System Level Simulator for 3D Mobile Networks

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***Abstract*—The development of Non-Terrestrial Networks (NTN) as a complement to Terrestrial Networks (TN) has emphasized the need for advanced performance analysis tools for integrated 3D mobile networks. NTNs, such as Low Earth Orbit (LEO) satellite systems, are crucial for enhancing global connectivity, particularly in underserved regions. This trend aligns with current research focusing on advanced 5G networks and future 6G networks, driven by 3GPP standards updates and supported by organizations like the Global Satellite Operators Association (GSOA). To evaluate hybrid TN-NTN systems, advanced system-level simulators are essential. Current tools often struggle to model complex TN-NTN interactions and user mobility. This paper introduces a novel NTN system-level simulator capable of simulating various node mobility, including satellites and High-Altitude Platforms (HAPs), and incorporating appropriate channel models and enhanced Physical layer abstraction. The simulator also features an API for integrating machine learning (ML) models, enabling flexible and comprehensive analysis of network behaviors. This simulator bridges existing tool limitations and aids researchers and engineers in optimizing next-generation TN-NTN networks, supporting seamless global connectivity and paving the way for future 6G network innovations.**

***Index Terms*—3D Networks, SLS, 3GPP, 5G-NTN, Hybrid TN-NTN, 6G**

I. Introduction

As mobile networks continue to evolve, Non-Terrestrial Networks (NTN) have become essential for addressing the limitations faced by traditional Terrestrial Networks (TN), particularly in achieving extensive coverage in remote or hard-to-reach areas. These networks are vital for ensuring ubiquitous connectivity and supporting use cases where terrestrial infrastructure is insufficient, such as maritime and rural applications. The integration of NTNs with TNs is gaining momentum, underscoring the potential of NTNs to enhance global connectivity. Additionally, the 3rd Generation Partnership Project (3GPP) has been incorporating various enhancements into the 5G New Radio (5G-NR) standard to facilitate seamless NTN integration.

Accurate and reliable system-level simulations are critical for the effective evaluation and optimization of these integrated TN-NTN networks. Such simulations enable the modeling of large-scale networks with dynamic nodes in realistic environments, providing valuable insights into network performance, resource allocation, and algorithm testing. This allows for better network planning, risk assessment, and cost-effective decision-making. While existing simulators offer some of these capabilities, they often fall short in handling TN-NTN handovers and dynamic user scenarios due to high computational demands [1].

To address these limitations, we present in this paper a comprehensive system-level simulator capable of simulating various node mobilities—ranging from satellites to High-Altitude Platforms (HAPs)—and incorporating realistic channel models and enhanced Physical layer abstractions. The simulator also provides interfaces for machine learning (ML) model integration across different programming languages to facilitate adaptive and optimized network behaviors. In Section II we describe the design and main components of the simulator in details. Furthermore, in Section III we present an example case study showcasing the types of analysis possible utilizing the simulator. Finally, in Section IV we summarize the work presented in this work and discuss the future enhancements and improvements planned to the proposed simulator.

II. Simulator Design

Our simulation framework is implemented in OMNeT++ [2] and uses the implementation of the 5G-NR user plane protocol stack implementation from Simu5G [3] as a baseline. The framework was further extended with the capability to simulate and model multiple types of NTN nodes as base stations in the sky with regenerative payloads. An overview of the general simulation flow and type of nodes is shown in Fig.1.

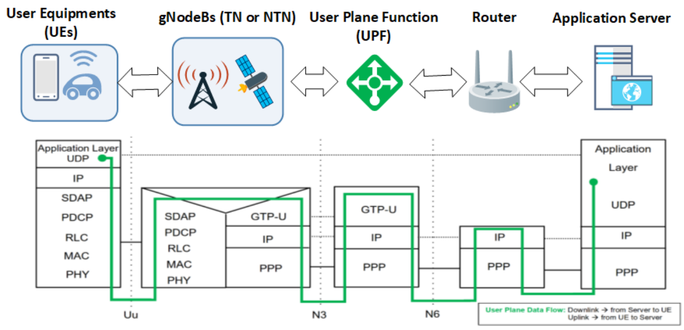

Fig. 1: User plane data flow in simulation

A. Main Component Definitions

The simulator architecture as shown in Fig.2 builds on the design principles of Simu5G for the protocol stack implementation and main procedures, ensuring a robust and modular framework for simulating end-to-end wireless communication systems. On the User Equipment (UE) side, the architecture, encapsulated within the NrNicUe block, includes a layered

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protocol stack consisting of IP, IP2Nic, NrSdap, NrPdcp, NrRlc, NrMAC, and NrPhy. These layers handle critical functions such as IP packet adaptation, header compression, retransmission control, scheduling, and physical-layer signal transmission. Similarly, the gNB side, represented as the NrNicGnb block, mirrors the UE's stack while also incorporating an Xn Manager for managing inter-node communication, such as handover signaling. The architecture also adopts the QoS model implementation from [4], ensuring consistency and accuracy in evaluating traffic and service differentiation and configurable scheduler decisions.

