Multi-RAT Dual Connectivity Using MPTCP: Bridging Emulation and Real-System Deployments

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***Abstract*—The integration of Non-Terrestrial Networks (NTN) with terrestrial 5G networks (TNs) presents unprecedented opportunities for achieving ubiquitous connectivity, particularly for data-intensive and latency-sensitive applications. However, effectively managing multiple network interfaces across heterogeneous terrestrial and non-terrestrial Radio Access Technologies (RATs) remains challenging. In this paper, a Multi-RAT Dual Connectivity enabler for SUNRISE-6G experimentation platform is proposed, that relies on MultiPath TCP (MPTCP) as a key enabler for ubiquitous connectivity over TN-NTN infrastructure. The approach encompasses two complementary experimental setups: a fully virtualized emulation environment and a hybrid setup combining physical devices with emulated NTN elements. Results demonstrate that while MPTCP successfully enables multi-connectivity across terrestrial and satellite networks, optimal performance requires careful consideration of path characteristics and protocol parameters.**

***Index Terms*—5G/6G, TN, NTN, Multi-RAT, MPTCP**

I. Introduction

The development of data-intensive and latency-sensitive applications (e.g., real-time streaming, cloud gaming, ultra-high-definition video transmission, and extended reality services) as well as the need for more resilient networks for mission-critical applications, has piled new requirements on existing communication networks. In addition, devices are increasingly (or expecting to be) equipped with multiple network interfaces, supporting both terrestrial 5G networks (TN), and Non-Terrestrial Networks (NTN). This multi-interface capability enables seamless integration between terrestrial and non-terrestrial networks, ensuring ubiquitous connectivity even in remote or challenging environments where traditional cellular coverage may be limited or unavailable. The convergence of these technologies, for which standardization of NTN integration in 5G networks is already in progress in 3rd Generation Partnership Project (3GPP), creates new possibilities for enhanced coverage, reliability, and service continuity across diverse geographical locations [1].

Naturally, traditional single-path communication architectures, which primarily rely on a single ingress/egress network interface, are becoming inadequate, and shall evolved toward multi-connectivity paradigms that can effectively and simultaneously leverage multiple network interfaces, both operating on homogeneous or heterogeneous Radio Access Technologies (RATs). This paradigm shift is essential to address the heterogeneity of today's networking landscape and to meet the diverse Quality of Service (QoS) requirements of upcoming applications.

Several established mechanisms have already been proposed to leverage such multi-connectivity capabilities. Access Traffic Steering, Switching, and Splitting (ATSSS), standardized by 3GPP, enables traffic distribution across multiple access networks, particularly in 5G scenarios combining cellular and non-cellular access. In addition, multi-homing mechanisms allow devices to maintain simultaneous connections to multiple networks, enhancing reliability and facilitating seamless failover. Additional technologies such as Multipath TCP (MPTCP) provides transport-layer solutions for managing multiple network paths. These mechanisms, individually or in combination, provide the foundation for robust multi-connectivity implementations in modern networks. In particular to MPTCP, it has emerged as a significant enhancement of the standard TCP protocol, facilitating simultaneous data transmission across several end-to-end (E2E) pathways. In doing so, MPTCP is capable of using several network interfaces to e.g. improve data transmissions, increase fault tolerance, and enable dynamic load balancing across all pathways [2].

The convergence of terrestrial and non-terrestrial networks, allied with MPTCP mechanisms, present an opportunity towards the realization of ubiquitous connectivity. NTNs enhance the spatial coverage of the network, whereas MPTCP provides protocol-level strategies for the smooth and adaptive aggregation and management of various pathways, both terrestrial and non-terrestrial [3] [4]. This is where this work aims to contribute by proposing a *Multi-RAT Dual Connectivity enabler using MPTCP* integrated into the SUNRISE-6G experimentation platform [5]. The proposed enabler leverages the flexibility and path management capabilities of MPTCP to establish and maintain simultaneous connections across heterogeneous Radio Access Technologies (RATs), namely 5G and NTNs. The enabler is implemented in two distinct flavors: a fully-emulated environment and a hybrid deployment combining real and emulated systems. This dual approach

also enables validation of the emulation environment against real-world implementations. Thus, the emulation framework can be confidently used for extensive experimentation across diverse scenarios while producing results that closely mirror real-world behaviors.

