# NR-NTN-SIM: Bridging 5G NR Access and Dynamic LEO Topology in Full-Stack NTN Simulation

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***Abstract*—Evaluating 5G New Radio over Non-Terrestrial Networks remains challenging because NR access, time-varying LEO topology, and end-to-end networking are typically studied with separate tools. Available 5G-LENA NTN configurations also use an isotropic user-equipment antenna model suited to handheld terminals rather than directional VSAT-class access. We present NR-NTN-SIM, an open-source co-simulation framework integrating ns-3.46, 5G-LENA v4.2, and Hypatia to jointly model 3GPP-compliant NR access, full-stack IP/EPC networking, and dynamic LEO topology. The framework corrects the UE antenna configuration and a silent EPC routing pitfall that can bypass the NR air interface, while precomputed Hypatia forwarding states are applied by ns-3 every 100 ms. Over the Paris–Madrid and Paris–New York corridors, mean downlink throughput differs from static-backhaul references by only 1.5% and 0.1%, respectively, while topology changes produce substantially larger end-to-end delay variations. Multi-UE evaluation further shows aggregate-throughput mean values within 3.6 % of the single-UE baseline, with Jain's fairness index above 0.99. Released under Apache 2.0, NR-NTN-SIM provides a reproducible foundation for full-stack NR-NTN simulation.**

***Index Terms*—Non-Terrestrial Networks, 5G NR, LEO constellations, Hypatia, ns-3, inter-satellite links, 3GPP.**

## I. Introduction

Low-Earth-Orbit (LEO) satellite constellations are increasingly used to provide broadband connectivity, while 3GPP has progressively developed New Radio (NR) support for Non-Terrestrial Networks (NTN), from the initial study in TR 38.811 to subsequent NTN solutions [1], [2]. End-to-end NR-NTN evaluation remains challenging because it requires combining three typically separate capabilities: a 3GPP-based NR air interface, time-varying LEO topology, and a packet-level IP/Evolved Packet Core (EPC) stack. Existing ns-3 satellite studies abstract NR access or assume static satellite connectivity; link-level tools provide detailed radio modeling but limited end-to-end behavior; and Hypatia captures constellation dynamics without an NR radio-access stack.

A second challenge is configuring the NR access link for the intended NTN terminal class. Available 5G-LENA NTN configurations use an isotropic user-equipment (UE) antenna suited to handheld terminals, whereas broadband Very Small Aperture Terminal (VSAT) scenarios require directional gain. This alters the link budget and can constrain Modulation and Coding Scheme (MCS) selection. We also identify a silent EPC routing pitfall: using the default ns-3 UE IP instead of the EPC-assigned address can bypass the Packet Data Network Gateway (PGW) and NR air interface while still producing plausible FlowMonitor statistics.

This paper presents NR-NTN-SIM, an open-source framework integrating ns-3.46, 5G-LENA v4.2, and Hypatia for full-stack NR-NTN co-simulation. It combines a TR 38.821-based `CosineAntennaModel` with 38.7 dBi total array gain, corrected EPC routing, and a time-varying LEO backhaul. Hypatia computes forwarding states offline, while ns-3 remains the sole runtime clock and applies topology updates every 100 ms. Static and dynamic runs share the same NR/EPC configuration, isolating LEO routing effects.

In this paper, we make three contributions. First, we integrate ns-3.46 [3], 5G-LENA v4.2 [4], and Hypatia [5] under a single discrete-event clock for full-stack NR access and time-varying LEO topology. Second, we identify and correct an isotropic UE antenna assumption distorting the VSAT-class link budget and an EPC routing configuration bypassing the NR air interface [2], [4]. Third, we evaluate 100 ms Hypatia-derived topology updates over continental and transatlantic routes, including multi-UE operation, dynamic inter-satellite-link (ISL) route changes, and static-backhaul comparison. NR-NTN-SIM is released under Apache 2.0 and publicly available[1].

