

Stochastic Channel Modeling for Non-Terrestrial Networks

State of the Art and Recommended Research Directions

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Abstract

New non-terrestrial network (NTN) channel models are highly essential, as they are expected to differ significantly from conventional terrestrial systems owing to the much higher path loss, the high mobility of NTN base stations, the strong dependence on elevation angle, and the presence of atmospheric, ionospheric, and local scattering effects. The channel modeling literature broadly consists of deterministic and stochastic modeling techniques, each having its own advantages and limitations. This report presents a detailed review of the existing state-of-the-art channel modeling frameworks for NTNs, discussing their underlying assumptions, strengths, and limitations. The survey includes both non-geometric and geometry-based stochastic channel models. Within the stochastic modeling framework, we also present the large-scale and small-scale fading parameters that influence NTN channel models. These parameters include the Rician K -factor, large-scale shadowing, rain, cloud, and fog attenuation, cross-polarization ratio, maximum delay spread, Doppler spread, and coherence bandwidth. Next, standardized channel models are discussed, ranging from the early 3GPP/3GPP2 spatial channel model and the WINNER family of models to the current 3GPP TR 38.901 framework and its NTN-oriented extensions. The report also identifies the “QuaDRiGa” framework as one of the most advanced and comprehensive channel models currently available for LEO satellite communications. Finally, research gaps are identified, which the authors plan to investigate in future work.

I. INTRODUCTION

Non-terrestrial networks (NTNs) introduce propagation conditions that differ substantially from those encountered in conventional terrestrial communication systems, owing to the large transmitter–receiver separation, the high mobility of satellites and aerial platforms, the strong dependence of the propagation conditions on the elevation angle, and the presence of atmospheric, ionospheric, and local scattering effects. Accurate channel models are therefore essential for the design, evaluation, and standardization of NTN communication systems. Wireless channel models are commonly divided into deterministic and stochastic models, each with its own advantages and limitations.

Despite their differences, most wideband channel models rely on a common mathematical representation in which the received channel is expressed as the superposition of multiple propagation paths. Each path is characterized by parameters such as its complex gain, propagation delay, arrival and departure directions, Doppler shift, and polarization properties. A generic time-varying baseband channel impulse response can therefore be written as:

$$h(t, \tau) = \sum_{\ell=1}^{L(t)} \alpha_{\ell}(t) e^{-j2\pi f_c(\tau_{\ell}(t))} \delta(\tau - \tau_{\ell}(t)), \quad (1)$$

where $L(t)$ denotes the number of propagation paths, and $\alpha_\ell(t)$ and $\tau_\ell(t)$ denote the complex gain and propagation delay of the ℓ -th path, respectively. The various channel-modeling approaches differ primarily in how these quantities are obtained. Deterministic models derive them from the geometry and electromagnetic properties of a specific propagation environment. Geometry-based stochastic channel models instead generate the propagation paths, scatterers, or clusters statistically while retaining an abstract geometrical representation of the multipath propagation. Non-geometry-based stochastic channel models characterize the aggregate channel coefficients or their statistics directly, without explicitly identifying the underlying scatterers or individual propagation paths.

Deterministic models, and in particular ray-tracing approaches, can provide detailed and site-specific channel information because the propagation paths are obtained from the transmitter and receiver positions, the surrounding environment, and the electromagnetic properties of the interacting objects [1]. Their main limitations are the need for sufficiently accurate environmental information and the associated computational complexity. Stochastic models, in contrast, provide a more computationally efficient representation of the propagation environment and are therefore particularly suitable for link- and system-level evaluations requiring a large number of channel realizations. Their parameters are typically obtained from channel measurements, ray-tracing results, or empirical studies and can subsequently be incorporated into standardized channel-generation procedures.

For NTN systems, stochastic channel modeling must additionally capture propagation characteristics that are specific to space-to-ground links. These include the dependence of several propagation parameters on the satellite–terminal geometry and elevation angle, the motion of both the space platform and the ground terminal, atmospheric and ionospheric propagation effects, shadowing and blockage caused by the local environment, and the temporal evolution of the multipath components. Depending on the considered model, these effects may be represented through large-scale parameters such as shadow fading, Ricean K-factor, delay and angular spreads, and cross-polarization ratio, together with small-scale parameters describing individual multipath delays, powers, angles, phases, and Doppler shifts.

This report therefore reviews the main stochastic channel-modeling approaches developed for NTN systems, discusses their underlying assumptions, capabilities, and limitations, and identifies research directions toward more generic and physically consistent stochastic channel models for future NTN applications.

II. SUMMARY OF NTN STOCHASTIC CHANNEL MODELS - PRIOR ART DISCUSSION & COMMENTARY

Stochastic channel models for NTN can be broadly classified into non-geometry-based stochastic channel models (NGSCMs) and geometry-based stochastic channel models (GSCMs) [2]. NGSCMs describe the channel directly through probability distributions, stochastic processes, or transitions between a limited number of propagation states, without explicitly identifying the underlying scatterers or geometrical propagation paths. GSCMs, in contrast, retain an explicit multipath representation in which the delays, powers, arrival and departure angles, Doppler shifts, and polarization properties of the propagation components are generated statistically through virtual scatterers or clusters. These two families have been extensively used in satellite and aerial communication systems, ranging from classical land-mobile satellite fading models to recent standardized and simulation-oriented NTN channel frameworks.

A. *Non-Geometry-Based Stochastic Models*

Non-geometry-based stochastic channel models (NGSCMs) describe the channel directly through probability distributions, stochastic processes, or transitions between a limited number of propagation states, without explicitly identifying the scatterers or geometrical propagation paths. Rather than representing each reflected, diffracted, or scattered component separately, these models capture the aggregate effect of multipath propagation using a small number of random channel components and distribution parameters. Their main advantage is therefore their relatively low complexity, which makes them attractive for link-level and system-level simulations when an explicit geometrical representation of the scattering environment is not required.

One of the classical NGSCMs for land-mobile satellite communication is the Loo model, which represents the received signal as the sum of a lognormally shadowed direct component and a Rayleigh-distributed diffuse component [3]. This construction captures the coexistence of a dominant satellite-to-terminal component affected by slow shadowing and a collection of weaker multipath contributions generated by the surrounding environment. The model is particularly relevant to mobile satellite links in which the direct path remains present but undergoes varying degrees of obstruction or shadowing.

The Corazza–Vatalaro model follows a related statistical philosophy by combining lognormal shadowing with Ricean fading [4]. It was developed as a compact channel representation applicable to both geostationary and non-geostationary satellite links. In this class of models, the

influence of the propagation environment is represented through the parameters of the underlying fading distributions rather than through an explicit description of individual propagation paths or scatterers.

Another important family of NGSCMs relies on finite-state propagation models. The Lutz model, for example, represents the satellite channel through transitions between different propagation conditions, with each state characterized by an appropriate fading distribution [5]. More elaborate land-mobile satellite models extend this approach using two-state or three-state Markov or semi-Markov formulations to distinguish between clear, shadowed, and severely blocked propagation conditions. In particular, the ITU-R land-mobile satellite model employs GOOD and BAD propagation states whose spatial or temporal durations are statistically modeled, while the fading behavior within each state is described using state-dependent distributions [6]. Such models are useful for representing the temporal evolution of shadowing and blockage along a user trajectory without explicitly modeling the physical objects responsible for the transitions.