The remainder of this document is structured as follows: Section II provides a brief state-of-the-art overview, followed by the envisioned 6G enabler structure and its' stack specification in Section III. Section IV elaborates on two experimental setups as well as introduces the experiments chosen for enabler evaluation. The evaluation results are described and analyzed in Section V and general conclusions on the feasibility of the MPTCP and TN-NTN synergy are provided in Section VI.

II. Background and related work

The idea of integrating Terrestrial and Non-Terrestrial Networks as a multipath transport is not new, and the first technical integration and evaluation works date back to as far as 2018 [6]. As the technology developed, and standards began adopting the integrated TN-NTN direction into the upcoming 5G releases, many streams of academic research emerged, including use of custom architecture protocols for multi-rat, specific to TN-NTN [7], benchmarking standard transport protocols against non-emulated satellite and terrestrial links [8], and implementation. Several critical integration challenges persist, notably resource management, routing, mobility management, and security [9] [10]. On top of that, most of the aforementioned studies do not compare different NTN emulation strategies, do not consider the incorporation of broader number of technologies, crucial for 5G/6G solutions, and do not analyse the propagation of the benefits to the application layer. At the same time other approaches rely only on simulation-based evaluations which are valuable for early-stage assessments, nonetheless, they often fail in capturing the complexities of real-world deployments, such as hardware variability, integration issues, and runtime dynamics of a physical infrastructure.

To bridge this gap, this paper proposes a novel 6G-enabled architecture that integrates terrestrial networks with NTN components, also leveraging a realistic 6G testbed. Our methodology encompasses two complementary approaches: a fully softwarised emulation environment and a hybrid setup combining physical devices with emulated NTN elements. This dual approach allows us to capture both controlled scenarios and real-world complexities introduced by hardware and runtime dynamics. By evaluating multi-connectivity across these setups, we demonstrate how satellite-terrestrial convergence can deliver more resilient, flexible, and ubiquitous connectivity, advancing beyond the limitations of purely simulation-based studies.

III. Multi-RAT Dual-Connectivity Enabler

3GPP Release 17 introduced the support for satellite communication within 5G NR, enhancing terrestrial networks in underserved areas. This includes satellite-based backhaul communication for Customer Premises Equipments (CPEs) and direct links to smartphones for low-data-rate services, utilizing sub-7 GHz S-band. Additionally, the subsequent releases, such as Rel-18, are expanding the support to higher frequency bands (e.g., 10+ GHz). However, beyond enabling 5G NR support for satellites and utilizing transparent or regenerative satellite types, as well as dual connectivity at the physical layer, it is crucial to explore how the application layer can leverage this dual connectivity to enhance performance by utilizing both channels simultaneously. In this direction, and within the scope of the SUNRISE-6G project[1], an end-to-end (E2E) multi-radio access technology (RAT) dual connectivity enabler utilizing 5G and NTN technologies with the usage of the MPTCP protocol, is proposed. The Multi-RAT dual connectivity enabler is explored in two approaches, which mainly differ in how they integrate with the experimentation framework provided by the project. The first approach is tightly coupled with experiments managed through the project's adaptation framework and experimentation portal, enabling dynamic configuration and real-time performance monitoring. In contrast, the second approach is a standalone setup and is not coupled with any experiment through the adaptation framework and the portal of the project.

A. Multi-RAT (5G and Satellite) Dual-Connectivity Devices

In the SUNRISE-6G project, the initial scenario envisions Terrestrial Networks (TNs) and Non-Terrestrial Networks (NTNs) being developed, implemented, and operated as entirely separate networks, interconnected through ground stations that function as gateways [11]. This has been the preferred deployment model for more than two decades to provide satellite-based Internet, in which the satellite network relies on border gateways (also referred to as access gateways) to interconnect with the terrestrial networks [12]. Although the selected approach does not provide direct convergence between the satellite network and the 5G/6G ecosystem, it enables basic multi-RAT capabilities to be implemented at the IP layer (or higher). This is essential for collecting baseline performance metrics to better understand the impact of more advanced convergence approaches for TN-NTN integration, such as the direct integration of satellite components into the 5G core network) [13]. In doing so, the device is capable of communicating with both the satellite and 5G Terrestrial Network via its dedicated network interfaces (as depicted in Figure1), allowing for seamless integration and enhanced connectivity across two completely disjoint networks.