## II. Background and Related Work

### A. NR-NTN Standardization Context

3GPP NTN work progressed from the initial NR study in TR 38.811 [1] to the NTN solution study in TR 38.821 [2], while TS 38.300 [6] addresses NR/NG-RAN system and mobility aspects. Two payload architectures are defined: transpar-

[1] `https://github.com/jawharbenabed/NR-NTN-SIM-Framework`

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ent, where the satellite acts as a bent-pipe relay with the next-generation Node B (gNB) on the ground, and regenerative, where gNB functions are placed partly or fully onboard; the choice of architecture directly affects where routing and scheduling decisions can be made within the network. NR-NTN differs from terrestrial deployments in three main respects: one-way propagation delay is about 2 ms at 600 km and doubles at 1 200 km, motivating extended Hybrid Automatic Repeat reQuest (HARQ) timers and modified Random Access Channel (RACH) procedures [1], [2]; Doppler shift at orbital velocities near 7.5 km/s requires active compensation at Ka-band and reverses sign during a satellite pass; and handover intervals can be as short as six to eight minutes at 600 km, driven by the high angular velocity of LEO satellites relative to a fixed ground terminal. These characteristics combine radio adaptation, protocol timing, and topology evolution, motivating their joint evaluation within a common packet-level simulation framework.

Among the tools surveyed in Table I, none simultaneously spans the three domains required for NR-NTN evaluation: radio access, orbital dynamics, and end-to-end networking. Packet-level engines such as **ns-3** [3] and **OMNeT++/INET** [7] typically model satellites as static relays with generic propagation; ns-3.48's recently introduced `LeoCircularOrbitMobilityModel` adds LEO kinematics to the mainline but still lacks an NR stack, an NTN channel model, and ISL routing. **Hypatia** [5] provides high-fidelity Two-Line Element (TLE)-derived constellation topology and shortest-path ISL routing, but no radio layer, preventing standalone evaluation of NR performance. Conversely, radio-focused tools lack constellation-scale topology dynamics: **5G-LENA** [4] provides NR PHY/MAC operation and 3GPP NTN channel models but no time-varying multi-satellite topology or ISL routing; **ns3-NTN** [8] validates TR 38.811 channel behavior to within $\leq$0.5 dB of Friis but is Time Division Duplex (TDD)-only, whereas this work uses Frequency Division Duplex (FDD), and retains the isotropic antenna assumption; and **MATLAB 5G Toolbox** [9] resolves PHY-layer behavior but provides no Medium Access Control (MAC) scheduler or EPC. **STK** [10] models orbital geometry without a protocol stack, with no means of linking radio-link performance to the satellite geometry it computes. **OAI** [11] provides a full 5G RAN/core stack but no constellation-scale orbital topology or routing model, whereas **SNS-3** [12] models satellite networks, including LEO/GEO constellations and ISLs, but lacks a 5G NR PHY/MAC scheduler.

### B. Gap Analysis

Table I summarizes this fragmentation across capability dimensions: tools that model NR access accurately lack constellation dynamics, and tools that capture LEO topology realistically carry no NR air interface or packet-level network view. This separation also prevents controlled end-to-end studies in which radio and topology effects can be isolated under a common configuration. NR-NTN-SIM closes this gap by combining ns-3, 5G-LENA, and Hypatia within a single coordinated environment.

## III. NR-NTN-SIM Architecture

### A. Design Philosophy and Component Overview

NR-NTN-SIM follows three design principles. **Integration rather than reimplementation:** ns-3.46, 5G-LENA v4.2[2], and Hypatia provide established implementations for packet-level networking, NR radio access, and LEO topology modeling, respectively [3]–[5]; the framework therefore focuses on integrating these components consistently rather than reproducing their functionality. **Simulation clock sovereignty:** independent clocks in a co-simulation can introduce ambiguous event ordering and synchronization errors. NR-NTN-SIM consequently designates the ns-3 discrete-event scheduler as the sole runtime time authority, with topology updates inserted into the same event queue as packet-level events. **Localized coupling:** Hypatia-specific runtime integration is confined to a small C++ adapter layer, primarily `HypatiaInit()` and `HypatiaUpdate()`, so changes to the topology engine or its data representation remain localized rather than propagating through the NR and application layers.

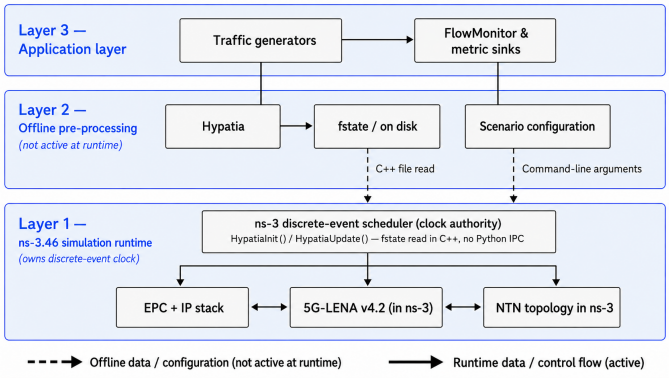



Fig. 1. NR-NTN-SIM three-layer co-simulation architecture.