B. Geometry-based stochastic channel models

Geometry-based stochastic channel models (GSCMs) retain the multipath decomposition of the channel while introducing an abstract geometrical representation of the propagation environment. In contrast to non-geometry-based stochastic models, the individual multipath components are explicitly characterized through parameters such as their delays, powers, angles of arrival and departure, Doppler shifts, phases, and polarization properties. These components are organized through statistically generated scatterers or clusters. A scatterer represents a virtual interaction point associated with one or more propagation paths, whereas a cluster groups multipath components with similar delays and angular characteristics. These statistical scatterers and clusters do not necessarily correspond to actual physical objects in a specific environment, but are instead modeling entities introduced to reproduce the propagation statistics observed in measurements or obtained from ray-tracing simulations [7], [8]. These empirically derived statistics may subsequently be incorporated into standardized channel models, such as the 3GPP and WINNER models, which provide unified parameter sets and channel-generation procedures for representative deployment scenarios [9]–[11]. The resulting paths are therefore statistically representative of a class of propagation environments rather than associated with the actual objects present at a particular site.

The generation of a GSCM realization generally starts from the specification of the network

layout and simulation configuration [12]. The considered propagation scenario is first selected, for example dense urban, urban, suburban, or rural in the NTN context. The positions and trajectories of the transmitting platform and ground terminals are then defined, together with the carrier frequency, bandwidth, antenna configurations, polarization, simulation duration, and spatial or temporal sampling resolution. For satellite systems, the transmitter trajectory may be derived from orbital information, whereas the ground terminals can be fixed, randomly distributed, or moved along predefined trajectories [2]. The carrier frequency and channel bandwidth are selected according to the considered frequency band, communication service, and waveform [10], [12]. The simulation duration is chosen according to the desired observation interval, whereas the temporal or spatial sampling density must be sufficiently high to capture the channel variations caused by terminal and platform mobility, [2], [13]. Finally, the transmit and receive antenna configurations are defined, including the array geometry, element radiation patterns, polarization, and orientation [10], [13].

Once the network geometry has been specified, the model generates the large-scale parameters (LSPs) and the associated small-scale parameters (SSPs) for each link. The LSPs describe slowly varying characteristics of the propagation environment and typically include shadow fading, Ricean K-factor, delay spread, azimuth and elevation spreads of arrival and departure, and cross-polarization ratio. These parameters may depend on the propagation scenario, carrier frequency, elevation angle, and LOS/NLOS condition, and they are generally spatially correlated so that nearby terminal positions experience similar channel characteristics. In NTN systems, additional large-scale losses such as atmospheric absorption, rain attenuation, cloud attenuation, scintillation, and building or foliage losses may also be incorporated as functions of the link geometry and propagation conditions.

Conditioned on the LSPs, the SSPs describing the individual multipath components are subsequently generated. These include the cluster and ray delays, powers, angles of arrival and departure, initial phases, polarization coefficients, and, when mobility is considered, Doppler shifts. For example, the delay spread controls the dispersion of the generated cluster delays, while the angular spreads determine the distribution of arrival and departure directions. The Ricean K-factor governs the relative power between the dominant LOS component and the diffuse multipath contributions. Once the SSPs are generated, the contribution of each propagation path is computed and the individual components are coherently summed to form the time-varying channel impulse response. Below, we review the literature on large-scale and small-scale channel

parameters in the context of NTN systems.

1) Large-Scale Parameters

The LSPs can be broadly separated according to their role in the channel-generation procedure. A first group consists of stochastic parameters that control the distributions of the small-scale parameters. These include the delay spread, azimuth and elevation angular spreads, Ricean K -factor, cross-polarization ratio, and, in many models, shadow fading. For example, the delay spread determines the dispersion of the generated cluster delays, the angular spreads govern the distribution of the arrival and departure directions, and the K -factor specifies the relative power between the dominant LOS component and the scattered multipath components. These parameters generally vary relatively slowly with position and are therefore generated with spatial correlation.

A second group consists of large-scale propagation losses that primarily determine the overall received signal level rather than the relative distribution of the multipath components. For NTN links, these include free-space path loss, clutter and building penetration losses, atmospheric gaseous absorption, rain attenuation, cloud and fog attenuation, foliage loss, and ionospheric or tropospheric scintillation. These effects are strongly dependent on carrier frequency and on the Earth–space slant-path geometry. In particular, several of them become increasingly important at low elevation angles because the signal traverses a longer path through the atmosphere or local clutter.

a) Stochastic LSPs controlling multipath generation

- i) **Elevation-Dependent Shadow Fading (SF):** Represents signal power fluctuations caused by terrain features, buildings, or clutter near the ground terminal blocking the slant path. In NTN standards [10], [12], [14], SF is modeled as a zero-mean log-normal random variable in decibels, i.e. $SF_{\text{dB}} \sim \mathcal{N}(0, \sigma_{\text{SF}}^2(\theta))$, where the standard deviation $\sigma_{\text{SF}}(\theta)$ decreases as the elevation angle θ increases toward zenith (90°). The remaining large-scale parameters (LSPs) quantify multipath dispersion, angular spread, and polarization purity, which are predominantly dictated by local ground clutter around the UE and space-segment geometry. An important distinction here is that even though these are parameters that describe small scale fading phenomena, the parameters themselves change over relatively large distances and hence, come under the purview of large-scale fading parameters.

- ii) **Ricean K-Factor (KF):** The ratio of the average power in the dominant direct LOS slant component to the total average power of indirect multipath components reflected off ground clutter:

$$K(\theta) = \frac{P_{\text{LOS}}}{\sum_i P_{\text{NLOS},i}} \quad (2)$$

In NTN, $K_{\text{dB}}(\theta)$ is significantly higher than in terrestrial networks due to the clear slant path. It increases monotonically with elevation angle θ , approaching pure Line-of-Sight conditions at zenith.

- iii) **RMS Delay Spread (DS):** Measures the temporal dispersion of multipath components generated strictly by local scattering near the ground terminal:

$$\tau_{\text{RMS}} = \sqrt{\frac{\sum_i P_i \tau_i^2}{\sum_i P_i} - \left(\frac{\sum_i P_i \tau_i}{\sum_i P_i} \right)^2} \quad (3)$$

In NTN, the overall propagation delay is dominated by large bulk free-space delay ($t_{\text{prop}} \approx d/c$), but the RMS Delay Spread (τ_{RMS}) remains relatively small (typically nanoseconds to sub-microseconds) as remote scatterers contribute negligible power compared to local clutter.

