MOSAIC : Piecing Together 5G and LEOs for NTN Integration Experimentation

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ABSTRACT

Despite the rapid growth of 5G technologies, geographical network coverage remains a significant challenge. The impending decommissioning of legacy technologies such as 2/3G will compound this further. In certain areas - notably rural - it is anticipated that removing these technologies will result in a complete lack of service. To address this, standards bodies, such as 3GPP, have begun advancing toward 5G-and-beyond architectures incorporating Non-Terrestrial Networks (NTNs), most notably using Low-Earth Orbit (LEO) satellite constellations. These NTNs offer promising solutions to expand coverage and improve network resilience. However, these also introduce integration challenges due to satellite mobility, network characteristics, and deployment costs. To address these operational challenges, and to understand the impact of integrated 5G-NTN architectures on end-to-end performance, we propose MOSAIC (MObile-SAtellite Integration Cradle) , a novel end-to-end 5G-NTN integration emulation platform that can recreate the unique features and software of emerging mobile infrastructures. We model the NTN network characteristics using a Generalized Additive Model for Location, Scale, and Shape (GAMLSS), evaluating it against open-source satellite link measurement data from Starlink. Additionally, we assess the performance of the Multipath TCP (MPTCP) protocol during handover scenarios between TN and NTN, focusing on metrics such as throughput stability, failover latency, and service continuity.

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1 INTRODUCTION

5G technologies have transformed mobile infrastructures from a telephony network into a programmable platform that supports a wide range of network services. The growing bandwidth demands influence the use of new access technologies, including millimetre-wave (mmWave) and massive MIMO to increase link speed, which negatively affects mobile coverage. 5G coverage remains a significant challenge, particularly in rural areas, considering that mobile networks cover only 20% of habitable areas [4]. In parallel, the forthcoming 2/3G decommission further compounds the problem.

To address these challenges, 3GPP explores the integration of NTN into the 5G ecosystem. NTNs can extend mobile network coverage to regions where terrestrial infrastructure is either unavailable, difficult to deploy, or economically impractical, such as rural, remote, or disaster-prone areas. NTNs can fill coverage gaps and provide truly ubiquitous connectivity using satellites, high-altitude platforms, and other spaceborne systems. Recent developments have moved beyond theoretical models, with real-world test deployments already underway as of 2025, showcasing practical feasibility and growing industry adoption [22].

5G NTN integration requires 5G architecture extension to improve resource utilization and guarantee user experience. For example, 3GPP proposes a series of RAN architectures (*e.g.* regenerative payload, O-RAN) [1] to improve spectral efficiency using on-board satellite compute resources for signal processing. Similarly, a primary 5G Core challenge is service continuity during handovers between access technologies. Dual/ fallback connectivity proposes that each User Equipment (UE) simultaneously connects to both a terrestrial (TN) and non-terrestrial networks using two parallel sessions, thus enabling resiliency [2, 21]. During periods of reduced coverage from the TN, the UE can use the NTN link to maintain connectivity. To manage multi-homing on the UE across the two connections, MPTCP establishes backup subflows to maintain connectivity during handovers [24].

To support the mobile community in designing an integration architecture, we need a flexible, realistic and scalable experimentation platform to test NTN scenarios and evaluate end-to-end performance. These tools are essential for practitioners and network operators to assess the trade-offs between end-to-end performance, costs, and operational capabilities, and in doing so, they guide the development of future mobile and NTN technologies.

Efforts to develop satellite emulation platforms for 5G integration remain relatively limited. Existing solutions, such as StarryNet [11] and the framework presented by [17], primarily focus on modelling satellite constellation dynamics but require substantial effort to incorporate 5G network functions. Consequently, they focus less on some of the link characteristics in their model, such as latency spikes during handover [16].

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Moving towards the goal of developing 5G TN/NTN platforms for measuring end-to-end performance that address these challenges, we present MOSAIC , an emulation platform that enables the testing and evaluation of 5G NTN integration in a controlled environment. MOSAIC automates the deployment of custom 5G network topologies, using off-the-shelf software components. In parallel, using open measurement from LEO satellites, we develop a link emulation model that captures the characteristics of the NTN link, including latency and packet loss. The contributions of this paper are the following:

- We present the design and implementation of MOSAIC , a novel emulation platform that enables testing and evaluation of end-to-end performance in 5G NTN integration scenarios in a controlled environment.
- We develop an open link emulation model that captures the characteristics of the NTN link, including latency and packet loss.
- We use MOSAIC to evaluate the performance of the MPTCP protocol and its congestion control (CC) algorithms in realistic TN-NTN handover scenarios and evaluate its impact on throughput and latency.