A central feature of the architecture is the Binder element, which manages the exchange of abstracted control plane messages and supports the collection of various Key Performance Indicators (KPIs). It plays a pivotal role in initializing and facilitating data exchange between external modules, such as error models and the AI engine. By abstracting interactions and integrating external tools, the Binder ensures seamless communication and efficient evaluation of system-level behaviors.

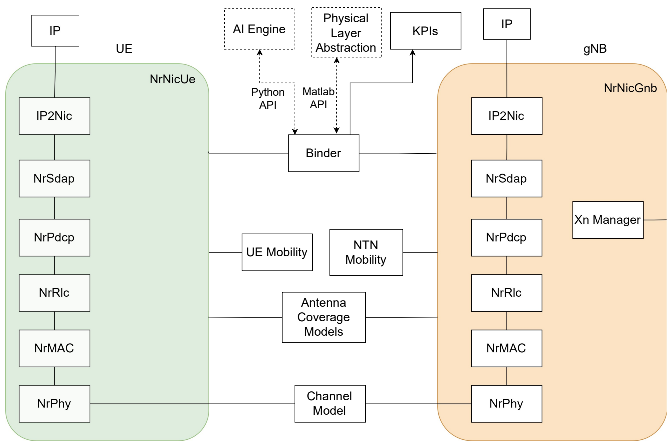


Fig. 2: Main simulation components and node breakdown

B. Mobility Models

Mobility modeling is a core feature of the simulator, supporting both terrestrial and non-terrestrial network scenarios. The UE Mobility model simulates terrestrial movement patterns, such as pedestrian and vehicular dynamics using vehicle tracks from the Simulation of Urban Mobility (SUMO) [5] library, interfaced via the Veins framework [6] to evaluate system performance in dynamic environments. Airborne gNodeBs can follow flight paths based on NORAD-TLE orbital parameters, or simpler linear/circular trajectories defined by latitude, longitude, altitude, and Euler angles. These mobility models are closely integrated with the antenna coverage models to provide accurate simulations of beam/satellite handovers, link continuity, and dynamic user connectivity.

C. Channel Models

The framework incorporates a variety of channel models that represent both terrestrial and non-terrestrial transmission environments. These models account for multipath propagation as well as Line of Sight (LOS) and None Line of Sight (NLOS) conditions, with applicability to S-band and Ka-band use cases. For both TN and NTN links, the simulation framework leverages the evaluation parameters outlined in [7, 8] as a general reference for system-level configurations, including antenna gain, transmission power, and noise figure across different terminal types.

For TN links, the channel modeling approach adheres to the specifications defined by 3GPP in [9]. This includes modeling path loss and shadowing components to assess link quality, as well as using the stochastic model described in the same document to determine the presence of a LOS component, or utilizing the veins/sumo interface to determine whether an obstacle is between the links deterministically. For NTN links, the framework employs the propagation models outlined by 3GPP in [10], which cover free-space path loss, shadowing, and cluster loss. Furthermore, atmospheric losses—including gaseous absorption, cloud attenuation, and rain effects—along with scintillation losses, are modeled using International Telecommunication Union (ITU) recommendations as defined in [11, 12, 13].

This comprehensive approach ensures accurate representation of channel characteristics across diverse scenarios, supporting detailed evaluation of both TN and NTN communication systems.

D. Error Models

The simulator integrates external error models implemented in Matlab which follows the architecture proposed in [14] to evaluate transmission performance accurately under diverse channel and system conditions. This enhanced architecture is interfaced to the simulator as shown in Fig.3, where the orange block produces Signal to Interference and Noise Ratio (SINR) per resource block calculated using the channel models discussed in the previous section. These SINR values are then passed on to the external error model which is integrated into the simulator as a compiled C++ library through the Matlab runtime API. based on the procedure proposed in [14] these SINR values are mapped into the equivalent effective AWGN SINR which is then used to calculate the corresponding error probability using precalculated look up tables for each code block size and code rate as defined by 3GPP in [15].