Fig. 1 illustrates the resulting three-layer architecture. Layer 1 comprises the ns-3.46 runtime together with the compiled 5G-LENA v4.2 module. It owns the discrete-event clock and hosts the IP/EPC stack, NR access network, satellite and gateway nodes, and point-to-point backhaul links. During dynamic runs, the propagation delay and activation state of these backhaul links are updated every 100 ms through `HypatiaUpdate()`. Layer 2 performs the offline topology processing and generates the time-indexed forwarding-state sequence consumed during the ns-3 run. Layer 3 comprises the experiment-level traffic applications, measurement hooks, and metric collection instantiated within ns-3.

5G-LENA v4.2 provides the NR air interface, including PHY and MAC processing, link adaptation, scheduling, and NTN-specific channel modeling. Scenario parameters such as orbital altitude, carrier frequency, numerology, bandwidth, and

[2]5G-LENA v4.2 is officially validated against ns-3.47; NR-NTN-SIM was developed and evaluated using ns-3.46, for which no incompatibility was observed in the features exercised in this work.

TABLE I
COMPARISON OF NTN SIMULATION TOOLS ACROSS CAPABILITY DIMENSIONS RELEVANT TO FULL-STACK NR-NTN EVALUATION. ✓ DENOTES NATIVE SUPPORT, ● PARTIAL OR LIMITED SUPPORT, AND ✗ NO SUPPORT.

| Tool | NR PHY/MAC (Rel-17+) | 3GPP NTN channel | FDD Ka-band support | Multi-sat time-varying topology | ISL routing (Hypatia-class) | Full EPC / IP stack | Open source & reproducible | End-to-end multi-UE |
|---|---|---|---|---|---|---|---|---|
| ns-3 mainline (3.48) | ✗ | ✗ | n/a | ●[a] | ✗ | ✓ | ✓ | ✓ |
| 5G-LENA v4.2 | ✓ | ✓ | ✓ | ✗ | ✗ | ✓ | ✓ | ✓ |
| ns3-NTN | ✓ | ✓ | ●[b] | ✗ | ✗ | ✓ | ✓ | ● |
| MATLAB 5G Toolbox | ●[c] | ✓ | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ |
| STK / Ansys | ✗ | ✗ | n/a | ✓ | ● | ✗ | ✗ | ✗ |
| OpenAirInterface | ✓ | ● | ✓ | ✗ | ✗ | ✓ | ✓ | ● |
| SNS-3 | ✗ | ● | ● | ● | ✗ | ✓ | ✓ | ✓ |
| Hypatia | ✗ | ✗ | n/a | ✓ | ✓ | ●[d] | ✓ | ✗ |
| OMNeT++/INET | ✗ | ✗ | n/a | ● | ● | ✓ | ✓ | ✓ |
| **NR-NTN-SIM (this work)** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

[a] ns-3.48 introduces `LeoCircularOrbitMobilityModel` for LEO orbital kinematics; no NR stack, NTN channel model, or ISL routing is included, leaving the gap addressed by NR-NTN-SIM open in the ns-3 mainline.
[b] ns3-NTN is natively TDD-based; the corresponding ns-3 workshop study [8] explicitly restricts evaluation to DL-only to remove dependency on the duplexing implementation.
[c] MATLAB 5G Toolbox provides validated PHY-layer blocks but no MAC scheduler, HARQ stack, or packet-level network model.
[d] Hypatia uses ns-3 point-to-point links and a custom shortest-path manager; it does not include LTE/NR EPC procedures.

transmit power are configured at launch, while 5G-LENA governs the UE-to-satellite access link and its resulting radio-layer behavior. Hypatia, in contrast, acts as the topology engine: before the ns-3 simulation begins, it produces the time-indexed topology and forwarding information required to reproduce the evolving LEO backhaul.