For the paper organization, we first discuss related research towards open network emulation platforms (§ 2) and elaborate on 5G experimentation limitations. Furthermore, we present MOSAIC design (§ 3), and evaluate the performance of the platform (§ 4). Finally, we conclude the paper and discuss future work (§ 5).

2 RELATED WORK

Initial attempts to develop NTN experimentation platforms were based on simulation, and include systems like ns-3-LEO [20], SCNE [10] and Hypatia [7]. The use of simulation, however, creates non-realtime execution times, while existing network applications had to be rewritten to support the simulation time.

StarryNet is one of the first attempts to emulate networking over large satellite constellations using container-based emulation. The platform uses analytical models to predict satellite mobility and translate them into link characteristics and topologies for emulation nodes. StarryNet offers an extended API, integration with hardware acceleration and pre-built models for production LEO constellations, nonetheless, the use of Docker limits the scalability of the platform. Xeoverse [6] improve the scalability of Starrynet, by optimising the require computations to predict satellite mobility, and precompute topology changes, and thus improve experimental execution time. Similarly, OpenSN [13] improves further experimental scalability by optimizing the integration of the emulator with the Docker service and improving state management. Celestial [18] offers a LEO emulator platform with support for edge cloud, by using resources onboard satellites.

It is worth highlighting that 5G service coverage is typically limited geographically to a single country, and thus satellite mobility patterns are simpler than a constellation offering global coverage. Furthermore, precise link emulation has a higher impact on experimental fidelity in such scenarios than constellation dynamics. In parallel, 5G function configuration in an emulation environment is not trivial and exhibits increased configuration complexity. Effective 5G-NTN emulation requires tools that simplify 5G configuration.

Commercial NTN broadband services, like Starlink, have motivated several measurement studies of NTN link characteristics. The LENS dataset [25] offers a large and open trace of long-term RTT and packet loss data from multiple Starlink terminals in several locations worldwide. The study of LENS has revealed that Starlink RTTs are highly variable, whilst Inter-Satellite Links (ISL) significantly impact RTT. In parallel, Mohan *et al.* [16] conduct a similar study using real network applications and highlight that control plane synchronisation processes create noticeable performance degradation to network applications at fixed intervals. Similarly, the WetLinks dataset [12] combines satellite network performance measurements with weather data, providing a unique perspective on how environmental factors affect LEO satellite connectivity. These datasets offer empirical foundations for validating and refining emulator models and have enhanced the realism of recent simulation and emulation platforms. By incorporating trace-based characteristics from LENS and WetLinks, systems, like MOSAIC , can better replicate real-world link behaviour, including latency and intermittent packet loss, leading to more accurate performance evaluations.

OpenAir Interface (OAI) is an open-source 5G gNodeB implementation, used extensively in research testbeds. OAI can be used in conjunction with hardware link emulators to inject NTN link impairments [8], while ESA has deployed OAI instances on LEO and GEO satellites to experiment with the impact of NTN links on 5G connectivity [23]. OAI offers high realism in emulating the RAN domain, but exhibits limitations since NTN integration is underdeveloped [15], and the real-time requirements of the core mean that it is demanding to run at scale. In parallel, precise NTN emulation using the OAI stack requires hardware acceleration to recreate the NTN link characteristics.

3 SYSTEM DESIGN

The integration of NTN technologies in the 5G ecosystem unlocks many parameters and architectural options that

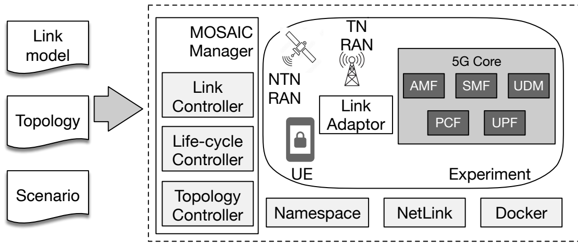

Figure 1: MOSAIC design.

can significantly enhance the performance and reliability of mobile networks. MOSAIC provides an integrated and automated emulation platform that allows researchers and network experimenters to recreate realistic 5G infrastructures with satellite connectivity and evaluate the end-to-end service performance. This section describes the design of the platform (§ 3.1) and presents the design of the satellite emulation mechanism (§ 3.2).

