systems (HAPS), and air-to-ground networks. Satellite-based NTNs span Low-Earth Orbit (LEO), Medium-Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) systems. In recent years, global momentum has strongly shifted toward LEO constellations, driven by their ability to deliver lower latency, higher capacity, and broadband-class user experiences at scale.

The satellite ecosystem has played an active role in 3GPP standardization, culminating in the formal integration of NTN into the 5G framework starting with Release 17 and continuing through Release 18. These releases define key aspects of NTN operation, including physical-layer adaptations, protocols, system architecture, radio resource management, RF requirements, and supported frequency bands. Standardized deployment scenarios now cover satellite-based systems as well as high-altitude platforms such as balloons, airships, and uncrewed aerial vehicles operating in the stratosphere. Early commercial implementations have primarily focused on satellite NTNs with transparent payloads, however, regenerative payloads with on-board baseband processing capabilities have started to emerge as part of 3GPP Release 19.

Achieving robust NTN performance requires early validation of gateway infrastructure, airborne platforms, and user equipment—including handheld devices and very small aperture terminals—through system-level simulation. This is particularly critical for phased-array antennas and broadband power amplifiers employing digital predistortion (DPD), where nonlinearities, memory effects, antenna coupling and beamforming accuracy, and Doppler effects must be jointly analyzed. These challenges intensify as the industry transitions toward 6G, with higher carrier frequencies, ultra-wide bandwidths, larger antenna arrays, and tighter energy-efficiency constraints. As a result, NTNs are widely viewed as one of the key use cases shaping 6G system design.

High-fidelity virtual analysis has therefore become indispensable. Engineers must adopt shift-left design methodologies to accelerate development and reduce risk, using simulation-driven digital twins to evaluate performance across RF, baseband, antenna, and network domains. The ability to model realistic impairments, dynamic channels, and end-to-end KPIs at scale is now a prerequisite for delivering reliable NTN solutions. In an increasingly competitive landscape, success hinges on leveraging advanced simulation to explore complex 5G and pre-6G NTN scenarios and unlock the full potential of global, space-enabled wireless connectivity.

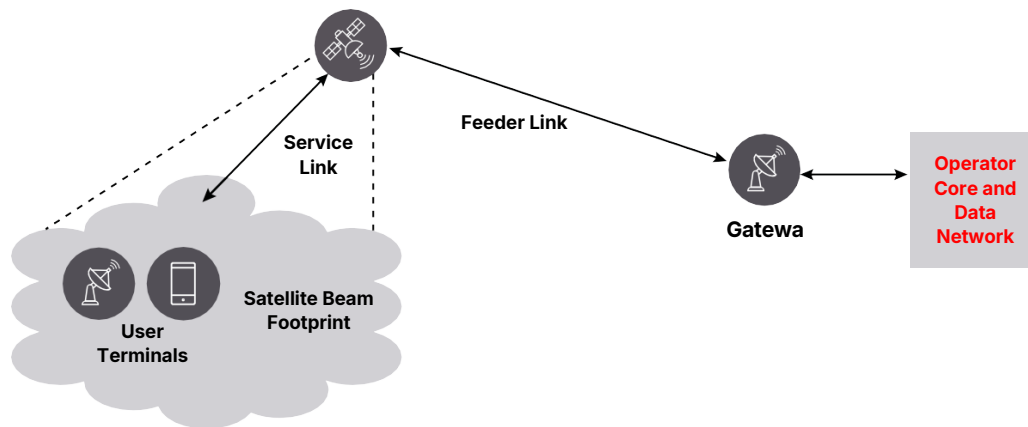


Figure 1. NTN scenario with a transparent payload source

This solution brief explores the key RF link design and channel modeling challenges associated with 5G/6G NTN and demonstrates how to simulate an end-to-end link between the gateway, satellite, and user equipment in a transparent or regenerative payload architecture. Using Keysight SystemVue, the workflow enables high-fidelity analysis of propagation effects, RF impairments, and link performance to support early-stage validation and optimization of NTN designs.

System-Level Modeling

System-level modeling and simulation are foundational to the successful design of non-terrestrial networks because the dominant challenges span multiple tightly coupled domains that cannot be analyzed in isolation. NTN links are simultaneously impacted by dynamic propagation environment, large delays and Doppler, large phased-arrays, power amplifier nonlinearity, spectrum coexistence, and constellation-level mobility. Decisions made at the RF or antenna level directly influence baseband performance, network capacity, and end-to-end KPIs such as throughput, latency, reliability, and availability. Without system-level simulation, these cross-domain interactions remain hidden until late integration stages, significantly increasing cost and risk. Early, end-to-end modeling enables engineers to validate link budgets, stress-test waveforms under realistic impairments, evaluate beam management strategies, and quantify performance margins across time-varying orbital scenarios before hardware is committed.

Digital twins extend system-level simulation by creating high-fidelity, executable representations of NTN architecture that evolve throughout the design lifecycle. By combining accurate RF impairments, antenna characteristics, satellite dynamics, and network behavior into a single virtual environment, digital twins enable shift-left design, rapid design-space exploration, and predictive performance analysis. This approach is particularly critical as NTN moves toward 5G-Advanced and 6G, where higher frequencies, wider bandwidths, and massive phased arrays leave little tolerance for error. Digital twins allow engineers to assess the impact of design tradeoffs, optimize DPD-enabled power amplifiers and beamforming algorithms, and validate compliance with 3GPP NTN requirements under realistic operating conditions. As NTN systems scale in complexity and ambition, digital twins are no longer optional — they are essential for delivering robust, globally scalable, and future-ready non-terrestrial networks.