### *B. Identification and Correction of a Silent EPC Routing Error*

A non-obvious EPC routing pitfall can silently corrupt radio-layer measurements in 5G-LENA NTN simulations. When the traffic generator addresses the default ns-3 UE IP address rather than the EPC-assigned address, downlink packets can bypass the Packet Data Network Gateway (PGW) and the NR air interface entirely. The NR scheduler is then never consulted, throughput becomes insensitive to radio conditions, and FlowMonitor can nevertheless report plausible packet-delivery statistics. This failure mode is not flagged by 5G-LENA v4.2 and is not addressed in its NTN tutorial scripts.

NR-NTN-SIM corrects this configuration by binding the traffic generator to the EPC-assigned UE address and installing the corresponding static PGW route toward the UE subnet, following the CTTC reference implementation [4] (Fig. 2). The access link uses a 3GPP NTN Ka-band configuration with 19.7/29.5 GHz DL/UL carriers, 400 MHz per direction, and 120 kHz subcarrier spacing ($\mu = 3$), under the 3GPP NTN dense-urban line-of-sight channel model [1]. The experiments reported in this paper use a fixed-nadir access geometry and therefore isolate steady-state radio behavior.

### *C. Hypatia Topology Ingestion*

The constellation model summarized in Table II is used as a controlled ISL-scaling topology rather than as a reproduction of a specific operator deployment. The Hypatia preprocessing stage selects the relevant 66-satellite subset for the Paris–Madrid and Paris–New York corridors and generates one

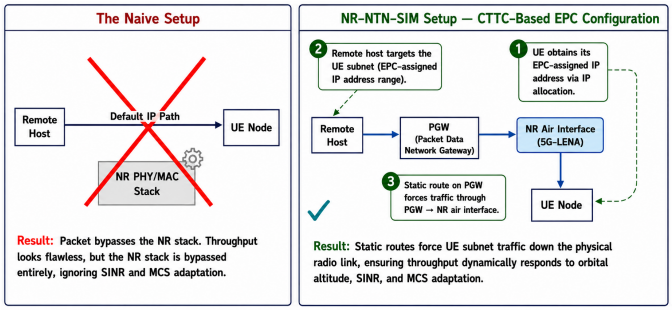



Fig. 2. EPC routing in NR-NTN-SIM. Naive configuration (left): packets bypass the NR stack when addressed to the default ns-3 UE IP. Corrected configuration (right): EPC-assigned UE addressing routes packets through the PGW and NR air interface.

forwarding-state (*fstate*) snapshot every 100 ms. Each snapshot provides the time-indexed forwarding information required to determine the selected next hop and to update the corresponding link state and propagation delay.

At runtime, these precomputed states are consumed by two C++ functions embedded directly in the ns-3 executable. `HypatiaInit()` loads the $t = 0$ topology and establishes a deterministic mapping between Hypatia node indices and concrete ns-3 point-to-point links, ensuring that subsequent *fstate* entries refer to the correct simulated links. `HypatiaUpdate()` is then scheduled every 100 ms through the ns-3 discrete-event scheduler and updates the affected link delays and activation states in place. No Python inter-process communication is required during simulation; topology evolution therefore enters the same ns-3 event queue as packet-level activity rather than being applied asynchronously by an external process.

The static and dynamic experiments use the same NR access and EPC configuration. In the static-backhaul reference, point-to-point backhaul delays and activation states remain fixed throughout the entire run. In the dynamic configuration, these

fixed values are replaced by the 100 ms updates derived from the precomputed Hypatia *fstate* sequence. This isolates the effect of LEO topology evolution while keeping the NR access stack fully unchanged.

## IV. Downlink Load Calibration

Before presenting the dynamic co-simulation results, we define how the downlink offered load $\lambda_{\mathrm{DL}}$ is selected for each operating configuration. A fixed load is unsuitable because achievable NR throughput depends on the radio conditions: excessive offered load introduces queue buildup, whereas insufficient load makes throughput traffic-limited rather than radio-limited.

*Why analytical estimation is insufficient:* A Shannon-based approximation, $\lambda_{\mathrm{DL}} = B\log_2(1+\mathrm{SINR}) \times 0.90/P_{\mathrm{size}}$, does not directly translate into an NR offered load. First, the scheduler maps SINR to one of 28 discrete MCS levels [13], with non-zero control-channel and reference-signal (PDCCH/DMRS) overhead [14] and NTN-extended HARQ operation [2], producing a throughput staircase rather than the smooth Shannon curve. Second, the SINR reported by 5G-LENA's `DlDataSinr` callback differs from the quantity used internally by `NrAmc` for MCS selection [4], preventing reliable capacity inference directly from the logged value. Third, `DlCqiReport` does not fire in FDD mode in 5G-LENA v4.2 [4], removing the standard Channel Quality Indicator (CQI)-based estimation path. NR-NTN-SIM therefore calibrates the offered load empirically from the delivered packet rate.