3.1 Emulation Platform

MOSAIC leverages containerization to virtualize network functions and efficiently build complex 5G topologies on a single host machine. This architecture enables scalable, modular experimentation without the overhead of deploying on physical infrastructure. A schematic overview of the system architecture is shown in Figure 1. Each MOSAIC experiment is defined by three key configuration files: the topology file, the NTN model parameter file (discussed in Section 3.2), and the evaluation scenario file.

The topology file extends the standard Docker Compose format to include experiment-specific details. It defines the layout and components of the 5G network, specifying which network functions (NFs) are deployed, how they are distributed across terrestrial and non-terrestrial segments, the number of UPFs, SMFs, and other core functions, and how they are interconnected across networks. This file acts as a blueprint for the experimental setup. The *Topology Controller*, processes this information and creates a virtual topology using Docker containers.

The evaluation scenario file, on the other hand, defines the logic for testing and monitoring within the emulated environment. It includes parameters and scripted actions for executing network tools (e.g., iperf, ping, or custom probes), collecting performance data, and orchestrating evaluation workflows. One of the strengths of MOSAIC is its ability to automate experiments beyond initial topology deployment—scenario actions can be composed into pipelines where the output of one task serves as the input for the next. Additionally, parallel action execution is supported, thus allowing realistic and complex testing scenarios, supporting efficient, repeatable experimentation workflows. The *Life-cycle Controller*coordinates the execution of an experimental scenario by executing actions within the namespace of each container instance.

The MOSAIC Manager coordinates the experiment. Written in GoLang, the manager contains a set of modules that can interface with the Docker daemon and the Linux network stack to deploy the topology and configure the network interfaces. This platform manages the full lifecycle of all major 5G components—including core network functions, gNodeBs, and User Equipment (UEs)—which are deployed as Docker containers. This containerized architecture allows for highly flexible and repeatable testbed configurations, making it well-suited for a wide range of experimental scenarios.

3.2 Satellite Link Modelling

One of the emulator's key strengths is its ability to accurately emulate real-world network conditions, particularly for hybrid TN and NTN networks. This is achieved by integrating satellite link characteristics sourced from the LENS dataset [25], a repository of Starlink RTT latency measurements from hosts in different locations. We rely on the Linux kernel network stack to replicate these characteristics in the emulated environment and use the netem queue in the traffic control subsystem to emulate latency, loss, and bandwidth characteristics. These tools allow us to model critical link properties, including latency, jitter, bandwidth constraints, and packet loss, providing a realistic and controlled networking environment across terrestrial and satellite paths. To apply these link characteristics, we embed a router in the experimental topology to connect the different network segments. The *Link Controller* manages the router network configuration using a netlink socket and adapts the queue configuration in real time, according to the link model.

The input values for the network emulation tools require upper and lower bounds for the latency, and values for the jitter and packet loss. This creates a modelling challenge distinct from the usual time series forecasting problem as we need to estimate the distribution of time series values at a given time – to obtain the quantiles – rather than a single expected value. To compound this problem there is a need to capture nonstationarity in the model parameters over time.

To address these issues, we propose a statistical modelling approach based on a Generalised Additive Model for Location, Scale, and Shape (GAMLSS) as this offers a convenient way to capture the nonstationarity and simultaneously estimate both point values and the distribution over time. A final issue is that the data are high frequency – recorded on the order of nanoseconds – however, we observe that the data are trend-stationary on some sufficiently fine-grained time period, for example, a per-minute basis. This can be identified in practice using the KPSS test [9], and we show this is true for a period of LENS data in our evaluation. We exploit this property in our model so that we do not need to fit the model for each recorded packet, as this would quickly become computationally impractical.

Let t index the trend stationary interval of time, for example, a minute, and let $1 \leq t \leq T$, where T is the time horizon. Suppose that n_t latency values are recorded during this interval, and let $y_{t,1}, \ldots, y_{t,n_t}$ denote these latencies. We assume that each is independent and identically distributed following the data-generating process $Y_t \sim N(\mu(t), \sigma(t))$. Note that the mean and variance are themselves nonstationary over the different time intervals.

To model this nonstationarity between the different time intervals t we use the GAMLSS model. Under this approach, the model for the latencies is given by:

$$Y_t = \mu(t) + \epsilon_t, \tag{1}$$

where $\epsilon_t \sim N(0, \sigma^2(t))$.