RF Modeling Challenges in the End-to-End NTN Links

5G NTN deployments typically rely on aerial platforms, most commonly LEO satellites, to extend terrestrial radio access using transparent or regenerative payload architectures. In transparent, or “bent-pipe,” systems, the satellite functions as an RF relay between User Equipment (UE) and a ground-based gNodeB (gNB), forwarding signals between the access and feeder links without onboard baseband processing. Frequency translation and frequency division duplexing enable simultaneous uplink and downlink over wide coverage areas, while terrestrial gateways connect the feeder link to the 5G core and public data networks (see Figure 3).

Regenerative payload architectures go a step further by hosting some or all gNB functions onboard the satellite, enabling local baseband processing, reduced feeder-link dependency, and improved latency and resource efficiency. In both architectures, the UE uses Global Navigation Satellite Systems (GNSS) for timing and positioning and to compensate delay and Doppler. As NTN evolves toward 5G-Advanced and 6G, supporting both transparent and regenerative payloads increases system complexity, making system-level modeling and digital twins essential for accurately capturing RF impairments, beamforming behavior, orbital dynamics, and end-to-end network performance.

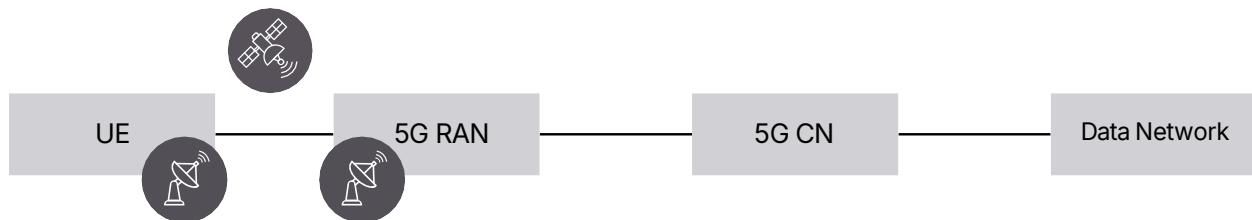


Figure 2. Overall architecture of a satellite access network

RF Link and Airborne Mobility

At the mission level, system designers must identify optimal NTN configurations that deliver robust performance across a wide range of operating conditions, including geographic coverage, atmospheric effects, satellite orbits and constellations, network architecture, and diverse UE use cases. These factors interact dynamically and vary over time, making static analysis insufficient. As a result, mission-level evaluation increasingly depends on system- and scenario-based modeling that can capture spatial, temporal, and environmental variability across the entire NTN lifecycle.

Digital twins play a central role in this process by providing a high-fidelity virtual representation of the NTN system that supports early validation and design-space exploration. Effective 5G/6G NTN digital twins must incorporate accurate RF models, including realistic phased-array antenna behavior, beamforming impairments, and broadband power amplifier nonlinearity with digital predistortion (DPD). By integrating these RF effects with channel dynamics, mobility, and network behavior, digital twins enable engineers to predict end-to-end performance, optimize system configurations, and reduce risk before deployment.

RF Link

In NTN scenarios, propagation is dominated by large free-space path loss due to the long satellite–UE separation, while multipath behavior differs fundamentally from terrestrial channels. Because the dominant propagation paths arrive from a very narrow angular spread and are nearly parallel, classical rich multipath fading is generally reduced; however, signal degradation is strongly influenced by clutter loss, shadow fading, and intermittent blockage from buildings, terrain, and other obstacles. Accurate NTN channel modeling therefore extends free-space path loss with additional loss components that capture environment-dependent attenuation and time-varying availability, which are critical for realistic performance evaluation, especially for handheld and urban deployment scenarios.

Latency

End-to-end latency in satellite communications is strongly dependent on orbital altitude. Geostationary Earth Orbit (GEO) systems exhibit the highest round-trip latencies, typically on the order of several hundred milliseconds, while Medium Earth Orbit (MEO) systems offer moderate latency in the low hundreds of milliseconds. Low Earth Orbit (LEO) constellations provide the lowest latency, often in the tens of milliseconds, making them the most suitable for 5G and 6G use cases that are sensitive to delay and jitter. Achieving these latency benefits in practice requires careful gateway placement, efficient feeder-link design, and optimized network architecture to minimize backhaul delays and support seamless mobility across fast-moving satellites.

Doppler Effect

LEO satellites travel at very high orbital velocities — on the order of several kilometers per second — which introduces significant Doppler shifts on both the service and feeder links between the satellite, gateway, and user equipment. This Doppler effect varies continuously with satellite motion, elevation angle, and beam geometry, and can be several orders of magnitude higher than in terrestrial systems. To ensure reliable 5G/6G NTN operation, engineers must accurately model, estimate, and compensate for Doppler during waveform design, synchronization, beam management, and handover, making Doppler-aware system-level simulation a critical requirement for robust NTN performance.

Accurate Power Amplifier Gain Model

Designing power-efficient amplifiers for NTN and advanced 5G/6G systems has become increasingly challenging as modulation schemes grow more complex, bandwidths widen, and capacity and regulatory requirements tighten, all while pressure mounts for lower power consumption, reduced footprint, and improved sustainability. High-efficiency amplifier architectures inherently exhibit nonlinear behavior, and when driven by high-PAPR, non-constant-envelope waveforms, they can significantly degrade signal quality and out of band emissions. As a result, advanced linearization techniques, most notably wideband digital predistortion that accounts for memory effects and dynamic operating conditions, are essential to achieving the required balance between efficiency, linearity, and compliance in modern satellite and NTN deployments.