- iv) **Azimuth/Elevation Spread of Departure at Space Payload (ASD/ESD):** Because the distance between the satellite/HAPS payload and the earth surface is vast relative to the coverage beam footprint, the angular spreads at the transmitter (Space segment) are extremely narrow (often $< 0.1^\circ$), making ASD and ESD at the space payload practically negligible.
- v) **Azimuth and Elevation Spread of Arrival at UE (ASA/ESA):** Measures the angular dispersion of incoming multipath rays at the ground UE terminal in the horizontal (ASA) and vertical (ESA) planes. These spreads are dictated entirely by local clutter height, density, and distance from the receiver, and are strongly conditioned on the arrival elevation angle θ .
- vi) **Cross-Polarization Ratio (XPR) and Polarization Impairments:** Quantifies the ratio of co-polarized power to cross-polarized power resulting from polarization state alteration:

$$\text{XPR} = \frac{P_{\text{co}}}{P_{\text{cross}}} \quad (4)$$

In NTN, XPR degradation stems from two primary space-path phenomena in addition to local ground scattering:

- **Faraday Rotation (Sub-3 GHz):** Interaction with the Earth's magnetic field in the ionosphere rotates the linear polarization state by an angle $\Omega \propto f_c^{-2}$, severely degrading XPR for linearly polarized antennas unless circular polarization (CP) is used.
- **Rain Depolarization (Ku/Ka/Q/V Bands):** Non-spherical falling raindrops induce differential attenuation and phase shift between orthogonal polarization components, converting linear or circular polarization states into elliptical polarization.

b) Additional large-scale propagation effects specific or particularly relevant to NTN.

- i) **Atmospheric Gaseous Absorption:** At frequencies above 10 GHz, resonant absorption by oxygen (O_2) and atmospheric water vapor (H_2O) along the slant path introduces frequency-dependent, deterministic signal attenuation. According to Recommendation ITU-R P.676-13 [15], for link elevation angles $\theta \geq 5^\circ$, the total slant path gaseous attenuation $A_g(\theta, f)$ at carrier frequency f is evaluated as

$$A_g(\theta, f) = \frac{\gamma_o(f) h_o(f) + \gamma_w(f) h_w(f)}{\sin \theta} \quad [\text{dB}] \quad (5)$$

where f is the operational carrier frequency in GHz ($1 \leq f \leq 350$ GHz for the Annex 2 approximate method; $1 \leq f \leq 1000$ GHz for Annex 1 line-by-line integration), $\gamma_o(f)$ and $\gamma_w(f)$ are the surface specific attenuation coefficients (dB/km) for dry air (oxygen) and water vapor, respectively. These are calculated as functions of frequency f , atmospheric pressure P (hPa), temperature T (K), and water vapor density ρ (g/m³). The parameters $h_o(f)$ and $h_w(f)$ are the effective equivalent scale heights (km) for oxygen and water vapor, which model the vertical atmospheric thickness and are non-linear functions of frequency f . Finally, θ is the path elevation angle ($\theta \geq 5^\circ$), where $1/\sin \theta$ accounts for the slant path length extension through a plane-parallel atmosphere.

The specific attenuation is given by $\gamma(f) = 0.1820 \cdot f \cdot N''(f)$, which depends on the imaginary part of the complex refractivity $N''(f)$, given by the summation of discrete absorption spectral lines

$$N''(f) = \sum_i S_i(P, T, \rho) F_i(f, P, T) + N_D''(f, P, T), \quad (6)$$

where S_i is the line strength of the i -th line, $F_i(f)$ is the frequency-dependent line-shape factor, and $N_D''(f)$ represents the non-resonant Debye continuum. Dominant absorption peaks occur at 22.235 GHz and 183.3 GHz for water vapor, and across the 50–70 GHz absorption band and at 118.75 GHz for oxygen.

- ii) **Rain Attenuation:** Rain is the dominant source of propagation impairment at Ku, Ka, and Q/V bands. Because raindrop dimensions are comparable to the signal wavelength, rain attenuation operates in the Mie scattering regime. Per Recommendation ITU-R P.838-3 [16], the specific attenuation γ_R (dB/km) is modeled via an empirical power-law relationship with rainfall rate R (mm/h)

$$\gamma_R(f, \theta, \tau) = k \cdot R^\alpha \quad [\text{dB/km}] \quad (7)$$

where the frequency-dependent coefficients k and α ($1 \leq f \leq 1000$ GHz) account for path geometry and polarization state

$$k = \frac{k_H + k_V + (k_H - k_V) \cos^2 \theta \cos(2\tau)}{2} \quad (8)$$

$$\alpha = \frac{k_H \alpha_H + k_V \alpha_V + (k_H \alpha_H - k_V \alpha_V) \cos^2 \theta \cos(2\tau)}{2k} \quad (9)$$

Here, $k_H, k_V, \alpha_H, \alpha_V$ are horizontal and vertical polarization coefficients, θ is the path elevation angle, and τ is the polarization tilt angle ($\tau = 45^\circ$ for circular polarization). The total slant-path attenuation A_R is given by $A_R = \gamma_R \cdot d_{\text{eff}}$ (dB), where d_{eff} is the effective path length incorporating spatial rain non-uniformity [16].

- iii) **Cloud and Fog Attenuation:** Non-precipitating clouds and fog consist of microscopic liquid water droplets (< 0.01 cm). Thus, for frequencies up to 200 GHz, droplet absorption and scattering strictly adhere to the Rayleigh approximation. According to Recommendation ITU-R P.840-9 [17], local specific cloud attenuation γ_c is linearly proportional to the liquid water density ρ_l (g/m^3)

$$\gamma_c(f, T) = K_l(f, T) \cdot \rho_l \quad [\text{dB/km}] \quad (10)$$

where $K_l(f, T)$ ($(\text{dB/km})/(\text{g/m}^3)$) is the cloud liquid water specific attenuation coefficient computed using a double-Debye model for the complex dielectric permittivity of water at temperature T .

For Earth-space links with elevation angles $5^\circ \leq \theta \leq 90^\circ$, total slant-path cloud attenuation A_C is evaluated by integrating along the path length

$$A_C(f, \theta) = \frac{K_L(f) \cdot L}{\sin \theta} \quad [\text{dB}] \quad (11)$$

where L is the total integrated columnar cloud liquid water content (kg/m^2 or mm) extending from the Earth's surface to the top of the atmosphere, and $K_L(f)$ ($\text{dB}/(\text{kg/m}^2)$) is the standardized cloud liquid mass absorption coefficient.

- iv) **Ionospheric Scintillation and Trans-Ionospheric Impairments:** At lower frequency bands (e.g., L/S bands below 3 GHz), spatial variations in total electron content (TEC) in the ionosphere cause random phase and amplitude fluctuations known as scintillation [18]. Amplitude scintillation is parameterized by the normalized variance of received power, while phase scintillation is quantified by the standard deviation of phase fluctuations.

Ionospheric scintillation is most severe in equatorial regions within twenty degrees of the magnetic equator and at high latitudes. These disturbance events typically onset after local ionospheric sunset or during geomagnetic storms, lasting anywhere from thirty minutes to several hours. The resulting deep signal fades and phase instability disrupt temporal signal coherence, leading to tracking loss and performance degradation in trans-ionospheric radar and communication links [18].

- v) **Slant-Path Foliage Attenuation:** Attenuation caused by trees and canopy along the direct line-of-sight (LOS) path is formally characterized in Recommendation ITU-R P.833-10 [19]. For slant paths involving platforms above the Earth's surface (e.g., satellites or aircraft), the foliage attenuation L is parameterized as a function of carrier frequency f , slant path depth through foliage d , and elevation angle θ . For Earth-space and airborne links, the total foliage attenuation L (in dB) is modeled using empirical relationships of the form:

$$L(\text{dB}) = A \cdot f^B \cdot d^C \cdot (\theta + E)^G \quad (12)$$

where f is the carrier frequency in MHz, d is the vegetation depth in meters along the path, θ is the path elevation angle in degrees, and A, B, C, E , and G are empirical fit parameters determined by specific tree species, canopy geometry, and foliage conditions. For single vegetative obstructions, the geometric path

length within the canopy (l_{tree}) dynamically varies with both elevation angle θ and terminal antenna geometry.