The following procedure is applied to the NR access configuration used in the dynamic co-simulation experiments.

*Calibration procedure:* NR-NTN-SIM uses an empirical three-step procedure for each operating configuration.

**Step (i) — Probe run:** A 60 s simulation runs with a deliberately saturating load:

$$\lambda_{\mathrm{probe}} = 200{,}000 \text{ pkt/s} \approx 2.05 \text{ Gbps} \qquad (P_{\mathrm{size}} = 1{,}280 \text{ bytes}) \tag{1}$$

FlowMonitor records the end-to-end Packet Delivery Ratio (PDR):

$$\mathrm{PDR}_{\mathrm{probe}} = \left.\frac{N_{\mathrm{rx}}}{N_{\mathrm{tx}}}\right|_{60\,\mathrm{s}}. \tag{2}$$

The corresponding delivered packet rate provides an empirical capacity estimate:

$$C_{\mathrm{real}} = \lambda_{\mathrm{probe}} \times \mathrm{PDR}_{\mathrm{probe}}. \tag{3}$$

**Step (ii) — Target load:** The offered load is then set to:

$$\lambda_{\mathrm{DL}} = \lambda_{\mathrm{probe}} \times \mathrm{PDR}_{\mathrm{probe}} \times \rho, \tag{4}$$

with target utilization $\rho = 0.90$, leaving headroom below the empirical saturation estimate.

**Step (iii) — Validation:** A second 60 s run at $\lambda_{\mathrm{DL}}$ checks the achieved PDR against the target window $[0.90, 0.99]$. Values within the window are retained; $\mathrm{PDR}_{\mathrm{val}} > 0.99$ triggers an increase in offered load ($\lambda \leftarrow \lambda \times 1.15$), whereas $\mathrm{PDR}_{\mathrm{val}} < 0.90$ triggers a reduction ($\lambda \leftarrow \lambda \times 0.85$), followed by another run. These multiplicative corrections move the operating point toward the target window. The interval $[0.90, 0.99]$ is used as a calibration target rather than a hard acceptance criterion. Because of discrete MCS transitions and the finite correction step, the resulting PDR may remain outside this interval and is reported as an observed outcome rather than forced to a prescribed value.

TABLE II
Simulation parameters and 3GPP-compliant configuration. Radio-access parameters follow TR 38.821, Section 6, unless otherwise stated.

| Parameter | Configuration |
|---|---|
| **Radio access (3GPP conformance)** | |
| Duplex, carrier freq. / bandwidth | FDD; DL 19.7 GHz, UL 29.5 GHz (Ka-band); 400 MHz/direction, 120 kHz ($\mu = 3$)[a] |
| UE antenna | `CosineAntennaModel`, 26.7 dBi element gain; 4×4 array, 38.7 dBi total array gain[b] |
| UE TX power / noise figure | 43 dBm / 7 dB |
| gNB TX power / noise figure | 55 dBm / 2 dB |
| HARQ / Block Error Rate (BLER) | 3.0 dB HARQ margin; 10% BLER target[c] |
| Channel / access geometry | 3GPP NTN dense-urban LOS[d]; fixed-nadir access geometry |
| **Constellation and topology** | |
| Constellation / altitude / inclination | Controlled Walker Star topology (66-satellite subset); 1 200 km / 87.9° |
| Hypatia topology-update interval | 100 ms (TLE-derived *fstate* sequence) |
| **Traffic and simulation setup** | |
| DL offered load $\lambda_{\mathrm{DL}}$ | $\rho = 0.90\, C_{\mathrm{real}}$, calibrated as described in Section IV |
| Topology-probe load | 10 000 pkt/s (Scenario 1) |
| UEs / scheduler | $N_{\mathrm{UE}} \in \{1, 2, 4, 8\}$ / Proportional Fair (Scenario 1) |
| Simulation duration | 30 s (Scenario 1); 400 s (Scenario 2) |
| Independent seeds | Five for the Scenario 1 multi-UE evaluation |
| EPC configuration | Static PGW–UE route, CTTC NR stack[e] |

[a] TS 38.211. [b] TR 38.821, Table 6.3-1. [c] TS 38.214, Sec. 5.2.2. [d] TR 38.811, Sec. 6.6. [e] CTTC `cttc-nr-demo`.