Phased-Array Load Pull on the Power Amplifier

Modeling load-pull effects in phased-array transmitters becomes significantly more complex as beams are electronically steered across wide scan angles. As the array scans, the active impedance presented to each power amplifier varies dynamically due to mutual coupling, beamforming weights, and frequency-dependent effects, directly impacting gain, efficiency, and linearity. These challenges intensify in NTN scenarios, where arrays must continuously track fast-moving satellites and support multiple beams simultaneously. As channel counts scale toward massive arrays on the path to 6G, accurately capturing these time-varying load interactions at the system level becomes essential for predicting real-world performance and ensuring stable, efficient amplifier operation.

Modeling the RF Link with SystemVue

SystemVue provides a high-fidelity system-level prototyping and design environment for complex RF systems, combining fast simulation performance with measurement-grade RF accuracy. System designers can perform end-to-end RF link simulations that capture realistic impairments across the waveform, RF front end, phased array, and propagation channel. This approach enables early validation of 5G/6G NTN designs against 3GPP physical-layer requirements, including those defined in 3GPP TR 38.811, while supporting tradeoffs and optimization before hardware implementation. Figure 3 illustrates a representative SystemVue workflow that integrates link-level simulation, RF impairment modeling, and KPI evaluation within a unified simulation environment.

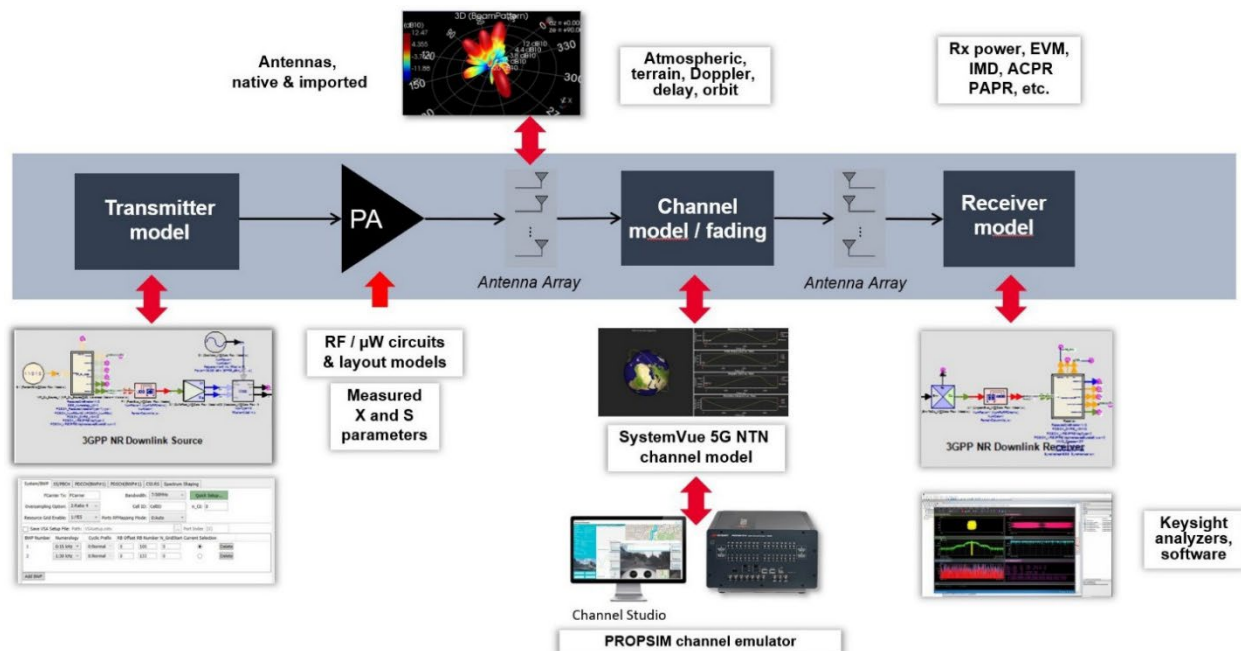


Figure 3. SystemVue digital twin of the entire RF link level scenario for 5G NTN modeling.

SystemVue offers a unique and comprehensive NTN test bench for these use cases. This test bench uses the Keysight **W4812B 5G and cellular bundle**, which contains the following elements:

- **W4522E** 5G and cellular library (reference transmitters and receivers for cellular standards).
- **W4804B** System Design complete system simulation environment (Spectrasys, data flow, and phased array).
- **W4519E** DPD Designer (DPD modeling and analysis for RF systems).

Modeling the Transmitter

SystemVue provides a flexible 5G NR and NB-IoT source configuration that can be adapted to a wide range of NTN deployment scenarios while maintaining standards-compliant operation. An advanced NR receiver architecture incorporates delay- and Doppler-aware compensation to accurately track fast-moving satellites and long propagation paths, ensuring reliable demodulation and performance assessment. By offering a comprehensive set of measurements spanning the transmitter and receiver chains, phased-array antennas, and airborne payloads, the system enables a holistic, system-level understanding of NTN behavior and performance across the end-to-end system.

Modeling the Power Amplifier Gain with DPD

Keysight W4540E DPD Explorer enables rapid assessment of how effectively a power amplifier can be linearized under complex, wideband modulated waveforms typical of 5G, NTN, and emerging 6G systems. By characterizing accurate nonlinear amplifier behavior — including frequency-dependent memory effects — early in the design phase, engineers can evaluate linearization potential before committing to hardware. The environment supports benchmarking

custom DPD algorithms against proven DPD Designer reference implementations, while delivering fast, high-fidelity evaluation of key performance metrics such as ACPR and EVM. This accelerated, model-based workflow shortens design cycles and provides confidence that amplifier designs can meet efficiency, performance, energy saving, and regulatory requirements (See Figure 4).