This dual connectivity approach ensures that the device can maintain robust communication links, even in challenging environments, by dynamically switching between satellite and terrestrial networks based on the selected scheduling algorithm (e.g., MPTCP).

B. MultiPath TCP Protocol

MPTCP plays a central role in enabling the effective use of the Multi-RAT dual connectivity framework discussed in this paper. MPTCP is a transport layer protocol (layer 4 of

[1]https://sunrise6g.eu/

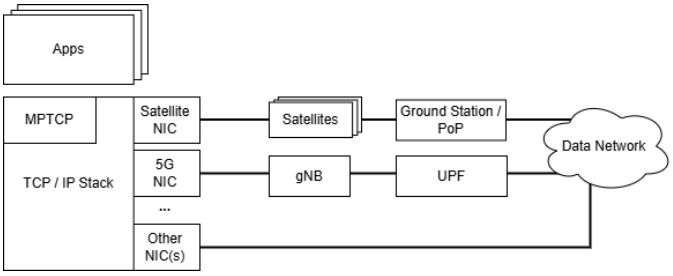

Fig. 1. Multi-RAT Dual Connectivity Device

the Internet stack) developed as an extension of traditional TCP, which supports only a single path per connection. In standard TCP, a connection is tied to a specific pair of IP addresses between communicating nodes. However, with the rise of multipath environments (such as, mobile devices with multiple wireless interfaces and data centers with redundant network paths), this limitation became increasingly problematic. MPTCP operates as an overlay on the existing IP infrastructure and maintains full compatibility with traditional TCP applications and networks. Each path, or subflow, is a standard TCP flow identified by a unique four-tuple (source and destination IP addresses and port numbers). MPTCP handles the setup and teardown of these subflows similarly to conventional TCP. Once subflows are established, MPTCP can transmit data over them concurrently. Its default scheduler selects the subflow with the lowest Round Trip Time (RTT), switching to others as needed based on congestion and availability. To ensure reliable, in-order delivery at the application layer, MPTCP assigns standard TCP sequence numbers to each subflow and uses an additional data sequence number to reconstruct the original data stream across all paths.

IV. Experimental Validation

A thorough evaluation of the performance implications and behavioral characteristics of various architectural integration approaches within the 5G/6G TN-NTN user plane is crucial for successful large-scale deployment and widespread adoption. The user plane, responsible for carrying actual user traffic and implementing critical functions such as data encryption, packet routing, and Quality of Service (QoS) enforcement, requires particular attention to ensure optimal network performance and reliability.

A. Evaluation Setups

To achieve robust validation and ensure results' reproducibility across different deployment scenarios, we established two parallel testing environments with complementary capabilities: *(i)* the first setup follows a fully emulation-based approach for both the 5G and NTN network components; and *(ii)* the second setup incorporates a real-system 5G network components (including physical Radio Access Network (RAN) elements, core network functions, and end-user devices) together with an emulated NTN.

This dual-environment approach serves multiple purposes: *(i)* enabling comprehensive cross-validation of results between real and emulated systems; *(ii)* providing insights into the accuracy and limitations of emulation-based testing; *(iii)* facilitating the identification of potential deployment challenges before production implementation; and *(iv)* allowing for the assessment of scalability and performance under various network conditions and loads. The correlation between results obtained from both environments helps establish confidence in the emulation platform's ability to predict real-world performance, thereby streamlining the transition from laboratory testing to actual network deployment while minimizing operational risks.