- vi) **Land Mobile Satellite (LMS) Channel State Transitions:** Because the UE or satellite moves, the channel alternates between distinct shadowing states (e.g., Line-of-Sight, Shadowed, and Fully Blocked). NTN models utilize 2-state or 3-state Markov chain models (e.g., Lutz [5] or Perez-Fontan [20] models) with state transition probability matrices conditioned on θ and the land-use environment (Urban, Suburban, Rural).

In ITU-R P.681.11 [6], mixed LMS propagation environments are modeled using an **enhanced 2-state semi-Markov chain** consisting of **GOOD** and **BAD** states. Crucially, these states do not strictly correspond to binary Line-of-Sight (LoS) versus Non-Line-of-Sight (NLoS) conditions; the GOOD state encompasses clear LoS as well as slight shadowing, while the BAD state covers moderate to severe shadowing and blockage. Unlike conventional memoryless Markov models with exponentially distributed dwell times, the spatial and temporal durations of GOOD and BAD state events follow **log-normal distributions**. Within each state event, fading is characterized by a **Loo distribution** whose parameter triplet (mean direct-path amplitude, standard deviation, and diffuse power) is dynamically drawn per event. State transitions incorporate a finite spatial transition length conditioned on the direct-path amplitude difference between the GOOD and BAD states, over which parameters smoothly interpolate in decibels to avoid step-discontinuities. Model parameter sets are empirically tabulated across satellite elevation angles, carrier frequencies (from 1.5 GHz up to 20 GHz), and specific deployment environments (Urban, Suburban, Village, Rural Wooded, and Residential).

As opposed to these, there are several works that combine all these effects into a single random variable modeled as a Shadowed Rician random variable [21]–[23].

- 2) **Small scale parameters:** Small-scale parameters (SSPs) describe the detailed multipath structure of a channel realization. They typically include the delays, powers, angles of arrival and departure, Doppler shifts, phases, and polarization properties of the individual paths or clusters. In stochastic channel models, these quantities are generated conditionally on the propagation scenario and the large-scale parameters, so that the resulting multipath

realization exhibits the prescribed delay, angular, power, and polarization statistics.

- **Delays:** The multipath delays characterize the temporal separation between the different received components and are generally represented as excess delays with respect to the earliest arriving path. In a stochastic GSCM, the cluster delays are randomly generated according to a prescribed delay distribution whose scale is controlled by the RMS delay spread. In the 3GPP methodology underlying the NTN frequency-selective channel model, cluster delays are generated randomly, for example through an exponentially decaying delay law proportional to the generated delay spread DS .
- **Powers:** The path or cluster powers determine how the received multipath energy is distributed among the different components. They are generally generated conditionally on the corresponding delays, with the average power decreasing with increasing excess delay and additional random fluctuations introduced around this trend. Under LOS conditions, the Ricean K -factor determines the relative strength of the dominant component with respect to the diffuse multipath contribution. In the 3GPP-based NTN GSCM procedure, generation of the cluster powers follows generation of the cluster delays and is conditioned on the previously generated LSPs. **Angles of arrival and departure:** Each path or cluster is associated with azimuth and elevation angles at the transmitter and receiver. In stochastic GSCMs, these angles are randomly generated according to distributions whose dispersions are controlled by the corresponding large-scale angular spreads, such as the azimuth and elevation spreads of arrival and departure. Thus, the angles are not necessarily obtained from actual physical scatterer positions. In the 3GPP-based NTN generation procedure, cluster powers are followed by generation of the arrival and departure angles, which are conditioned on the previously generated angular-spread LSPs.
- **Doppler shifts:** Doppler characterizes the temporal variation of the multipath components due to mobility. Each component may experience a different Doppler shift depending on its propagation direction and on the motion of the transmitter and receiver. This produces a Doppler spectrum and Doppler spread in addition to the overall frequency shift. For NTN, TR 38.811 introduces an important additional contribution associated with satellite motion. This satellite Doppler is applied on top of the conventional multipath Doppler contribution; in the TDL formulation, the additional

satellite-motion Doppler is applied to all taps.

- **Phases and polarization:** Each multipath component is additionally assigned an initial phase and a polarization coupling. Random phases determine the coherent addition of the multipath components, while polarization coupling characterizes the transfer of power between orthogonal polarization components. In the 3GPP stochastic generation procedure, the rays within the generated clusters are randomly coupled, cross-polarization ratios are generated, and random initial phases are subsequently assigned before construction of the channel coefficients. NTN implementations based on TR 38.811 can additionally incorporate propagation-specific polarization effects such as Faraday rotation.

It is important to distinguish this generation of a single stochastic channel realization from the question of spatial consistency. The procedure above specifies how the SSPs are generated statistically from the scenario and LSPs. Spatial consistency concerns how these SSPs are correlated and evolved when the transmitter or receiver moves. TR 38.901 defines an explicit spatial-consistency procedure for terrestrial GSCMs [10], whereas TR 38.811 does not adopt the complete TR 38.901 trajectory-based spatial-consistency procedure as part of its NTN channel model [12]. QuaDRiGa goes further in this respect by supporting continuous evolution of statistically initialized multipath components through effective scatterer geometry and drifting along transmitter and receiver trajectories.

C. Standardized Channel models

Standardized geometry-based stochastic channel models provide common procedures and parameter sets for generating statistically representative channel realizations across a range of deployment scenarios. Their objective is not to reproduce one specific physical environment, but rather to provide reproducible and computationally tractable channel models for link- and system-level evaluation. The development of such models can be traced from the early 3GPP/3GPP2 Spatial Channel Model and the WINNER family of models to the current 3GPP TR 38.901 framework and its NTN-oriented extensions.

The early 3GPP spatial channel models followed a predominantly drop-based approach, in which the propagation condition, large-scale parameters, and small-scale multipath parameters were generated for a particular network realization, [24]. A new drop generally resulted in a newly generated channel realization and therefore did not inherently ensure continuity between

nearby terminal positions. The model was subsequently extended toward three-dimensional propagation through the introduction of elevation-domain angles and angular spreads, together with more detailed three-dimensional antenna modeling. Spatial-consistency procedures were later incorporated into 3GPP TR 38.901 so that propagation states, LSPs, and multipath parameters can evolve in a correlated manner across nearby locations [10], [25].

For NTN systems, 3GPP further introduced propagation characteristics specific to space-to-ground links, notably through TR 38.811 and TR 38.821. In these models, several channel parameters and propagation losses depend on the satellite–terminal geometry, particularly the elevation angle and link distance. Additional NTN-specific effects, including atmospheric attenuation, scintillation, and other propagation impairments associated with the Earth–space path, are incorporated on top of the underlying stochastic channel-generation procedure.

In parallel, the WINNER and WINNER II projects developed generic cluster-based GSCMs for multi-antenna and multi-user communication systems. These models introduced a unified double-directional channel representation with scenario-dependent path-loss models and statistical distributions for the large- and small-scale channel parameters. Although WINNER II was not itself a formal standard, its modeling framework strongly influenced subsequent channel-modeling approaches and provided the basis for several simulation frameworks.