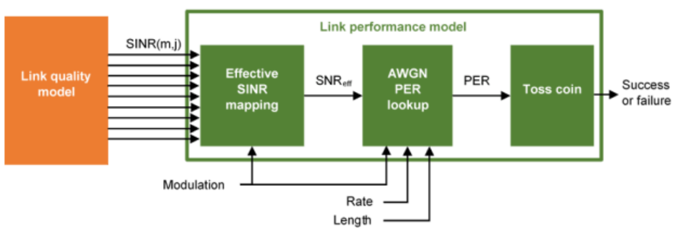


Fig. 3: Physical layer abstraction and error model interface

We validated this enhanced physical layer abstraction implementation using 5G-NR compliant link level simulations

(LLS) over the Tapped Delay Line (TDL) channel and compared the results against the existing Simu5G error models as shown in Fig.4. The result show that the implemented error model was able to align very accurately with the reference LLS results with both the Exponential and Mutual-Information Effective SINR Mapping techniques (EESM and MIESM). These two methods were implemented as proposed in previously in [14] with updated and optimized fudge factors β based on our LLS results. Comparing these results across the existing Simu5G error models shows a significant improvement that bridges the gap and allows for flexibility in the evaluated channel model scenarios as well as more reliable results.

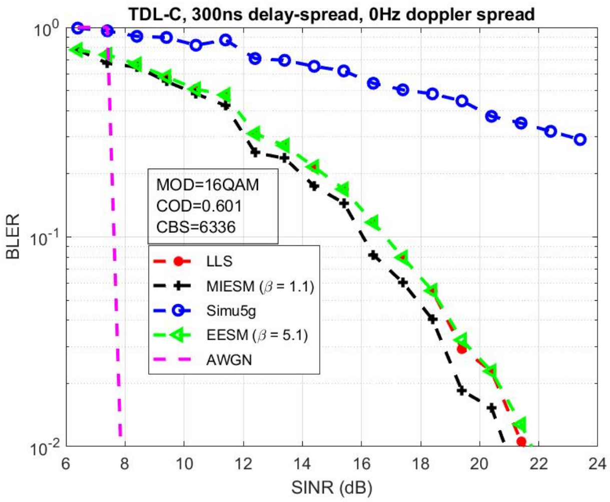


Fig. 4: validation of the enhanced error model for an example Modulation and Coding Scheme (MCS) configuration

E. AI Engine

As 6G networks are envisioned to be immensely complex, requiring more deployment time, cost and management efforts. ML is envisioned to be the answer to lots of these challenges. ML algorithms are envisioned to be deployed and trained at different levels/layers of the network for various purposes such as: management layer, core, radio base stations, and as well as in mobile devices [16]. The simulator leverages further external modules to enhance its flexibility and analytical capabilities. We integrate an AI Engine, accessible via Python APIs namely the Omnetpy framework available in [17], to support predictive decision-making, such as resource optimization and adaptive error correction. The efficacy of this integration has been used to already propose native integration of ML models to enhance network functions such as the work in [18].

III. Case Study

In this section we present an example case study conducted using the developed SLS based on our previous work in [1]. The evaluation scenario is shown in Fig.5, which is based on a a Region of Interest (ROI) of around 20 Km^2 on Open Street Map (OSM) which for this analysis is assumed to be based on the German city of Rosenheim. Vehicular routes are generated using the SUMO tool for a fixed number of ground users. We simulate two variations of this scenario, one of which we have already shown in [1] which consider an integrated TN-NTN scenario where The terrestrial gNodeB is positioned around the edges of the ROI and serves the region along with a synthetic constellation of multiple LEO satellites. the LEO satellite are equipped with regenerative payloads, acting as a NTN gNodeB and their trajectories are defined using the INET's mobility framework, such that these satellites fly approximately over the center of the ROI. The second variation we show here considers the same terrestrial layout and in place of the satellite enhanced coverage we replace it with a regenerative gNodeB deployed in a HAP that circles the area on a lower altitude and a much wider beam. An overview of the simulation configuration parameters are shown in the following Table.I.