*1) **Fully-Emulated Setup**:* The fully-emulated setup is built upon three key components, as depicted in Figure 2: *(i)* COSNO Emulator [14], an emulation framework for NTN networks and devices; *(ii)* UERANSIM, an open-source tool for simulating RAN and UE interactions, *(iii)* Open5GS, an open source 5G core network implementation. Together, these components form an experimental setup for an E2E 5G/6G TN-NTN testing infrastructure. Their detailed role within the testing playground is as follows:

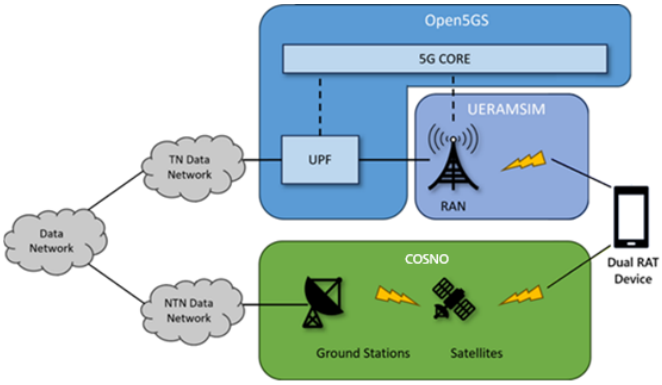

Fig. 2. Multi-RAT Dual Connectivity for TN-NTN with Emulated NTN and TN Segments

- **COSNO Emulator**: The COSNO Emulator is an orchestration and emulation framework designed to build distributed and dynamic NTN edge networks and computing systems, such as those involving satellites, ground stations, and devices. By doing so, this tool can serve as a one-stop shop for defining and instantiating NTN testbeds. The NTN segment is mostly emulated or simulated. It can be connected to a real networking segment (e.g., a private LAN or even the Internet itself) and/or to real industrial systems.
- **Open5GS**: Open5GS is an open-source, 3GPP-compliant 5G Core implementation that serves as the mobile core network, managing essential functionalities such as user authentication, session establishment and control, mobility management, and infrastructure monitoring. Although it provides an implementation of a wide range of 5G NFs, it still lacks the implementation of N3IWF and TNGF,

which are necessary to fully support interworking as a non-3GPP Access Network option.

- **UERANSIM**: UERANSIM is an open-source tool that mimics the behaviour of a 5G User Equipment (UE) and Radio Access Network (RAN) (i.e., gNB). Although it does not fully implement the physical layer, it emulates the 5G-New Radio (NR) interface over the UDP protocol and, consequently, it can model the physical and protocol layers (including the establishment of the user plane via GPRS Tunneling Protocol), as well as the signaling procedures between the UE, RAN and 5G Core (including authentication and key agreement procedures).

*2) **Real-System Setup**:* The hybrid system (real and emulated), highlighted within the red frame in Figure 3, is fundamentally built upon three key components: *(i)* Amarisoft, which provides the terrestrial network (both RAN and core); *(ii)* OpenSand, an emulator for the non-terrestrial (satellite) segment with configurable orbit parameters to simulate delay; and *(iii)* MPTCP block (client-server), deployed on modified OS kernel at both endpoints to enable traffic distribution across multiple paths. To assess network performance, the iperf utility is also used, with a client and a server placed at opposite ends of the system. MPTCP manages the splitting of traffic after the iperf client and reassembles it at the server, ensuring reliable transmission over both the TN and NTN links. This setup is also integrated with a custom orchestrator, which is responsible for forwarding the experimental results to the upper layer, specifically the project's central portal.