QuaDRiGa was subsequently developed as an open-source extension and implementation of the WINNER II modeling philosophy. It retains the underlying cluster-based GSCM structure while introducing more detailed three-dimensional propagation, arbitrary antenna-array configurations, continuous channel evolution along user trajectories, improved spatial consistency, and multi-link support. Unlike purely drop-based implementations, QuaDRiGa explicitly represents user tracks and allows them to be divided into multiple segments, each associated with different scenarios or propagation states. The resulting channel realizations are smoothly combined across segment boundaries, enabling continuous evolution of delays, angles, powers, and phases along a trajectory.

A particularly relevant feature of QuaDRiGa is its quasi-deterministic drifting mechanism. Statistically generated multipath components are mapped to effective scatterer geometries, and the delays, angles, Doppler shifts, and phases are subsequently updated according to the motion of the transmitter and receiver. This provides a stronger geometrical coupling among the time-varying channel parameters than would be obtained by independently regenerating them at successive positions. QuaDRiGa has therefore become a useful baseline for NTN channel-modeling research

and has been extended in several works to account for satellite motion, dual mobility, propagation-state transitions, atmospheric attenuation, and ionospheric effects [12], [26].

More recent open-source frameworks provide alternative implementations of standardized channel models. Sionna implements several terrestrial channel models defined in 3GPP TR 38.901, including UMi, UMa, RMa, CDL, and TDL models, while OpenNTN extends the Sionna framework with channel models based on 3GPP TR 38.811 and NTN-specific propagation and mobility effects. Similarly, ns-3-based implementations have been proposed for system-level simulation of NTN links. These platforms are particularly useful for evaluating communication-system performance, although the physical fidelity of the generated channel remains fundamentally determined by the statistical model and parameter sets on which they are based.

D. Implementation

More recent open-source frameworks have provided alternative implementations of standardized channel models. Sionna implements several channel models defined in 3GPP TR 38.901, including the UMi, UMa, RMa, CDL, and TDL models, and allows the network topology, terminal positions, velocities, antenna arrays, and propagation conditions to be configured programmatically. Its standard GSCM implementation is primarily intended for terrestrial scenarios [27]. OpenNTN extends the Sionna framework with channel models based on 3GPP TR 38.811, including NTN-specific mobility, propagation losses, and fading effects, thereby providing an open-source simulation framework for satellite and other non-terrestrial links [28].

In parallel with the evolution of the 3GPP spatial channel models, the European WINNER and WINNER II projects developed generic GSCMs for link- and system-level evaluation. These models introduced a unified cluster-based, double-directional representation applicable to multiple deployment scenarios, multi-antenna systems, and multi-user networks. The WINNER II model, documented in Deliverable D1.1.2, provided scenario-dependent path-loss expressions and statistical distributions for the large- and small-scale channel parameters [9]. Although WINNER and WINNER II were not formal standards, their publicly available specifications became influential reference models and formed the basis for several subsequent channel-modeling frameworks. QuaDRiGa was developed as an extension and open-source implementation of the WINNER II channel-modeling approach [13]. It retains the underlying cluster-based GSCM structure while introducing more detailed three-dimensional propagation, arbitrary antenna-array configurations, continuous channel evolution along user trajectories, improved spatial consistency, and support

for multi-link simulations. QuaDRiGa also allows parameter sets derived from WINNER, 3GPP, and measurement campaigns to be incorporated within a common simulation framework. It has subsequently been extended to dual-mobile and space-to-ground links, thereby enabling its application to satellite and other NTN scenarios.

Comparison between QuaDRiGa and 3GPP.

Both 3GPP TR 38.901 and QuaDRiGa construct the channel as a coherent sum of polarized multipath components. In 3GPP, the contribution of cluster n , composed of M rays, to the channel between transmit element s and receive element u can be expressed in compact form as

$$h_{u,s,n}(t) = \sqrt{\frac{P_n}{M}} \sum_{m=1}^M \mathbf{F}_{\text{rx},u}^T(\Omega_{n,m}^A) \mathbf{M}_{n,m}^{3\text{GPP}} \mathbf{F}_{\text{tx},s}(\Omega_{n,m}^D) e^{j\psi_{u,s,n,m}} e^{j2\pi f_{D,n,m}t},$$

where P_n is the cluster power, $\mathbf{F}_{\text{tx},s}$ and $\mathbf{F}_{\text{rx},u}$ denote the polarized transmit and receive antenna responses, $e^{j\psi_{u,s,n,m}}$ contains the transmit- and receive-array phase shifts, and $e^{j2\pi f_{D,n,m}t}$ represents the Doppler-induced phase variation [10]. QuaDRiGa employs a closely related path-based representation,

$$h_{u,s}(t, \tau) = \sum_{\ell} \sqrt{P_{\ell}(t)} \mathbf{F}_{\text{rx},u}^T(\Omega_{\ell}^A(t)) \mathbf{M}_{\ell}^Q(t) \mathbf{F}_{\text{tx},s}(\Omega_{\ell}^D(t)) e^{-j2\pi f_c \tau_{\ell}(t)} e^{j\psi_{u,s,\ell}(t)} \delta(\tau - \tau_{\ell}(t)).$$

Thus, the two frameworks use similar channel-coefficient structures. Their main differences lie not in the final coherent summation, but in how the path delays, angles, powers, propagation states, and polarization matrices are generated and evolved.

1) Evolution of Delays and Angles

Under the spatial-consistency procedure of 3GPP TR 38.901, cluster delays, powers, and arrival and departure angles are updated with terminal position to ensure a smooth channel evolution [10]. QuaDRiGa follows a related but more explicit geometrical approach through its quasi-deterministic drifting mechanism. The statistically generated paths are mapped to effective scatterer positions: in the single-bounce case, a common scatterer is used, whereas in the multi-bounce case, separate first- and last-bounce scatterers are placed along the generated departure and arrival directions. Their distances from the transmitter and receiver are determined so that the resulting propagation path reproduces the generated delay and arrival and departure angles, while the unresolved section between the two scatterers represents intermediate interactions. The

delays, angles, Doppler shifts, and phases are then jointly updated from this effective geometry as the terminals move [13], [29].

2) *Drops, Tracks, and Segments*

The baseline 3GPP model is organized around simulation drops. For each drop, the propagation condition, LSPs, cluster delays, powers, and angles are generated for the considered links. A new drop generally corresponds to a new channel realization, although the spatial-consistency extensions of TR 38.901 allow channel parameters to be correlated and updated across nearby positions [10].

QuaDRiGa instead represents terminal mobility explicitly through user tracks that can be divided into several segments. Each segment may be assigned its own propagation scenario, LOS or NLOS state, LSPs, and cluster realization. This allows a single trajectory to pass through different propagation environments, for example, from LOS to NLOS or from an outdoor to an indoor region. At the boundary between adjacent segments, the corresponding channel realizations are combined over a transition region so that the clusters associated with the previous segment gradually disappear while those associated with the new segment gradually emerge. This segment-based structure enables QuaDRiGa to generate continuous channel realizations over long trajectories while supporting changes in propagation state and scenario [13], [29].

3) *Propagation-State Transitions*

In 3GPP, the propagation condition is typically selected among LOS, NLOS, and, when applicable, outdoor-to-indoor states according to scenario-dependent probabilities. Under spatial consistency, the propagation condition is correlated across nearby terminal positions, preventing independent state changes at every position [10]. However, the standard does not fundamentally represent the complete user trajectory as a sequence of separately parameterized channel segments.