## V. Simulation and Performance Evaluation

Table II summarizes the simulation parameters and their 3GPP references. NR-NTN-SIM is evaluated over the Paris–Madrid and Paris–New York corridors, exercising the full NR stack under Hypatia-driven dynamic LEO topology from continental to transatlantic scale.

To distinguish errors in *fstate* ingestion from genuine topology changes, we first examine the Hypatia-driven delay evolution under a light traffic load before evaluating the complete NR traffic configuration. Scenario 1 considers the Paris–Madrid corridor, including a multi-UE evaluation, while Scenario 2 extends the same framework to the Paris–New York transatlantic route.

*1) Scenario 1: Paris–Madrid Full-Stack NR Co-simulation:* A 30 s light-load probe ($\lambda = 10{,}000$ pkt/s) first checks the *fstate* ingestion pipeline over the Paris–Madrid corridor at 1 200 km. At $t = 7.6$ s, corresponding to a 100 ms topology-

update boundary, the selected forwarding state changes, reducing the end-to-end propagation delay from 22.4 to 8.0 ms (−64 %). With a per-ground-space-link delay of $d_{\mathrm{GSL}} = 4.00$ ms and

$$d_{\mathrm{E2E}} = 2d_{\mathrm{GSL}} + d_{\mathrm{ISL}}, \tag{5}$$

the initial route contains approximately 14.4 ms of ISL propagation delay, whereas the updated route contains no ISL hop ($d_{\mathrm{ISL}} \approx 0$). The corresponding static point-to-point reference exhibits no delay transition, indicating that the observed change originates from the Hypatia-driven topology rather than from the NR access link.

With the full NR stack active for a single UE, the mean downlink throughput over the 30 s run is 1 343.8 Mbps, compared with 1 364 Mbps for the corresponding static-backhaul reference, a difference of 1.5 %. The topology transition remains visible in the delay trace but produces no measurable discontinuity in downlink throughput.

Scenario 1 then evaluates $N_{\mathrm{UE}} \in \{1, 2, 4, 8\}$ simultaneous UEs under Proportional-Fair scheduling at $h = 1\,200$ km and $P_{\mathrm{gNB}} = 55$ dBm. For each configuration, the total offered load is fixed at $\rho = 0.90\, C_{\mathrm{real}}$ and divided equally among the UEs,

$$\lambda_{\mathrm{DL}}^{(k)} = \frac{\lambda_{\mathrm{DL}}}{N_{\mathrm{UE}}}, \tag{6}$$

following Section IV. Results are collected over five independent seeds. The $N_{\mathrm{UE}} = 1$ value reported in Table III is therefore a five-seed mean and differs slightly from the individual 30 s run reported above.

TABLE III
SCENARIO 1 MULTI-UE RESULTS FOR PARIS–MADRID. AGGREGATE DL THROUGHPUT IS REPORTED AS MEAN ± 95 % CONFIDENCE INTERVAL OVER FIVE INDEPENDENT SEEDS (STUDENT'S $t$, df = 4). PER-UE THROUGHPUT DENOTES THE AGGREGATE THROUGHPUT NORMALIZED BY $N_{\mathrm{UE}}$, AND $\mathcal{J}$ DENOTES JAIN'S FAIRNESS INDEX.

| $N_{\mathrm{UE}}$ | Aggregate DL (Mbps) | Per-UE DL (Mbps) | $\mathcal{J}$ | PDR | Δ vs. $N_{\mathrm{UE}}$=1 |
|---|---|---|---|---|---|
| 1 | 1317.5 ± 191.4 | 1317.5 | 1.0000 | 0.830 | ref. |
| 2 | 1351.0 ± 143.4 | 675.5 | 0.9979 | 0.852 | +2.5 % |
| 4 | 1364.5 ± 47.0 | 341.1 | 0.9942 | 0.860 | +3.6 % |
| 8 | 1345.8 ± 47.1 | 168.2 | 0.9926 | 0.848 | +2.1 % |

Table III and Fig. 3 show three main trends. First, mean aggregate downlink throughput remains between 1 317.5 and 1 364.5 Mbps across the UE-count sweep, a maximum variation of 3.6 % relative to the $N_{\mathrm{UE}} = 1$ baseline, with overlapping confidence intervals. Normalized per-UE throughput approximately follows the expected $1/N_{\mathrm{UE}}$ scaling, reaching 675.5, 341.1, and 168.2 Mbps for $N_{\mathrm{UE}} = 2$, 4, and 8, respectively. Jain's fairness index remains above 0.99, indicating equitable Proportional-Fair allocation.