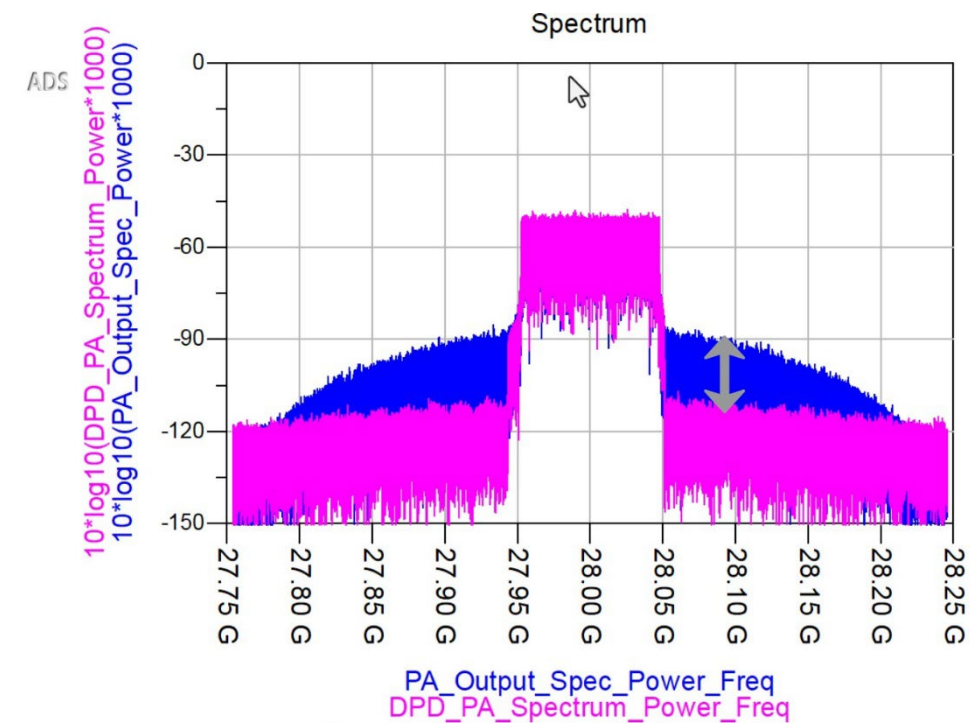


Figure 4. Characterize and optimize the power amplifier for linearity.

Modeling the Phased-Array Load Pull Effects on the Power Amplifier

The Keysight W4503E SystemVue Phased Array Beamforming Kit provides a tightly integrated environment for system-level phased-array simulation, enabling direct incorporation of electromagnetic antenna designs to capture realistic element patterns, mutual coupling, and array behavior. The kit supports active impedance and load-pull modeling, allowing engineers to analyze how the impedance presented to each power amplifier varies dynamically as beams are electronically steered across different scan angles. This capability is essential for comprehensive optimization of phased-array transmitters, where beam steering, frequency, and array geometry jointly influence amplifier efficiency, linearity, and stability.

As phased arrays scale to hundreds or thousands of channels and operate over ever-wider bandwidths — trends that accelerate on the path to 6G — the impact of load-pull effects on power amplifiers becomes increasingly significant. PathWave System Design enables these load-pull interactions to be simulated consistently at the system level as the array scans and tracks dynamic scenarios, without sacrificing fidelity at higher channel counts. This scalable, high-fidelity modeling approach allows designers to predict real-world performance, evaluate tradeoffs

between efficiency and linearity, and reduce risk early in the development of next-generation phased-array systems (See Figure 5).

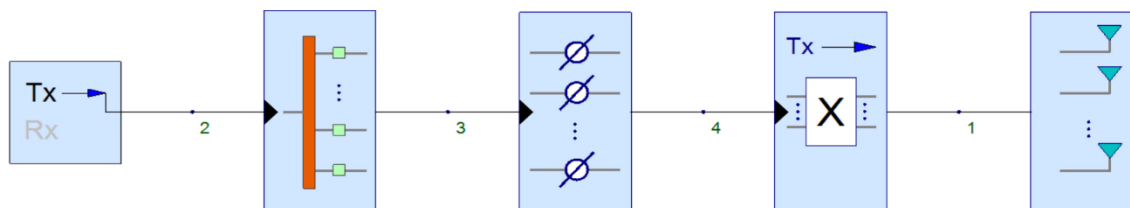


Figure 4. Modeling the phased-array load pull effects on the power amplifier.

Modeling the Channel

The Keysight W4516E 5G NR NTN Channel Model Kit delivers standardized NTN channel models aligned with 3GPP Release 18 and applicable to evolving 5G-Advanced NTN studies. The kit enables high-fidelity modeling of satellite and hybrid satellite-terrestrial links by capturing key NTN propagation effects such as long propagation delays, large and time-varying Doppler shifts, atmospheric losses, and mobility driven by satellite orbits. Satellite trajectories and link dynamics can be easily configured and visualized, allowing engineers to analyze realistic time-varying channel behavior.

The channel model framework supports multiple abstraction levels to match different stages of system analysis, including scenario-based models, Cluster Delay Line (CDL), Tapped Delay Line (TDL), and satellite-link-only configurations. By combining satellite and terrestrial channel representations within a unified environment, the W4516E kit enables system-level evaluation of waveform performance, synchronization robustness, and end-to-end KPIs under realistic NTN operating conditions, supporting early validation and optimization of 5G and future 6G NTN designs.