QuaDRiGa makes this segmentation explicit. Different portions of a user track can be assigned different scenarios and propagation states, and the channel realizations generated for adjacent segments are merged around their boundaries. The segment mechanism therefore provides a direct way to represent scenario transitions and the gradual appearance and disappearance of clusters along a trajectory. This is especially useful when the terminal moves between regions having distinctly different propagation characteristics.

4) Polarization Modeling

In 3GPP, the polarization coupling of ray m in cluster n is represented by the XPR-based matrix

$$\mathbf{M}_{n,m}^{3\text{GPP}} = \begin{bmatrix} e^{j\Phi_{n,m}^{\theta\theta}} & \kappa_{n,m}^{-1/2} e^{j\Phi_{n,m}^{\theta\phi}} \\ \kappa_{n,m}^{-1/2} e^{j\Phi_{n,m}^{\phi\theta}} & e^{j\Phi_{n,m}^{\phi\phi}} \end{bmatrix},$$

where $\kappa_{n,m}$ denotes the ray XPR and the four coupling phases are randomly generated [10]. The polarization transformation is therefore primarily statistical. QuaDRiGa employs a factorized polarization model. Let

$$\mathbf{R}(\alpha) = \begin{bmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix}, \quad \mathbf{J} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}.$$

For the LOS component,

$$\mathbf{M}_{\ell}^{\text{QuaDRiGa,LOS}} = \mathbf{R}^T(\alpha_{r,\ell}) \mathbf{J} \mathbf{R}(\alpha_{t,\ell}),$$

where $\alpha_{t,\ell}$ and $\alpha_{r,\ell}$ account for the geometrical transformations between the antenna and propagation polarization bases.

For an NLOS subpath,

$$\mathbf{M}_{\ell,m}^{\text{QuaDRiGa,NLOS}} = \mathbf{R}^T(\alpha_{r,\ell,m}) \mathbf{M}_{\ell,m}^{\text{linear}} \mathbf{J} \mathbf{M}_{\ell,m}^{\text{elliptic}} \mathbf{R}(\alpha_{t,\ell,m}),$$

with

$$\mathbf{M}_{\ell,m}^{\text{linear}} = \begin{bmatrix} \cos \gamma_{\ell,m} & -\sin \gamma_{\ell,m} \\ \sin \gamma_{\ell,m} & \cos \gamma_{\ell,m} \end{bmatrix}, \quad \mathbf{M}_{\ell,m}^{\text{elliptic}} = \begin{bmatrix} e^{-j\eta_{\ell,m}} & 0 \\ 0 & e^{j\eta_{\ell,m}} \end{bmatrix}.$$

Here, $\gamma_{\ell,m}$ controls depolarization in the linear polarization basis, whereas $\eta_{\ell,m}$ controls elliptical or cross-circular coupling through the relative phase between the two linear components. This factorization allows QuaDRiGa to model linear and circular or elliptical depolarization separately and to recover perfect polarization preservation by setting the corresponding coupling parameters to zero [29].

Main distinction. Although 3GPP TR 38.901 and QuaDRiGa use closely related cluster-based expressions for constructing the channel coefficients, they serve different purposes. TR 38.901 specifies a standardized statistical channel-generation procedure and provides optional spatial-consistency mechanisms for mobility. QuaDRiGa is an implementation and extension framework that adds explicit user tracks, segment-based scenario transitions, quasi-deterministic drifting of path parameters, and several polarization-processing options. The most significant difference is

therefore not the channel summation itself, but the manner in which the statistically generated multipath components are mapped onto a continuously evolving channel along the transmitter and receiver trajectories.

Beyond QuaDRiGa. QuaDRiGa is one of the most mature and comprehensive open-source GSCM frameworks used for NTN research, owing to its support for spatial consistency, dual mobility, arbitrary antenna configurations, and continuous channel evolution. However, it does not include all propagation mechanisms relevant to space-to-ground links. Several works have therefore used QuaDRiGa as a baseline and extended it with additional NTN-specific features.

Jaeckel *et al.* introduced a satellite-motion extension that enables the satellite position, elevation angle, delay, Doppler shift, and arrival and departure directions to evolve along the orbit [30]. Li *et al.* developed a QuaDRiGa-inspired non-stationary LEO channel model that additionally incorporates atmospheric attenuation and ionospheric Faraday rotation [31]. Zheng *et al.* combined QuaDRiGa with satellite and ground-terminal trajectories and an ITU state-duration model to represent transitions between LOS and shadowed propagation conditions in dual-mobile space-to-ground links [2]. These studies show that QuaDRiGa is often used as a flexible baseline and extended to include orbital motion, channel-state transitions, atmospheric effects, and ionospheric polarization rotation.

E. Other simulation platforms in literature

Open source NTN channel modeling framework: An open source NTN channel simulations is provided in [32]. OpenNTN is presented as an open-source software framework for simulating NTN channel models based on the 3GPP TR38.811 standard. OpenNTN is designed as an extension to the Python-based Sionna framework, providing channel models compatible with existing interfaces, enabling the use of the powerful tools found in Sionna [33].

NS3 simulation models: Recent studies on NS3 based simulation studies on NTN channel models are [34], [35].

F. Small-Scale Channel Parameter Modeling in the Research Literature

Small-scale fading results from the constructive and destructive interference of multipath components arriving at the receiver with different amplitudes, phases, and delays. It depends on the carrier frequency and characterizes the rapid fluctuations of the received signal over short distances and short time periods. Depending on the relationship between the signal bandwidth, delay spread, symbol duration, and channel coherence time, small-scale fading can be classified

as flat or frequency-selective fading, and as fast or slow fading. It is greatly affected by the electromagnetic propagation environment [36]. Recent frameworks for modeling small-scale fading in NTN include [37], [38], and [39].

The authors in [40] propose a small scale fading model for a High Altitude Platform (HAP), based on the presence of scatterers on the terrain. In particular, they derive the channel model in the 2-GHz frequency range utilized for cellular and localization applications. Rain attenuation effects have not been taken into account since they are negligible at the selected frequency range, while they are predominant at higher frequencies envisaged for some applications in NTNs. **From the small scale fading perspective, a mobile radio channel can be characterized by its power delay profile and its Doppler spectrum** [41].

1) Doppler spectrum

More generally, the Doppler spectrum can be interpreted through the time evolution of the phase of the individual multipath components. Consider a multipath channel written as

$$h(t, \tau) = \sum_{\ell=1}^L \alpha_{\ell} e^{j\phi_{\ell}(t)} \delta(\tau - \tau_{\ell}), \quad (13)$$

where α_{ℓ} , τ_{ℓ} , and $\phi_{\ell}(t)$ denote, respectively, the complex amplitude, delay, and time-varying phase of the ℓ th propagation path. The phase evolution can be expressed as

$$\phi_{\ell}(t) = \phi_{\ell,0} + 2\pi \int_0^t f_{D,\ell}(u) du, \quad (14)$$

where $f_{D,\ell}(t)$ is the instantaneous Doppler shift of the ℓ th path. If the Doppler shift is approximately constant over a sufficiently short observation interval, then

$$\phi_{\ell}(t) \simeq \phi_{\ell,0} + 2\pi f_{D,\ell} t. \quad (15)$$

For a moving terminal, the Doppler frequency associated with a ray depends on its direction of arrival. In the two-dimensional case, if the receiver moves with velocity v and a ray arrives at an angle θ with respect to the direction of motion, its Doppler shift is

$$f_D(\theta) = \frac{v}{\lambda} \cos \theta = f_m \cos \theta, \quad (16)$$

where λ is the carrier wavelength and

$$f_m = \frac{v}{\lambda}. \quad (17)$$

Therefore, the **angular distribution of the multipath components directly determines their Doppler distribution**. This provides an important connection between geometry-based channel modeling and Doppler characterization.