Second, the 95 % confidence interval of the aggregate throughput decreases from ±191.4 Mbps for one UE to approximately ±47 Mbps for four and eight UEs, indicating lower aggregate-throughput variability for the larger UE counts. The PDR remains between 0.830 and 0.860 across the sweep.

Third, the topology transition at $t = 7.6$ s affects all UEs simultaneously, reducing the end-to-end propagation delay

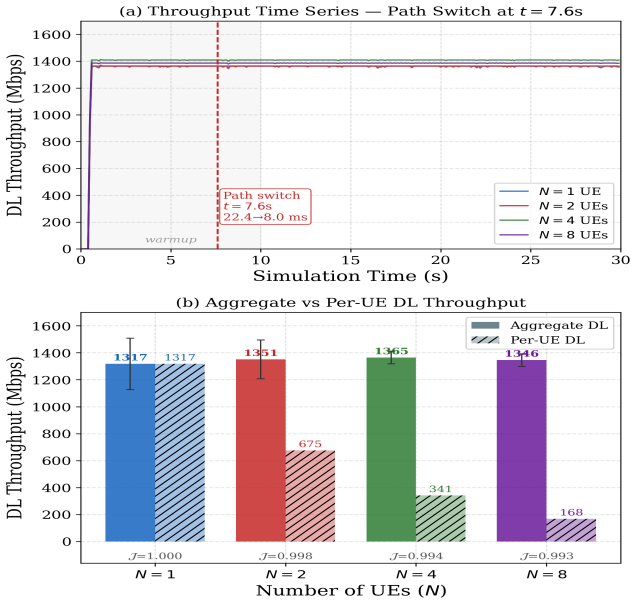



Fig. 3. Multi-UE evaluation for $N_{\mathrm{UE}} \in \{1, 2, 4, 8\}$ over 30 s. (a) DL throughput time series; the dashed line marks the topology transition observed at $t = 7.6$ s. (b) Aggregate mean DL throughput with 95 % confidence intervals, normalized per-UE throughput, and Jain's fairness index $\mathcal{J}$.

from 22.4 to 8.0 ms without an observed persistent per-UE asymmetry or throughput discontinuity. In this experiment, Hypatia-driven topology evolution therefore manifests primarily through end-to-end latency, while the measured downlink throughput remains stable.

*2) Scenario 2: Paris – New York Full-Stack NR Co-simulation:* Scenario 2 extends the same full-stack configuration to transatlantic scale and tests whether the limited throughput sensitivity observed over Paris–Madrid persists over a longer dynamic route. Rather than simulating from the start of the orbital cycle, the 400 s observation window is time-shifted to begin shortly before the first route change of interest, which occurs at $t = 167.8$ s on the local simulation axis. This transformation changes only the time origin: the *fstate* sequence remains that generated by Hypatia for the corresponding absolute TLE instants, preserving the satellite geometry and ISL delays for the selected epoch.

TABLE IV
SCENARIO 2 ISL PATH-SWITCH PROFILE FOR PARIS–NEW YORK ($h = 1{,}200$ KM, $P_{\mathrm{gNB}} = 55$ DBM, 400 S OBSERVATION WINDOW). THE DELAY FOLLOWS $d_{\mathrm{E2E}} = 2d_{\mathrm{GSL}} + d_{\mathrm{ISL}}$ UNDER THE FIXED-NADIR GSL MODEL.

| $t$ (s) | ISL hops | $d_{\mathrm{ISL}}$ (ms) | $d_{\mathrm{E2E}}$ (ms) | $\Delta d_{\mathrm{E2E}}$ | Event |
|---|---|---|---|---|---|
| 0.0 | 5 | 12.02 | 20.02 | — | Initial route |
| 167.8 | 6 | 14.42 | 22.43 | +12 % | Path lengthening |
| 288.1 | 5 | 12.02 | 20.02 | −11 % | Route restored |
| **396.2** | **1** | **2.40** | **10.40** | **−48 %** | **Shortest observed route** |

*Mean DL throughput over 400 s: 1 362 Mbps; overall PDR: 0.848.*

The simulation captures three topology-driven route changes (Table IV). At $t = 167.8$ s, the route changes from five to six ISL hops, increasing $d_{\mathrm{E2E}}$ from 20.0 to 22.4 ms (+12 %). The five-hop route is restored at $t = 288.1$ s, reducing the

delay by 11 %. The largest change occurs at $t = 396.2$ s, when the forwarding state selects a route containing a single ISL between the satellites serving the two ground stations, reducing the end-to-end propagation delay to 10.4 ms ($-48$ %).