Modeling Mobility with the W4516E Channel Model

The W4516E NTN Channel Model Kit brings essential satellite propagation effects into a high-fidelity simulation environment, enabling accurate modeling of a wide range of NTN service links. Aligned with 3GPP TR 38.811 and applicable to current and evolving 5G NTN studies, the model captures key characteristics such as long propagation delays, time-varying Doppler, mobility, and environment-dependent losses. Its versatile framework supports multiple non-terrestrial platforms, including GEO, MEO, LEO satellites, as well as airborne and high-altitude systems, allowing engineers to analyze diverse deployment scenarios within a single toolset.

The model offers flexible antenna pattern configuration, making it possible to account for realistic beam shapes, scan angles, and array effects as part of end-to-end system analysis. Seamless integration with the broader SystemVue 5G NR library enables detailed link-level simulations that combine waveform generation, RF impairments, phased-array behavior, and channel dynamics. Together, these capabilities provide a robust foundation for validating and optimizing 5G NTN designs and extending analyses toward 5G-Advanced and early 6G use cases (See Figure 7 for the components of the channel model and simulation attributes compliant with TR 38.811).

Visualization, trajectory display, and GUI

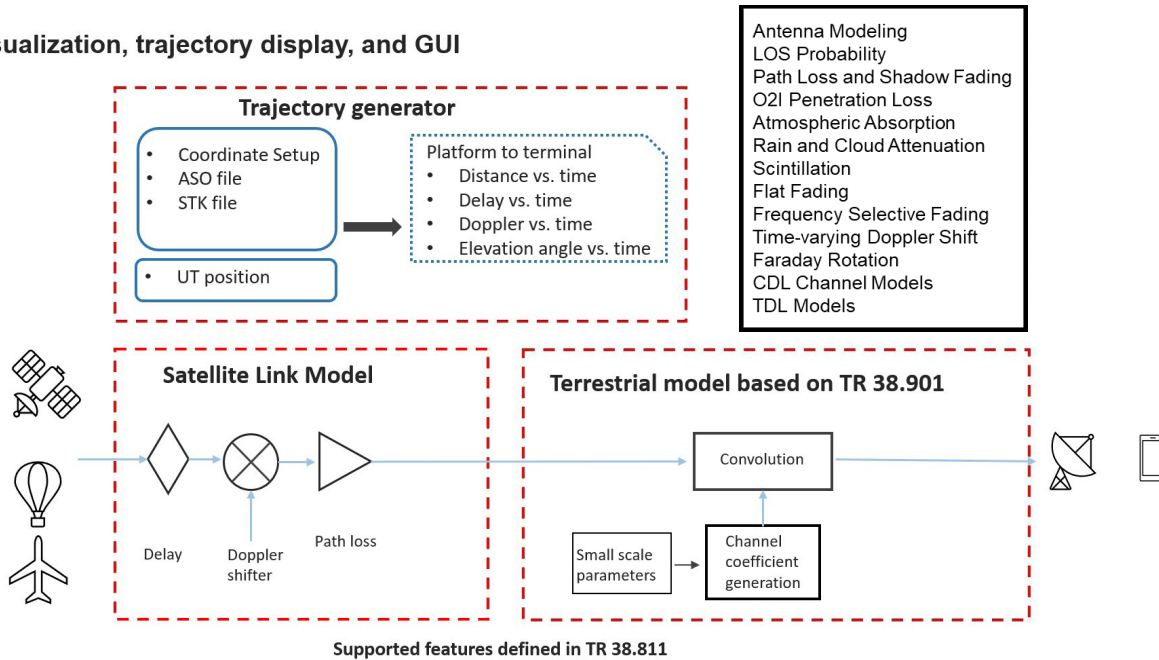


Figure 5. Components of the channel model and simulation attributes compliant with TR 38.811

Support for large-scale effects and time-varying channel dynamics enables realistic evaluation across a wide range of NTN deployment scenarios. The W4516E channel model includes an intuitive graphical user interface that visualizes satellite trajectories and link geometry over time, with an interactive playback mode that brings orbital motion, Doppler evolution, and coverage dynamics into the simulation. This combination of advanced channel modeling and visualization helps engineers gain deeper insight into system behavior under realistic, time-dependent operating conditions (See Figure 7).