The nonstationary mean and variance are modelled using a B-spline expansion as follows:

$$\mu(t) = \sum_{k=1}^{K} \beta_k B_k(t)$$
$$\log(\sigma^2(t)) = \sum_{k=1}^{K} \gamma_k B_k(t).$$

Here K is the number of splines in the system, and $\{B_k(t)\}$ are the K columns of the spline system design matrix. Note the reason that the log-variance is smoothed rather than the variance directly is that this ensures that the estimated variance is positive. As described in Rigby and Stasinopoulos [19], this model can be estimated using a variant of penalised maximum likelihood estimation. Once the GAMLSS has been estimated for each trend stationary period it is possible to identify the NTN model parameters. We use the 2.5% and 97.5% quantiles of the $N(\mu(t), \sigma^2(t))$ distribution for the latencies bound, and the estimated variance for the jitter.

The last parameter in the model is the packet loss proportion, which we propose to incorporate into our model by modelling the loss proportion on each stationary interval. We denote this value as p_t and assume they are independent and identically distributed as a Beta distribution with parameters a and b; that is, $p_t \sim Beta(a, b)$. This can be estimated from the LENS data using maximum likelihood estimation.

As a final comment, we remark that the GAMLSS model in equation (1) can be fitted to the LENS round-trip time (RTT) data, giving a model for the RTT. The advantage of doing this is that, combined with the packet loss model, one can use the Mathis model to estimate the link's TCP throughput:

$$T = \frac{MSS}{RTT} \times \frac{C}{\sqrt{p}}. \tag{2}$$

Here MSS is the maximum segment size, C is a constant, and p denotes the packet loss.

3.3 Implementation

MOSAIC is implemented in Go. To manage network topologies, the code base offers strong integration with the Docker and NetLink API. For our experiments, we use the Fraunhofer FOKUS Open5GCore [3] platform, which supports all 5G Core, gNodeB, and UE functions, and MOSAIC supports integration with the UERANSIM UE and RAN emulator and the open Free5GC 5 G Core.

The codebase offers a series of sample 5G-NTN topologies. Our baseline topology features a dual-path setup in which the UE connects to the internet via two independent Data Networks (DN) served by a dedicated UPF: a ground DN (TN path) and a satellite DN (NTN path). Experimenters can use this dual connectivity scenario to evaluate approaches to improve connectivity resilience in 5G-NTN services. For example, the satellite DN acts as a fallback when the ground DN is unavailable – whether due to network failure or during transient events such as a handover procedure, where the UE may temporarily lose connectivity. Our sample topologies offer a custom UE container with out-of-box support for MPTCP connectivity (§ 4.2.

4 MOSAIC EVALUATION

MOSAIC provides an emulation platform for testing and evaluating 5G services using NTN technologies. In this section, we present the evaluation of MOSAIC , focusing on the accuracy of our link emulation model and evaluating the performance during handovers using different congestion control algorithms in the MultiPath TCP (MPTCP) protocol, a recommended approach to improve resilience.

The evaluation uses the topology presented in Figure 2. Our scenario assumes two gNodeBs (a terrestrial and a non-terrestrial operating on-board the satellite) each served by a dedicated User Plane Function (UPF) offering coverage for our test UE. The UE establishes two parallel PDU sessions and we apply a host configuration to enable MultiPath TCP (MPTCP) on the UE, using the terrestrial link for the primarily subflow, and the NTN link for a backup link. We use the Open5Gcore software stack [3] to emulate the 5G core, RAN and UE components. The 5G Core is configure with two Data Networks, each serving the TN and NTN links respectively. We also operate two gNodeB instance and configure the UE instance to establish a connection via both gNodeBs in parallel, using different Subscription Permanent Identifiers (SUPI). The link emulator applies a fixed latency between the terrestrial RAN and the Core of 10 msec, while the link between the NTN RAN and the Core is emulated using the model described in Section 3.2. We also operate

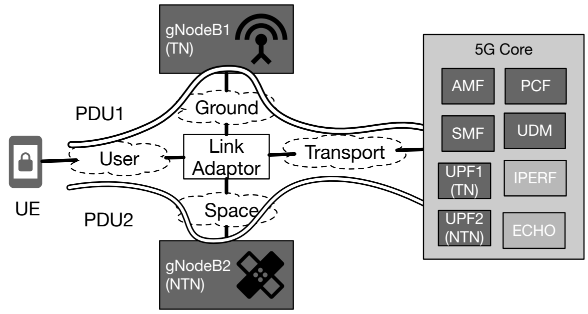

Figure 2: Experiment topology used for the evaluation of MOSAIC . The topology emulates a 5G network with two gNodes (TN and NTN) each served by a seperate UPF function.

an iperf3 server (IPERF) and an echo service (ECHO) in the core network to support transport layer measurements of bandwidth and latency.