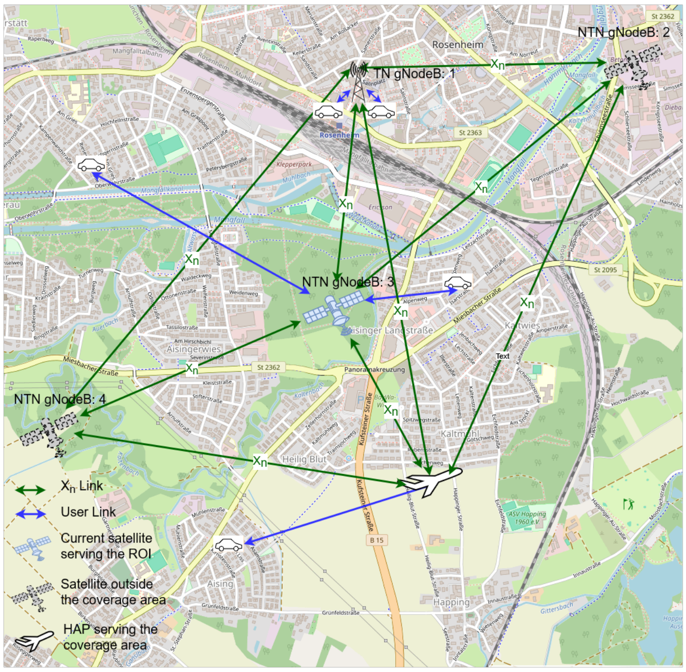


Fig. 5: Schematical simulation scenario layout

Fig.6 showcases how many vehicles are connecting with a particular gNodeB over the period of simulation. Fig.6(a) is the case when TN scenario is complemented with a NTN gNodeBs represented as LEO satellites, whilst Fig.6(b) represents when the TN scenarios is complemented with a single HAP gNodeB. It can be observed that all the deployed vehicles can be served with the vehicles connecting with the NTN gNodeB as required based on link qualtiy measurements.

The improvement in link quality can be seen in the comparisons shown in Fig.7 where in (a) we can observe how the measured SNR improves when connected to the satellites and how the link quality is affected by the mobility of the satellites as they come into view and move out of it requiring a handover to the next satellite terminal. Whilst in (b) we can see that a HAP flying over a lower altitude with a much wider

TABLE I: Parameter Configuration

Parameter	Value
Frequency	2.6 GHz
System Bandwidth	40 MHz
Duplex Type	Frequency Division Duplex (FDD)[1]
TN Bandwidth (bw_{tn})	20 MHz
NTN Bandwidth (bw_{ntn})	20 MHz
Sub-carrier spacing	15 KHz
Hybrid Automatic Repeat Request (HARQ), target BLER	Disabled, 0.01
Scheduling algorithm	Proportional Fair
Satellite altitude	600 km
HAP altitude	20 km
Satellite/HAP antenna pattern	Bessel type
Satellite transmit power (p_s)	46.8 dBm
HAP transmit power (p_s)	44 dBm
Satellite antenna gain (g_s)	30 dBi
HAP antenna gain (g_s)	8 dBi
3dB beamwidth (satellite/HAP) (Half Power Beam Width (HPBW))	4.4127 deg / 65 deg
Satellite beam diameter	50 km
HAP beam diameter	24 km
Noise figure (nf_s)	4.276 (LEO), 5 (HAP), 5 (TN), 7 (UE) dB
TN gNodeB antenna pattern	Omni
TN gNodeB antenna gain (g_t)	8 dBi
TN gNodeB transmit power (p_t) [2]	43 dBm
vehicle antenna pattern	Omni
vehicle antenna gain (g_u)	0 dBi
vehicle transmit power (p_u)	23 dBm

[1] This means the allocated network BW is divided between DL and UL.

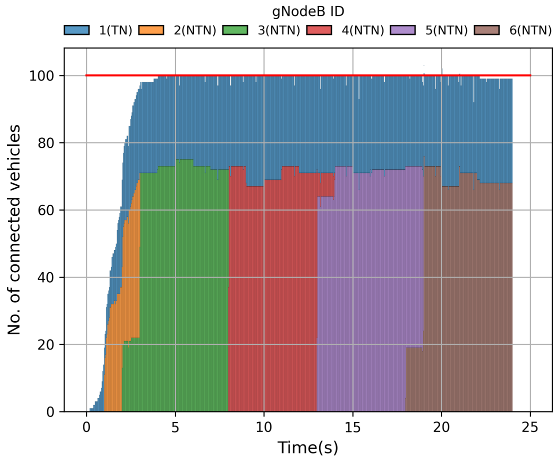
beam pattern delivers a stable link quality.