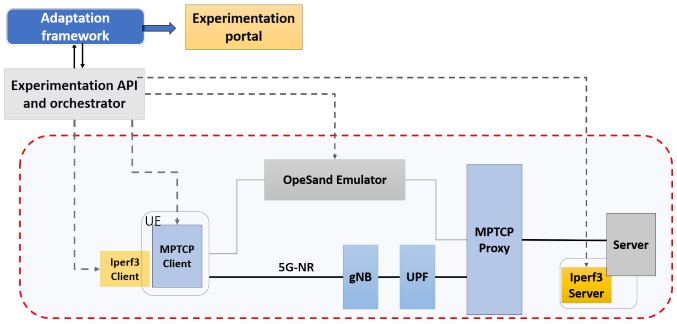

Fig. 3. Multi-RAT Dual Connectivity for TN-NTN with physical devices

- **OpenSAND**: The satellite link is implemented using the OpenSAND emulator, integrated into the Athens testbed. Its core components, namely the Satellite Terminal (ST), Satellite (SAT), and Gateway (GW), are each deployed as dedicated Virtual Machines (VMs) within an OpenNebula-managed cloud environment. These virtual machines are automatically launched and configured during the initialization phase of the experiment using dedicated automation scripts, which define the required IP addressing and interconnection logic.
- **5G Core and NR**: The TN part of the testbed is implemented using the Amarisoft Callbox, an all-in-one solution that integrates both NR and 5G Core functionalities. This configuration provides a complete end-to-end 5G environment within a single platform. The UE, equipped with a 5G Raspberry Pi Communication HAT connects to the Amarisoft RAN using a dedicated SIM card. The equipment used for the UE is the 5G communication HAT on top of a Raspberry Pi 4, which adopts the SIMCom 5G module SIM8200EA-M2, which supports 5G SA networking.
- **MPTCP** An MPTCP-enabled kernel was deployed to the Raspberry Pi 4 to enable simultaneous use of the multiple network interfaces. The custom MPTCP kernel was compiled and installed to replace the default Raspbian kernel, allowing the Raspberry Pi to establish and manage multiple TCP subflows across the two network paths. To enable MPTCP for the specific application, the tool mptcpize was used. This utility allows applications to utilise MPTCP instead of standard TCP by dynamically intercepting library calls and modifying socket creation to set the MPTCP protocol number, so in that sense, it enforced the topology running with MPTCP. Traffic is routed to the MPTCP proxy, which is hosted within the OpenNebula virtual infrastructure of the testbed.

B. Experiments

At the core of the system, the MPTCP software supports multipath communication and manages traffic routing across the different network paths, namely the TN and NTN. For network performance evaluation on the fully-emulated setup, the *ethr*[2] utility is used. The *ethr* client generates traffic on one end of the network. In contrast, on the other end, the *ethr* server receives the traffic and records core network performance metrics (throughput, latency, and jitter). To conduct the scoped network topology and implement a dual connectivity E2E experiment, traffic between the two *ethr* agents is steered over two paths. Baseline experiments on a single connectivity using legacy TCP (either over 5G or satellite) are also executed. These are depicted in Figure 4.

On the other hand, the real system setup was utilized to investigate the impact of various network configurations on end-to-end performance metrics by varying key parameters within the hybrid TN and NTN architecture. The evaluation centered on the Amarisoft 5G system, with particular focus on uplink throughput performance. To examine the interaction between terrestrial and NTN links, the traffic split ratio between the 5G uplink and satellite was dynamically adjusted across three representative scenarios: 5G-priority traffic, satellite-priority traffic, and equal utilization. The satellite segment included configurations for Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO) types to capture a range of link dynamics. Furthermore, multiple TCP window sizes were tested to assess their impact on throughput and delay.

V. Results and Analysis

This section presents the initial performance evaluation of the proposed Multi-RAT Dual-Connectivity integration approach. The results complementing the fully-emulated setup,