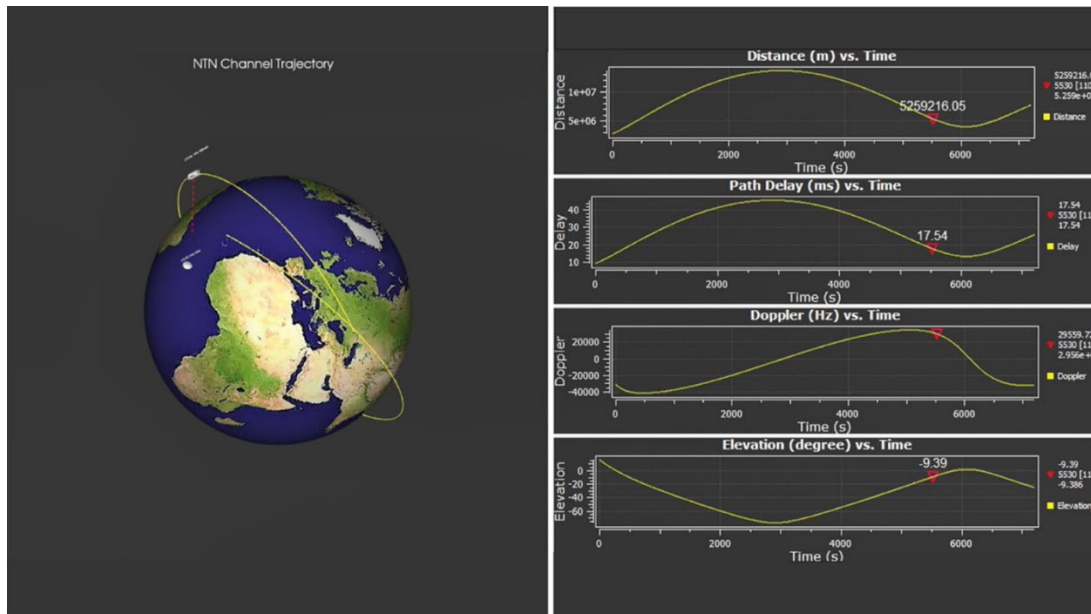
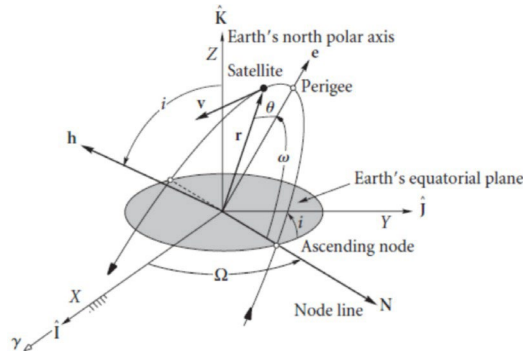


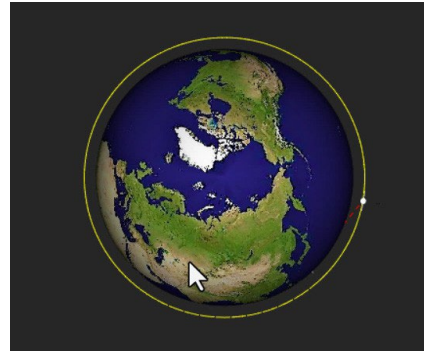
Figure 6. Satellite trajectory visualization.

Also included in the W4516E channel model is the ability to set up a platform trajectory with three flexible options (See Figure 8).

6 Keplerian elements



3GPP 38.811 Spherical Orbit



STK file from Ansys STK



ASO file from Keysight PropSim



Figure 8. Visualization, trajectory display, and GUI

Platform trajectories and user terminal locations can be defined using precise geographic coordinates, providing full control over geometry and motion within the simulation. Depending on modeling needs, trajectories may be specified using classical Cartesian or spherical coordinate representations. For streamlined interoperability, trajectories can also be imported from Keysight PROPSIM ASO files, enabling seamless reuse of channel emulation scenarios within the system-level simulation environment.

In addition, platform motion can be defined using Ansys Systems Tool Kit (STK) files or standard ephemeris (*. e) data, allowing direct integration with existing orbital analysis and mission-planning workflows. This flexible trajectory definition capability simplifies scenario setup, ensures consistency across tools, and supports accurate time-varying modeling of satellite and airborne platforms in NTN simulations.

Modeling the Receiver

Receiver throughput can be evaluated under realistic NTN channel conditions to quantify end-to-end performance in the presence of long propagation delays, Doppler dynamics, and time-varying link quality. In NTN scenarios, link geometry and beam alignment — rather than simple proximity between the UE and a terrestrial base station — play a dominant role in determining received signal quality. As a result, reference sensitivity becomes a critical metric, as it defines the receiver's ability to reliably detect and decode signals at very low signal levels. Accurate assessment of throughput and reference sensitivity ensures robust connectivity and service continuity, even under the challenging and highly dynamic conditions inherent to non-terrestrial networks (see Figure 9).