4.1 NTN Emulation Accuracy

In this section we evaluate the proposed satellite link modelling methodology, measuring the accuracy of the parameter estimation procedure. For this evaluation we use data from the LENS dataset. Our dataset was recorded during May 2024 and contains information on latencies and loss for 360, 000 packets passing through dishes located in Belgium, Germany, and the Seychelles, and the Frankfurt point-of-presence.

Recall that in our data model we observe latencies $\{y_{t,i}\}_{i=1}^{n_t}$ that are realisations of the random variable $Y_t \sim N(\mu(t), \sigma^2(t))$. In these experiments we consider three different sizes of stationary period: one minute, fifteen seconds, and one second, and estimate the NTN model parameters from one day of LENS data. We record the Mean Absolute Percentage Error (MAPE) of each estimate in Table 1. We see that the model fit is generally between 5% and 10% for each parameter except the variance for the 1 second interval; this may be because it is difficult to smoothly model the high volatility of this time series given it changes so frequently, suggesting that our model should use at least 15 second intervals.

We also use the fitted models and KPSS test to identify whether the segments in question are trend stationary. We normalise each LENS time series using the parameter estimates from each fitted model and perform these tests on the residuals. We observe that there is no evidence at the 5% level that any of the segments have a trend after normalisation, highlighting how our GAMLSS model captures the time-varying trend.

Finally, again working with the three different sizes of stationary period, we split the nonzero proportions of packets lost into a 50:50 test-train set and fit a Beta distribution to the training data. Comparing our estimated distribution with

Parameter Error (%) Interval Size	$\mu(t)$	$\sigma^2(t)$	$q_{0.025}$	$q_{0.975}$
1 minute	4.6	6.1	7.6	3.9
15 seconds	7.0	13.1	8.9	7.0
1 second	5.8	20.7	8.9	4.8

Table 1: Table showing the mean absolute percentage error (MAPE) for the estimated parameters in the NTN model, the average latency (μ), the variance (σ^2), and the 0.025 and 0.975 quantiles $q_{0.05}$ and $q_{0.975}$.

the empirical distribution of non-zero packets lost in the test set using a KS-test we find that there is no evidence at the 5% level that the estimated distribution is different from the observed distribution.

Putting these results together, we have shown that for a range of different size time periods the NTN model parameters can be accurately inferred from a dataset of satellite latencies. This evaluation therefore provides confidence that our proposed modelling procedure is effective.

4.2 TN-NTN Handover Evaluation

5G-NTN integration stresses the ability of the architecture to detect and coordinate connectivity handovers between access technologies. 5G standards define several handover mechanisms (e.g., Xn, N2, or inter-RAT (Radio Access Technologies)), each offering different performance trade-offs, with respect to the network configuration and mobility patterns. Xn-based handovers provide the best performance by minimizing signaling overhead [5], but their application in 5G-NTN integration is limited since they require gNodeB cooperation, which can contradict the network providers' privacy policies in multi-administrative domains.

3GPP proposes multi-connectivity, *i.e.* the establishment of multiple connections for a single UE device, as a mechanism to delegate 5G-NTN handovers to the UE [14]. Each UE connects in parallel to both the TN (primary) and NTN (backup) access network and directs traffic to the connection with the best coverage at any given time. This approach can negatively influence connectivity, since the UE changes its IP address during vertical handovers, which in turn requires re-establishing existing TCP connections. The MPTCP protocol can improve session continuity [24] during handover events. To understand the impact of the MPTCP protocol, we conducted a series of experiments using an iperf3 (capped at 50 Mbps) and an echo service (50 msec interpacket gap).

During an experimental run, we configure the host and the measurement services (IPERF and ECHO) to establish two MPTCP subflows (TN - primary, NTN - backup) and run an iperf3 and a ping measurement for 70 seconds. We trigger a handover after 20 seconds of runtime, by stopping the TN gNodeB, thus simulating coverage loss from the TN RAN. To

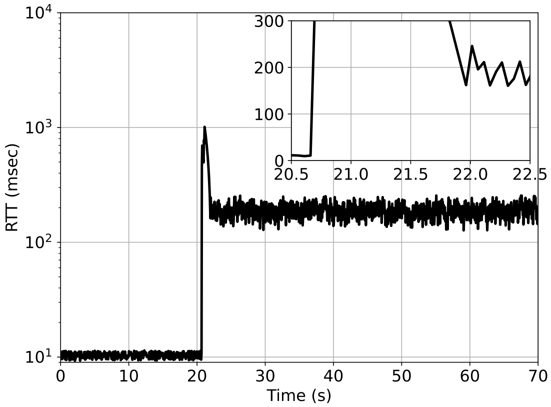

Figure 3: Link RTT estimation during an TN-NTN handover event using an echo service.