In terrestrial systems, the transmitter is typically fixed and the Doppler effect is mainly induced by the motion of the user and, potentially, by moving scatterers in the surrounding environment. In NTN systems, the situation is different because the transmitting platform or satellite can itself move with respect to the Earth. Consequently, the Doppler shift of a propagation path may contain contributions from both the platform or satellite motion and the user motion.

Moreover, the different multipath components generally propagate along different directions and therefore experience different Doppler shifts. Hence, an NTN channel may exhibit both a potentially large **common Doppler shift**, mainly associated with the platform or satellite motion, and a **Doppler spread** resulting from the differences between the Doppler shifts of the individual multipath components. Hence, the Doppler effect directly governs the temporal evolution of the phase of each multipath component.

In practice, the maximum Doppler frequency f_m can be used to characterize the temporal variability of the channel. It is related to the channel coherence time through the commonly used approximation

$$T_c \approx \frac{9}{16\pi f_m}. \quad (18)$$

For the HAP model considered in [42], the maximum Doppler frequency at carrier frequency f_0 is expressed as

$$f_m = f_{d,p} + f_{d,u} = (v_p + v_u) \frac{f_0}{c}, \quad (19)$$

where v_p is the platform speed and v_u is the user speed. In a HAP channel, the frequency variation can therefore be more pronounced than in a conventional terrestrial channel because both the platform motion and the mobile-user motion contribute to the Doppler effect.

This aspect becomes even more important in LEO satellite systems, where the satellite velocity is considerably larger and may induce a very large Doppler shift. However, it is important to distinguish between the **satellite-induced Doppler shift** and the **multipath Doppler spread**. The satellite-induced component mainly produces a common frequency displacement of the received signal. In contrast, the multipath Doppler spread results from the fact that the different propagation paths have different directions and therefore experience different Doppler shifts. It

is this relative dispersion of Doppler frequencies that governs the temporal selectivity of the small-scale fading channel.

Doppler spectrum characterization in current research. Several works have attempted to characterize NTN Doppler statistics through explicit spatial models. In [43], the authors derive the joint distribution of the azimuth and elevation angles of arrival by assuming that scatterers are uniformly distributed within a semi-ellipsoidal scattering volume, and subsequently derive the Doppler power spectral density from the resulting angular statistics. More recently, [44] models the scatterers as a homogeneous Poisson point process (PPP) within a hemispherical region around the receiver and uses stochastic geometry to characterize the corresponding Doppler statistics. A complementary line of work is considered in [45], where stochastic geometry is used to characterize the spatial statistics of the LoS Doppler experienced by terrestrial users, whose locations are modeled according to a Matérn cluster process.

2) Power delay profile and coherence bandwidth

With the growth of cellular and mobile communications, several theoretical and experimental models for the mobile radio channel have been presented (see for example [46]– [47]). Usually these models are developed for ground communication systems with a fixed antenna transmitter. In [40], first, the power delay profile for a platform-based system is obtained and then the coherence bandwidth and the coherence time are evaluated. In order to determine a realistic power delay profile for the platform case, the theoretical model proposed by Rappaport and Liberti [48] for a ground station (GS) has been considered and extended to the case of a platform station. In this case, the receiver and the transmitter are no longer on the horizontal plane and the height of the transmitter must be taken into account.

Consider the receiver (RX) placed at a point with coordinates $(x_0, 0, 0)$ and the transmitter (TX) at $(0, 0, z_0)$. The direct transmission path has length $r_0 = \sqrt{x_0^2 + z_0^2}$, and propagation delay $\tau_0 = r_0/c$, with c being the speed of light. A reflected wave impinging on the receiver with an excess delay τ must have covered a path length given by

$$k(\tau) = r_0 + c\tau. \quad (20)$$

The ellipsoidal set Σ , with TX and RX as foci, is defined by the set of points whereby the sum of the distance from the transmitter and the distance from the receiver equals $k(\tau)$. All the scatterers located inside Σ generate a total path length smaller than $k(\tau)$, correspondingly having a delay less than τ . Since scattered waves are mainly due to tall buildings, trees, poles,

or hills that cannot be found above a certain height h , **scatterers can be assumed uniformly distributed only in a thin layer close to the ground.**

Hence, the volume $V(\tau)$ is defined as the set of points (x, y, z) that satisfy

$$\begin{cases} \sqrt{(x - x_0)^2 + y^2 + z^2} + \sqrt{x^2 + y^2 + (z - z_0)^2} < k(\tau), \\ 0 < z < h. \end{cases} \quad (21)$$

The corresponding volume of the set of interest (containing the scatterers) is

$$V(\tau) = \frac{-\pi w(\tau)(r_0 + c\tau)}{4\sqrt{(z_0^2 + w(\tau))^3}} \left[\frac{4}{3}h^3 - 2z_0h^2 - w(\tau)h \right], \quad (22)$$

where

$$w(\tau) = c^2\tau^2 + 2r_0c\tau. \quad (23)$$

The cumulative distribution function (CDF) of the excess delay $F(\tau)$ can be expressed as the ratio between the volume $V(\tau)$ and the volume that corresponds to the **maximum excess delay** of the system $V(\tau_m)$,

$$F(\tau) = \frac{V(\tau)}{V(\tau_m)}. \quad (24)$$

The PDF can be obtained by differentiating the above equation. Note that we require the value of τ_m . While values for the ground station case are well known, there are no measurements available for the HAP-based platform case. Estimated values achieved with conventional aircraft are in the order of hundreds of nanoseconds, which are much smaller than in the ground station case [49].

The knowledge of the CDF of the excess delay allows one to evaluate the **average number of echoes** $n(\tau)$ having excess delay τ . The **power of a single echo** having excess delay τ , $P_S(\tau)$, can be evaluated using a free-space model with modified path lengths. The **power delay profile** of the system can then be obtained as

$$P(\tau) = n(\tau)P_S(\tau). \quad (25)$$

Once the power delay profile of the HAP channel has been obtained, it is possible to evaluate the **coherence bandwidth** of the channel. Coherence bandwidth roughly characterizes the channel selectivity when compared to the signal parameters used for communication over the channel. In particular, one can assess whether the channel is selective, i.e., causes inter-symbol interference

(ISI), or nonselective for the signal. The coherence bandwidth, defined as the bandwidth over which the frequency correlation is above 0.9, is approximately

$$B_c \approx \frac{1}{50\sigma_\tau}. \quad (26)$$

This requires the evaluation of the **RMS delay spread** σ_τ , which can be obtained from the power delay profile.