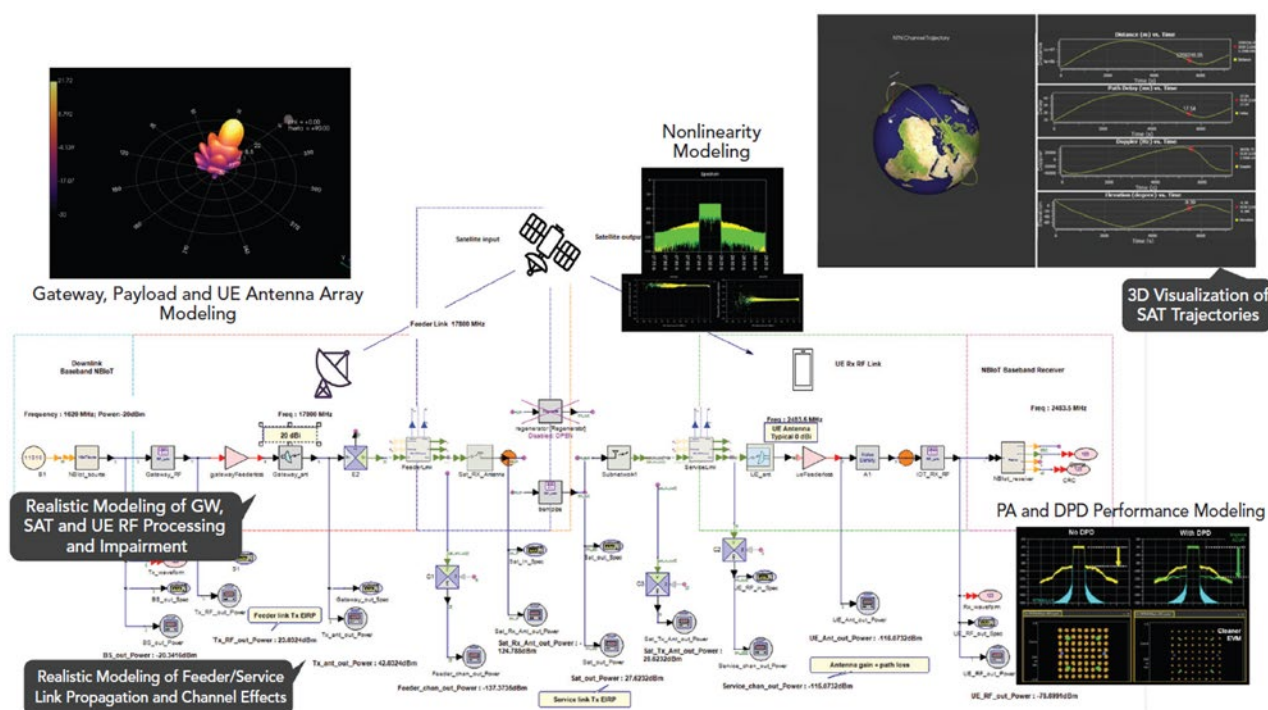


Figure 9. An example SystemVue 5G NTN link budget analysis workspace

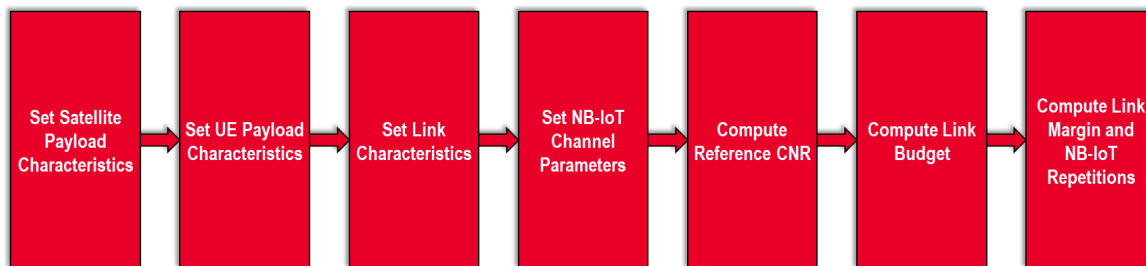
NTN Link Budget Analysis

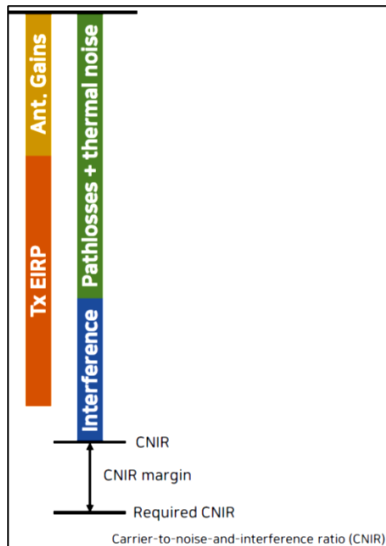
Non-terrestrial network link budget analysis is a structured, end-to-end evaluation of all gains and losses experienced by a signal as it propagates between a transmitter and receiver in satellite, high-altitude platform, or UAV-based systems. The analysis accounts for transmit power, antenna and beamforming gains, free-space path loss, atmospheric and rain attenuation, Doppler effects, polarization losses, and receiver noise performance. Compared with terrestrial networks, NTN link budgets must address much larger propagation distances, time-varying geometry, mobility-induced Doppler, and environment-dependent losses, making accurate and time-aware analysis both more complex and more critical.

Link budget analysis forms the foundation of reliable NTN system design by determining whether received signal levels can meet required quality-of-service targets under nominal and worst-case conditions. By explicitly modeling margins — such as fading, implementation, RF impairment, and antenna losses — engineers can correctly size antennas, select modulation and coding schemes, define power operating points, and balance throughput, latency, availability, and energy efficiency. Robust link budget analysis helps prevent coverage gaps, performance degradation, and excessive power consumption, while supporting early design trade studies and risk reduction.

Beyond link viability, link budget results directly influence architectural decisions, including orbit selection (LEO, MEO, GEO), frequency band choice (e.g., S-, Ku-, Ka-band), beamforming and reuse strategies, and gateway placement. For example, LEO systems benefit from lower path loss and latency but require sophisticated Doppler compensation design, while GEO systems trade higher path loss and latency for stable geometry. Evaluating these trade-offs through link budget calculations ensures regulatory compliance and cost-effective system performance, making link budgeting a cornerstone of feasibility assessment and optimization for NTN deployments.

As an illustrative example, a 5G NTN-IoT link budget workflow begins by defining satellite payload characteristics such as transmit power, antenna pattern, and beam configuration, followed by specification of user equipment parameters including receiver sensitivity and antenna gain. Link characteristics — frequency band, polarization, and propagation environment — are then established, along with NTN-specific channel parameters that capture fading and Doppler dynamics. These inputs are used to compute reference metrics such as Carrier-to-Noise Ratio (CNR) or Received Signal Strength Indicator (RSSI) which in turn drive the final link budget and margin calculations, including the number of signal repetitions required to meet reliability and coverage targets for NTN-IoT services.