IV. Conclusion

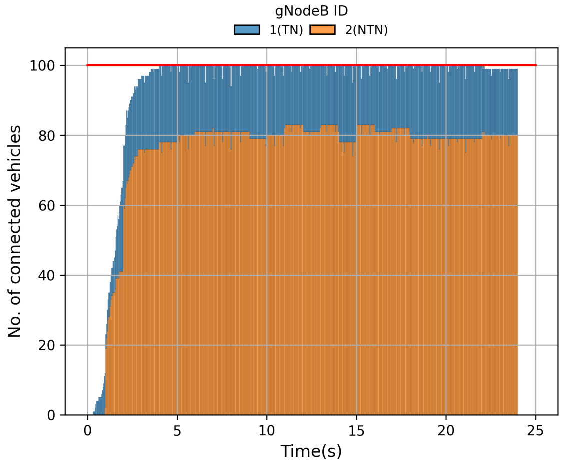
In this paper, we presented a modular and extensible simulation framework for evaluating the performance of both terrestrial and non-terrestrial network (NTN) architectures, integrating advanced protocol stack implementations and external tools such as MATLAB and AI engines. The design leverages the principles of Simu5G for protocol stack implementation and procedural consistency, while incorporating a previously validated QoS model to ensure realistic traffic and service differentiation. Key novel architectural components, such as external error models and AI-driven decision engines, enabling a holistic, flexible and more reliable simulation environment.

The framework supports a comprehensive suite of mobility models for terrestrial and NTN scenarios, including satellite and high-altitude platform systems, as well as realistic channel models. The channel models are tailored to both S-band and Ka-band use cases, accounting for path loss, shadowing, and stochastic factors like LOS availability for terrestrial links, as defined in [9]. For NTN links, the inclusion of 3rd Generation Partnership Project (3GPP) and ITU recommendations ensures accurate modeling of free-space path loss, atmospheric attenuation, and scintillation effects [10, 11].

This architecture provides a powerful simulation tool to analyze and optimize the performance of integrated terrestrial and non-terrestrial networks under diverse configurations and operating conditions. By combining realistic propagation, mobility, and error models with advanced analytical capabilities via external modules, the framework offers a versatile platform for researchers and practitioners to explore emerging challenges in wireless communication as we have shown examples of in our previous works in [19, 20]. Future work may focus on expanding the framework to support more complex architectures, such as multi-orbit NTN systems or heterogeneous TN-NTN deployments, as well as incorporating real-time AI-driven optimization for dynamic resource management between the TN and NTN deployments.



(a) Integrated TN-NTN with LEO Satellite



(b) Integrated TN-NTN with HAP

Fig. 6: Comparison of serving cell distribution stacked over simulation time. 1 refers to the terrestrial gNodeB and 2, 3, 4, 5, 6 refer to the six consecutive NTN gNodeBs that fly over the ROI in the first variation and 2 represents the HAP id in the second variation. The red line indicates the total number of vehicles.

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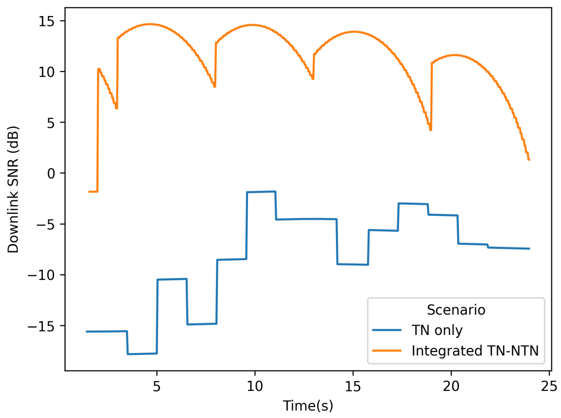

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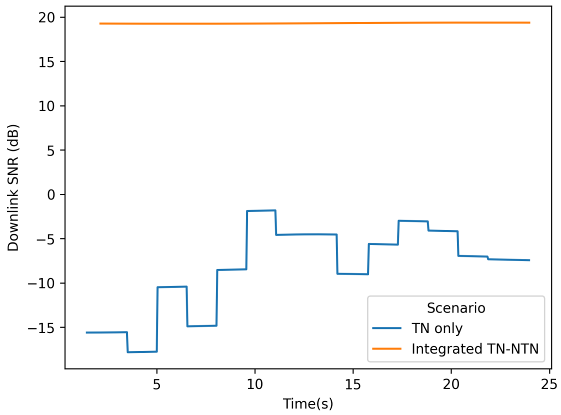

(b) Integrated TN-NTN with HAP

Fig. 7: comparison of measured SNR vs simulation time at an individual vehicle at a distance of around 2000m from the terrestrial gNodeB.

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