[2]Ethr -https://github.com/microsoft/ethr

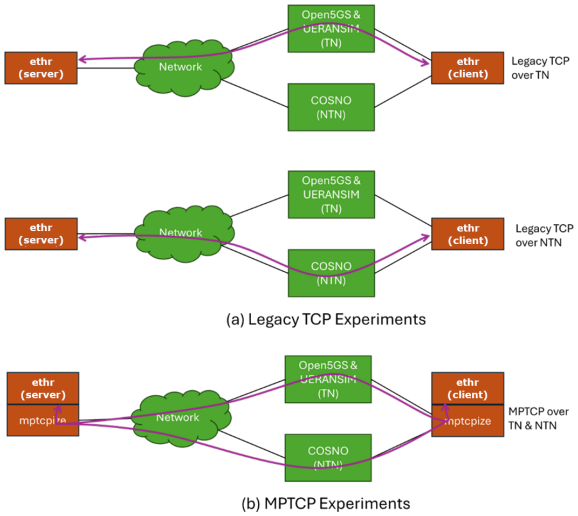

Fig. 4. *ethr* experiments over legacy TCP and MPTCP

showcase distinct patterns across three scenarios. As shown in Figure 5 in scenario (a), the 5G-only deployment with legacy TCP has a stable performance with consistent throughput around 50 Mbps, indicating efficient operation under traditional terrestrial conditions. Scenario (b), utilizing NTN-only with legacy TCP, demonstrates some performance instability with throughput fluctuating between 5-20 Mbps, mostly due to the inherent variability of satellite communications. Scenario (c), integrating 5G and NTN using MPTCP, presents unexpected challenges due to the combination of low-latency and high-latency paths, which leads to packet reordering issues. As a consequence, the aggregate performance at the application level exhibits variations, which is due to an attempt of the TCP/IP stack to handle out-of-order packet delivery. The E2E latency profiles presented in Table I show that latency remains comparable in the best conditions but still diverging at their maximum values.

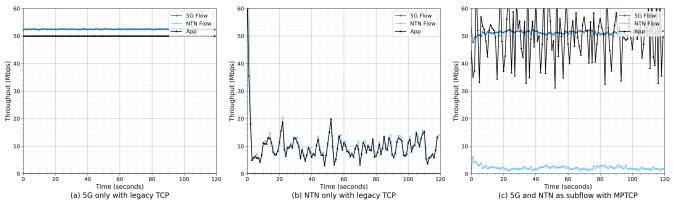

Fig. 5. MPTCP Subflow initial performance evaluation

TABLE I
LATENCY MEASUREMENTS ACROSS DIFFERENT NETWORK SCENARIOS

Scenario	Avg	Min	95%	Max
5G-only, legacy TCP	6.091ms	5.717ms	6.378ms	9.305ms
NTN-only, legacy TCP	41.071ms	29.172ms	52.826ms	286.849ms
5G and NTN (MPTCP subflow)	6.128ms	5.667ms	6.380ms	24.718ms

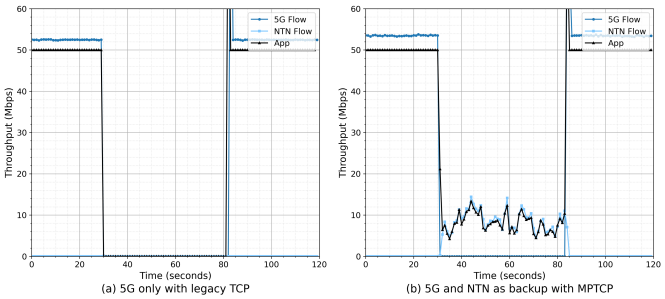

Fig. 6. MPTCP Subflow as Backup in case of a network failure

Figure 6 showcases the effectiveness of the same fully-emulated MPTCP deployment when managing network failures through backup paths. In scenario (a), the 5G-only deployment with legacy TCP demonstrates stable throughput during normal operation, but exhibits complete service interruption during failure periods ($t = 30s$ to $t = 60s$), highlighting the vulnerability of single-path communications. In contrast, scenario (b) implements MPTCP with NTN as a backup path, showing improvements in connection resilience. While maintaining similar performance during normal operation, the connection transitions to the NTN backup path during 5G failures, ensuring service continuity at a reduced throughput (switching between latency profiles measured in the baseline experiment Table I). This failover mechanism ensures session continuity without connection termination, demonstrating MPTCP's capability to manage path diversity, while also exhibiting efficient recovery behavior, when 5G connectivity is reestablished.