3) Stochastic-geometry extension

The geometrical model in [40] provides a particularly useful starting point for such an extension. As described above, for a prescribed excess delay τ , the admissible scatterer locations are determined through the condition

$$\|x - x_{\text{TX}}\| + \|x - x_{\text{RX}}\| - r_0 \leq c\tau, \quad (27)$$

together with the restriction that the scatterers lie within a thin region close to the ground. The corresponding volume $V(\tau)$ determines the probability that a scatterer produces an excess delay below τ when scatterers are uniformly distributed.

A natural first extension is therefore to exploit the same geometry to jointly characterize the **delay and angular distributions**. For a scatterer located at x , the excess delay and the angles of arrival and departure are deterministic functions of its position,

$$\tau = \tau(x), \quad \theta_{\text{AoA}} = \theta_{\text{AoA}}(x), \quad \phi_{\text{AoA}} = \phi_{\text{AoA}}(x), \quad (28)$$

with analogous expressions for the departure angles. Consequently, a spatial probability distribution for x induces a joint distribution of delay and angles,

$$p_{\tau, \theta, \phi}(\tau, \theta, \phi). \quad (29)$$

The uniformly distributed scatterer model can then be generalized by modeling the scatterer positions as a homogeneous PPP,

$$\Phi \sim \text{PPP}(\lambda_s), \quad (30)$$

within the admissible scattering region, where λ_s denotes the scatterer density. If $\mathcal{V}(\tau_m)$ denotes the region associated with the maximum excess delay τ_m , the number of scatterers, and therefore the number of potential multipath components, satisfies

$$N \sim \text{Poisson}(\lambda_s |\mathcal{V}(\tau_m)|), \quad (31)$$

and

$$\mathbb{E}[N] = \lambda_s |\mathcal{V}(\tau_m)|. \quad (32)$$

Under a single-bounce model in which each active scatterer generates one resolvable propagation path, N_s can also be interpreted as the number of potential multipath components. More generally, an additional visibility or activation model may be required to relate the number of physical scatterers to the number of observable MPCs.

Since the excess delay and propagation angles are deterministic functions of the scatterer location, the spatial point process induces corresponding joint delay–angle statistics. These statistics can subsequently be used to characterize the multipath Doppler distribution.

In three dimensions, if $u(\theta, \phi)$ denotes the unit vector associated with the direction of arrival of a multipath component and v_u is the receiver velocity, its receiver-induced Doppler contribution can be written as

$$f_{D,u} = \frac{1}{\lambda} v_u^T u(\theta, \phi). \quad (33)$$

For NTN systems, the platform or satellite motion can additionally be taken into account. For a single-bounce path involving a scatterer x , the total path length is

$$d_x(t) = \|x_p(t) - x\| + \|x_u(t) - x\|, \quad (34)$$

where $x_p(t)$ and $x_u(t)$ denote the platform and user positions, respectively. The Doppler shift of this path follows directly from the time variation of its propagation length,

$$f_D(x, t) = -\frac{1}{\lambda} \frac{d}{dt} d_x(t), \quad (35)$$

where the sign depends on the phase convention.

Hence, each scatterer position simultaneously determines its excess delay, its propagation angles, and its Doppler shift. The stochastic-geometry framework can therefore provide the joint characterization

$$p_{\tau, \theta, \phi, f_D}(\tau, \theta, \phi, f_D), \quad (36)$$

from which the power delay profile, delay spread, angular spreads, Doppler distribution, and Doppler spectrum can be obtained within a common modeling framework.

Hence, key small scale fading parameters to be modeled from a NTN perspective are

- 1) Power delay profile (coherence bandwidth, avg. number of multi-paths)
- 2) Doppler spectrum (Doppler spread, coherence time)

III. RESEARCH GAPS

The following two complementary research axes are proposed.

Research Axis 1: From Ray-Tracing Outputs to Generic Stochastic Channel Models

The first research direction aims at developing a generic methodology to derive and calibrate stochastic channel models from deterministic ray-tracing outputs. Ray tracing provides detailed path-level information for a given propagation environment, including the path delays, received powers, angles of arrival and departure, polarization characteristics, and Doppler shifts. However, these quantities are obtained for specific geometries and are therefore not directly suitable for large-scale system-level simulations.

The objective is to establish a systematic interface between ray-tracing simulations and stochastic channel modeling. For a sufficiently large set of receiver positions or trajectories, the ray tracer will first be used to generate the multipath channel parameters. These path-level quantities will then be processed to extract the corresponding large-scale and small-scale channel parameters, such as delay spread, angular spreads, Rician K -factor, shadow fading, cross-polarization ratio, path delays, path powers, and angular distributions.

The statistical distributions of these parameters, as well as their cross-correlations and spatial correlations, can subsequently be estimated from the ray-tracing database. The resulting statistics can then be used to parameterize a geometry-based stochastic channel model, for example QuaDRiGa or another 3GPP-like stochastic modeling framework.

An important aspect of this research direction is that the methodology should not be restricted to a particular city, propagation scenario, or ray-tracing software. Instead, the goal is to identify a common set of intermediate channel quantities and statistical descriptors that can be extracted from different deterministic propagation engines and subsequently used to calibrate stochastic channel models.

This framework would provide a bridge between highly accurate but computationally demanding deterministic models and computationally efficient stochastic channel models. It would also allow stochastic models to be adapted to new NTN scenarios for which extensive measurement campaigns may not yet be available.

Research Axis 2: Stochastic-Geometry-Based Modeling of Small-Scale Channel Parameters

The second research direction adopts an analytical approach in which the propagation environment is directly modeled through random spatial geometry. In contrast to the first axis, where

the statistics are inferred from ray-tracing realizations, the objective here is to derive channel statistics mathematically from an assumed spatial distribution of the scatterers.

Existing works provide useful starting points. The authors in [44] present a Poisson point process based framework to model the scatterers and further study the Doppler spectrum in a three-dimensional scenario. The authors in [40] study the small-scale fading caused by terrain scatterers for HAP systems, but the scatterer geometry is not modeled using a spatial point process.

Building on these works, the proposed research aims at developing a unified random-geometry framework in which the locations and number of scatterers are modeled using stochastic-geometry tools. For example, the scatterers may initially be represented by a homogeneous Poisson point process within a physically admissible near-ground scattering region.

The geometry of the satellite/platform, user, and scatterers can then be used to derive jointly the main small-scale channel parameters. The following directions are proposed to be studied for academic interest:

- 1) Characterize the excess delay distribution of the multi-path non-line of sight (NLOS) components.
- 2) Characterize the angle of arrival, mean number of multi-path components, and coherence bandwidth in a 3D random geometry based framework.
- 3) Comment on LEO satellite visibility based on the statistics of angle of arrival?

The above research direction is expected to be formalized and solved using stochastic geometry based tools in the upcoming months by A. Balakrishnan (with F. Baccelli, P. Martins), A. Kammoun (with M.-S. Alouini), and R. Rao.

The main objective is to construct a common analytical framework in which the channel parameters are not generated independently, but are jointly induced by the same underlying random propagation geometry. The two proposed axes are complementary. The stochastic-geometry approach provides analytical insight into the relationship between propagation geometry and channel statistics, while the ray-tracing-based approach provides a means of obtaining realistic statistics from detailed physical environments. In a later stage, the two approaches may also be compared or combined, for example by using ray-tracing results to validate or calibrate the parameters of the stochastic-geometry model.

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