Calculate Effective Code Rate

$$R_{\text{eff}} = \frac{N_{\text{bits}} + N_{\text{CRC}}}{N_{\text{SF}} N_{\text{symbols}} m N_{\text{Rep}}}$$

Calculate Required CNR for the Selected MCS

$$\left(\frac{C}{N}\right)_{\text{ref}} = \left(\frac{E_b}{N_0}\right)_{\text{ref}} + 10 \log_{10}(m R_{\text{eff}}) + 10 \log_{10}\left(\frac{N_{\text{DSC}}}{N_{\text{FFT}}}\right) + 10 \log_{10}\left(\frac{T_d}{T_d + T_{\text{CP}}}\right) - 10 \log_{10}(\text{OSR})$$

Calculate Receiver (GW,SAT,UE) Antenna G/T

$$\frac{G}{T} = G_R - N_f - 10 \log_{10}(T_0 + (T_a - T_0)10^{-0.1N_f})$$

Calculate the Actual CNR

$$\text{CNR} = \text{EIRP} + \frac{G}{T} - k - \text{PL}_{\text{FS}} - \text{PL}_A - \text{PL}_{\text{SM}} - \text{PL}_{\text{SL}} - \text{PL}_{\text{AD}} - B$$

Calculate Link Margin

$$\text{LinkMargin} = \frac{C}{N} - \left(\frac{C}{N}\right)_{\text{ref}}$$

Calculate the Number of Additional Repetitions to Achieve the Required CNR

$$\left\lceil N_{\text{Rep}} \left(10^{\frac{-\text{LinkMargin}}{10}} - 1 \right) \right\rceil$$

Figure 10. Example 5G NTN-IoT Link Budget Analysis

SystemVue's NTN link budget analysis includes coverage map visualization that plots Carrier-to-Noise Ratio (CNR) or Received Signal Strength Indicator (RSSI) contours on the Earth's surface, providing intuitive insight into spatial performance variations (see Figure 11). These coverage maps account for realistic propagation effects, satellite geometry, beam patterns, and phased-array steering, allowing engineers to see how payload transmitter power, antenna configuration, and beamforming strategies translate into real-world coverage. By correlating CNR or RSSI contours with service requirements, designers can optimize payload transmitters, phased arrays, and beam layouts to maximize coverage, ensure margin where needed, and efficiently balance performance, capacity, and power under realistic operating conditions.

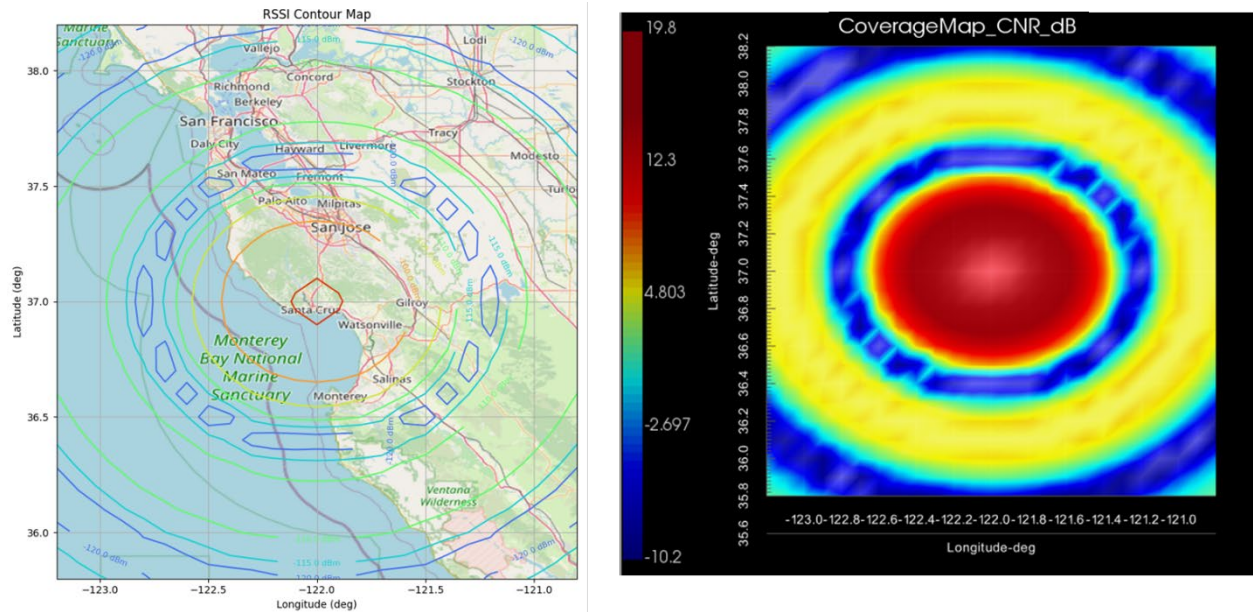


Figure 11. Example coverage maps generated by SystemVue.

Summary

Demand for 5G connectivity across consumer, industrial, and Internet of Things applications continues to expand, with the need for seamless coverage over remote, rural, maritime, and airborne environments accelerating global adoption of 5G non-terrestrial networks. While 5G New Radio was initially standardized in 3GPP Release 15, NTN capabilities were formally introduced in Release 17 and are being further refined in subsequent 5G-Advanced releases, enabling standardized satellite and high-altitude platform integration into the 5G ecosystem.

Using SystemVue, systems engineers can apply system-level modeling and simulation to create high-fidelity digital twins of 5G NTN networks, leveraging standardized channel models and test libraries to design, analyze, and optimize end-to-end NTN performance with confidence before deployment.

To learn more, take a look at some of our available resources:

[Product page – W4815B](#)

[White Paper](#)

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