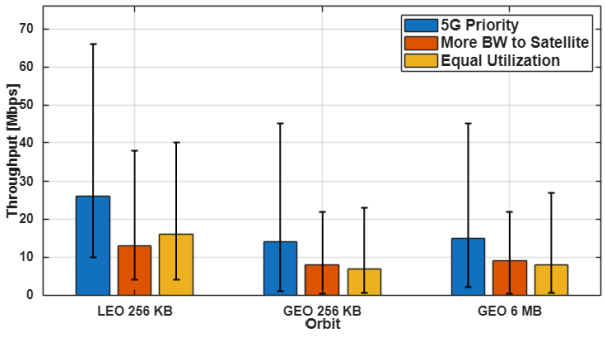

Fig. 7. Average throughput per orbit vs TCP window size

TABLE II
PARAMETERS CONFIGURATION ACROSS DIFFERENT SCENARIOS

Scenario	TCP Win	Avg TP	Min TP	Max TP	Orbit
5G-Priority	256 KB	∼26 Mbps	∼10 Mbps	∼66 Mbps	LEO
	256 KB	∼14 Mbps	∼1 Mbps	∼45 Mbps	GEO
	6 MB	∼15 Mbps	∼2 Mbps	∼45 Mbps	GEO
Satellite-Priority	256 KB	∼13 Mbps	∼4 Mbps	∼38 Mbps	LEO
	256 KB	∼8 Mbps	∼0.3 Mbps	∼22 Mbps	GEO
	6 MB	∼9 Mbps	∼0.3 Mbps	∼22 Mbps	GEO
Equal Utilization	256 KB	∼16 Mbps	∼4 Mbps	∼40 Mbps	LEO
	256 KB	∼7 Mbps	∼0.5 Mbps	∼23 Mbps	GEO
	6 MB	∼8 Mbps	∼0,5 Mbps	∼27 Mbps	GEO

In the context of the second experiment, an analysis of throughput performance has been performed in the hybrid 5G-satellite network setup, as shown in Figure 7. This analysis aims to evaluate how the varying orbits of satellites affect network throughput and to identify which configuration maximizes performance for different traffic priorities, as summarized in Table II. The results are shown for two TCP window sizes: 256 KB and 6 MB. Overall, LEO consistently outperforms GEO in terms of throughput, which aligns with LEO's lower latency features. Among the scenarios, 5G priority yields the highest throughput against both orbit types, which is an obvious suggestion that prioritizing terrestrial links results in better performance, due to their higher data rates and reduced delay. In contrast, allocating more bandwidth to the satellite significantly reduces throughput, while Equal Utilization offers a middle ground. Specifically, in LEO with a 256 KB window, the throughput under 5G priority reaches around 26 Mbps, compared to approximately 13 Mbps to Satellite-priority mode and 16 Mbps for Equal Utilization. For GEO, the maximum throughput under 5G Priority with a 6 MB window is around 15 Mbps, again outperforming the other scenarios. Additionally, a smaller TCP window (256 KB) achieves higher throughput than the larger one (6 MB), particularly in LEO, indicating that window size plays a key role in link efficiency. In particular, the oversized windows may lead to congestion or inefficient link utilization. Notably, the variability in throughput, represented by error bars, is highest in the LEO–5G priority scenario, implying potential instability or congestion despite high performance.

VI. Conclusion

In conclusion, this paper presented a novel 6G-enabled architecture that integrates terrestrial networks with NTN components, leveraging also a real 6G testbed. The results for the first setup highlight the trade-offs and benefits of using TN and satellite networks with MPTCP. The integration of 5G and NTN via MPTCP introduces performance challenges such as packet reordering, caused by the heterogeneous nature of the paths, which affects application-level throughput stability. For the second setup the tested scenarios revealed that smaller TCP windows (256 KB) result in better throughput than larger ones (6 MB), particularly in LEO. So this observed sensitivity to TCP window size highlights the importance of transport-layer tuning and emphasizes that optimal throughput in hybrid networks requires careful balancing of window size and link characteristics, to ensure both high performance and connection reliability. Moving forward, the architectural integration approach and experimental validations presented in this paper lay the groundwork for directly addressing two key use cases within the SUNRISE-6G project to demonstrate and validate two critical scenarios for achieving seamless integration of terrestrial and satellite networks. The first use case refers to Multi-Operator and Multi-Access in NTN with two subscenarios, namely the Inter-PLMN Handover and Dual Connectivity Using MPTCP. The second use case refers to Mobile Industrial Assets supported by NTN Edge Cloud and Communications. The key objective of this use case is to demonstrate how satellite-terrestrial convergence, together with the multi-connectivity capabilities of devices, can lead to more resilient, flexible, and ubiquitous connectivity solutions towards industrial services.