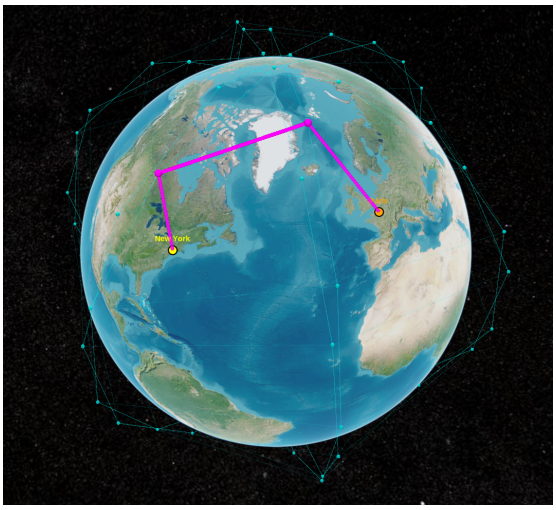


Fig. 4. Paris – New York topology at $t = 396.2$ s. The highlighted ground-space links and single selected ISL form the shortest route observed during the 400 s window, with $d_{\mathrm{E2E}} = 10.4$ ms compared with 20.0 ms for the initial five-hop ISL path.

Fig. 4 illustrates the shortest observed route. At high latitudes, the Walker Star geometry yields a selected path in which the two serving satellites are connected by a single ISL. End-to-end propagation delay remains between 20.0 and 22.4 ms across the first three routing phases and falls to 10.4 ms during the final phase.

Mean downlink throughput over the 400 s window is 1 362 Mbps, versus 1 364 Mbps for the static-backhaul reference, a difference of 0.1 %. The overall PDR is 0.848. Although this value lies below the nominal calibration target, the mean throughput remains essentially unchanged relative to the static-backhaul reference, indicating that the observed topology changes predominantly affect end-to-end latency rather than mean NR access throughput in this configuration.

Together, scenarios 1 and 2 show that NR-NTN-SIM preserves Hypatia-driven topology evolution while the complete NR stack remains active. Selected route changes produce substantial end-to-end propagation delay variations, whereas mean downlink throughput differs from the corresponding static-backhaul references by only 1.5 % for Paris–Madrid and 0.1 % for Paris–New York. This jointly exercises 3GPP-compliant NR access and time-varying LEO topology, which remain separated in the tools surveyed in Section II.

## VI. Conclusion and Future Work

This paper presented NR-NTN-SIM, an open-source framework integrating ns-3.46, 5G-LENA v4.2, and Hypatia under a single discrete-event clock for full-stack NR access and time-varying LEO topology. The framework addresses two NR-NTN configuration pitfalls: an isotropic UE antenna assumption that distorts the VSAT-class link budget and an EPC routing configuration that can bypass the NR air interface. Hypatia forwarding states are applied in ns-3 through 100 ms topology updates. Across the Paris – Madrid and Paris – New York corridors, mean downlink throughput differs from static-backhaul references by 1.5 % and 0.1 %, respectively, despite topology-driven delay variations. The Paris – Madrid multi-UE experiment yields aggregate throughput within 3.6 % of the single-UE baseline for $N_{\mathrm{UE}} \in \{1, 2, 4, 8\}$, with Jain's fairness index above 0.99. Under the fixed-nadir configuration, LEO route evolution primarily affects end-to-end latency while NR access throughput remains comparatively stable.

Future work includes elevation-dependent access dynamics, satellite and inter-satellite handover, regenerative payloads, heterogeneous traffic and QoS-aware scheduling, transport-layer behavior under abrupt route changes, and larger-scale runtime and memory characterization. Released under Apache 2.0, NR-NTN-SIM provides a reproducible foundation for full-stack NR-NTN studies.

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