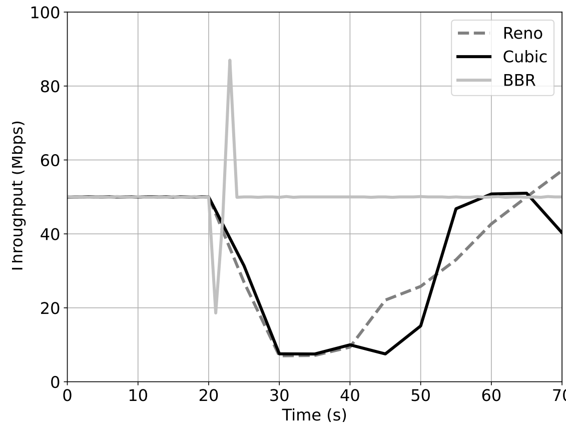

Figure 4: Link capacity estimation during an TN-NTN handover event with Reno, Cubic, and BBR CC.

further evaluate the impact of the MPTCP CC algorithm, we run the same experiment using three popular Linux implementations: Cubic, Reno, and BBR. Cubic and Reno represent the two most widely used congestion control algorithms, using loss-based congestion detection, while BBR is a more recent algorithm that uses RTT changes to detect congestion. Since the two paths do not share a congested links, TCP CC algorithms are sufficient to control the transmission rate.

Figures 3 illustrates the measured RTT over an MPTCP connection using the BBR CC algorithm (Reno and Cubic CC measurements exhibit similar behaviour). From the results, we note that the TCP connection maintains connectivity during handover; the RTT increases from 10 msec to approximately 1 seconds for a short period of time (1.3 seconds, based on the zoomed in view of the data). This latency inflation can be explained by the need for time-out timers to expire before attempting to transmit data over the backup subflow. The RTT stabilizes shortly after the handover event, and the connection RTT fluctuates between 100 and 280 msec.

Figure 4 presents a further bandwidth study using iperf3 average bandwidth reports (1-second interval). All three flows exhibit some level of performance degradation during handovers, but connectivity is maintained. We observe two distinct performance profiles. Cubic and Reno flows require approximately 30 seconds to adapt their Congestion and Receiver Window sizes to reflect the increased Bandwidth-Delay Product of the NTN link. In contrast, the BBR flow adapts faster, taking 5 seconds to adjust to the new network conditions. Our results highlight that MPTCP can be used to maintain connectivity during handover events. Still, the performance of the connection is highly dependent on the transport layer configuration, thus highlighting the importance of emulation-based experimentation with real applications.

5 CONCLUSION

Integrating 5G infrastructures with NTN technologies can significantly improve mobile service resilience and coverage. Nonetheless, active research on the topic proposes a range of 5G architectural extensions, which require a cross-layer evaluation to understand trade-offs. MOSAIC is a novel emulation platform for 5G NTN integration architecture evaluation. It automates experimental execution of 5G-NTN topologies, using off-the-shelf software. Furthermore, the platform uses a novel NTN link emulation service, that uses the Linux TC netem queue and the GAMLSS model to improve experimental accuracy. Based on statistical tests, the model generates a latency distribution similar to real latency and loss data from open NTN measurement data. Finally, we used MOSAIC to evaluate the performance of the MPTCP during TN-NTN handovers and identify a significant performance difference in bandwidth utilization when using different TCP CC algorithms, observing the estimated handover latency to be around 1.3 sec.

We believe that MOSAIC will be a valuable tool for researchers and experimenters in the field of 5G NTN integration. In future work, we plan to extend MOSAIC and integrate RAN emulation capabilities to improve fidelity in the Radio domain, using the OAI RAN software. In parallel, we will explore how MOSAIC can be used as a real-time validation for the configuration of 5G NTN networks, enabling automated orchestration services to validate configuration correctness before deployment, thus improving network resilience.

Upon acceptance of the paper, we will open-source MOSAIC to the community to improve further research and experimentation activities in this area.

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