Acknowledgment

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References

[1] S. Plastras, D. Tsoumatidis, D. N. Skoutas, A. Rouskas, G. Kormentzas, and C. Skianis, "Non-terrestrial networks for energy-efficient connectivity of remote iot devices in the 6g era: A survey," *Sensors*, vol. 24, no. 4, 2024. [Online]. Available: https://www.mdpi.com/1424-8220/24/4/1227

[2] L. Ding, Y. Tian, T. Liu, Z. Wei, and X. Zhang, "Understanding Commercial 5G and Its Implications to (Multipath) TCP," *Computer Networks*, vol. 198, p. 108401, 2021.

[3] B. Y. Kimura, D. C. Lima, and A. A. Loureiro, "Packet Scheduling in Multipath TCP: Fundamentals, Lessons, and Opportunities," *IEEE Systems Journal*, vol. 15, no. 1, pp. 1445–1457, 2020.

[4] H. Wu, S. Ferlin, G. Caso, Ö. Alay, and A. Brunstrom, "A Survey on Multipath Transport Protocols towards 5G Access Traffic Steering, Switching and Splitting," *IEEE access*, vol. 9, pp. 164 417–164 439, 2021.

[5] M. Mosahebfard, A. Betzler, M. Montagud, D. Camps-Mur, A. Fernández-Fernández, and C. Verikoukis, "Sunrise-6g: Demonstrating 6g federation concepts over distributed research infrastructures," in *2024 IEEE 29th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*. IEEE, 2024, pp. 1–6.

[6] A. Kapovits, M.-I. Corici, I.-D. Gheorghe-Pop, A. Gavras, F. Burkhardt, T. Schlichter, and S. Covaci, "Satellite communications integration with terrestrial networks," *China Communications*, vol. 15, no. 8, pp. 22–38, 2018.

[7] F. Lisi, G. Losquadro, A. Tortorelli, A. Ornatelli, and M. Donsante, "Multi-connectivity in 5g terrestrial-satellite networks: the 5g-allstar solution," 2020.

[8] A. Abdelsalam, M. Luglio, C. Roseti, and F. Zampognaro, "Linux mptcp performance evaluation in a combined terrestrial-satellite access," in *2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS)*, 2019, pp. 1–6.

[9] M. Majamaa, "Toward multi-connectivity in beyond 5g non-terrestrial networks: Challenges and possible solutions," *IEEE Communications Magazine*, vol. 62, no. 11, p. 144–150, Nov. 2024.

[10] S. B. R. Tirmizi, Y. Chen, S. Lakshminarayana, W. Feng, and A. A. Khuwaja, "Hybrid satellite–terrestrial networks toward 6g: Key technologies and open issues," *Sensors*, vol. 22, no. 21, p. 8544, 2022.

[11] Y. Zhang, Q. Wu, Z. Lai, and H. Li, "Enabling Low-Latency-capable Satellite-Ground Topology for Emerging LEO Satellite Networks," in *IEEE INFOCOM 2022-IEEE Conference on Computer Communications*. IEEE, 2022, pp. 1329–1338.

[12] Y. Hu and V. O. Li, "Satellite-based internet: A tutorial," *IEEE Communications Magazine*, vol. 39, no. 3, pp. 154–162, 2001.

[13] C. Guimarães, J. Quevedo, F. Zeiger, and M. Sauer, "Bridging Terrestrial and Satellite Networks: Exploring the Possibilities for 6G TN-NTN Convergence," in *IAF Space Communications and Navigation Symposium*. Milan, Italy: International Astronautical Federation (IAF), October 2024, pp. 536–546.

[14] Y. Breiting, E. Boriskova, C. Guimarães, A. Netti, M. Sauer, H.-P. Huth, and F. Zeiger, "A Non-Terrestrial Edge Infrastructure Testbed for Early Validation of Industrial Applications," in *2024 IEEE 29th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD) (CAMAD 2024)*, Athens, Greece, Oct. 2024.