# An Empirical Analysis of Multi-Connectivity between 5G Terrestrial and LEO Satellite Networks

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***Abstract*—Integrating Terrestrial Networks (TN) and Non-Terrestrial Networks (NTN) is crucial to providing fifth-generation (5G) ubiquitous coverage and exploiting the potential of connectivity-based solutions. This article presents an initial empirical evaluation of both broadband satellite and terrestrial cellular connectivity solutions. End-to-end latency, Packet Error Rate (PER), and uplink (UL) and downlink (DL) throughput statistics are obtained using a SpaceX Starlink satellite antenna terminal connected to the Starlink satellite network and a multi-band 5G New Radio (NR) modem connected over a public 5G Non-Standalone (NSA) network. Furthermore, we study how the maximum end-to-end latency can be reduced by using multi-connectivity between terrestrial and LEO satellite networks. Results suggest that the integration of terrestrial and NTN is a competitive solution to fill the existing coverage gaps and provide seamless service to low-latency and high throughput-requiring applications.**

***Index Terms*—cellular networks, satellite networks, non-terrestrial networks, multi-connectivity, ubiquitous coverage**

## I. Introduction

The deployment of 5G networks aims at providing connectivity to a wide variety of services, adapting to the requirements of different application use cases: ultra-low latency, increased reliability, higher throughput (tens of Gbps), and, overall, a better user experience. The flexibility of the 5G network to meet such requirements has led to the emergence of new products, applications, and business models [1]. Smart agriculture and farming, maritime communications, public safety, and post-disaster management are some examples that evidence the need for continuous, reliable, and seamless connectivity [2].

However, the mentioned use cases typically rely on cellular radio coverage. According to [3], 37% of the world population has no access to the Internet since there are uncovered areas where cellular networks are not a cost-effective solution due to the low population and the reduced number of users. Global broadband coverage can be achieved in rural and remote areas by integrating the existing cellular Terrestrial Networks (TN) with the so-called Non-Terrestrial Networks (NTN). The concept of NTN was first introduced by the 3rd Generation Partnership Project (3GPP) in the technical report [4] as part of the work in Release-15 and aims at ensuring global 5G service availability at any time using, among others, Low Earth Orbit (LEO) satellites. LEO satellites present lower path loss values and propagation delays than Geosynchronous Equatorial Orbit (GEO) systems due to shorter communication distances, and have lower production and launch costs, providing a more cost-effective solution that ensures global service. Several companies are on the way to deploying constellations with hundreds or thousands of satellites (e.g., Starlink, OneWeb, Kuiper), envisioning providing space-based broadband services. Since the integration of TN and NTN is crucial to providing global broadband coverage, there are several studies on how to integrate the two technologies (architectural considerations and radio management aspects) available in the literature [2], [5], [6].

Besides service continuity, applications such as the remote operation of automated vehicles, monitoring data, and positioning data will require real-time data transfer. A potential solution to ensure reliability is establishing two independent radio links to a terrestrial and a satellite network. This technique is known as multi-connectivity, and it is considered a key feature of 5G to enable low latency and high-reliability services [7]. Recent literature shows studies on how to ensure service availability and service continuity by integrating satellite and cellular networks and using multi-connectivity between them. The authors of [8] propose the architecture for a fully integrated satellite and cellular prototyping system for 5G and beyond 5G services, highlighting the necessary features to perform multi-connectivity between them. In [9], the authors use a multi-connectivity testbed that integrates a GEO satellite network with a 5G network to evaluate service continuity for video streaming in a static position with good coverage from both the serving GEO satellite and the serving 5G gNodeB. The authors claim that the cellular network can reach up to 700 Mbps while the GEO satellite link delivers 5 Mbps. No latency results are reported in the study. There is limited available literature based on experimental results, and it is lacking a comparison of simultaneous latency measurements from 5G cellular and LEO satellite networks. Furthermore, no studies are providing extensive measurement data that allows getting insight into high-reliability areas of latency and throughput statistics for 5G cellular and LEO satellite.

In this article, we compare the performance of LEO satellite and cellular networks in terms of latency, Packet Error Rate (PER) and throughput using experimental data. Additionally, multi-connectivity is explored as a potential solution to provide continuous and seamless service availability while meeting the

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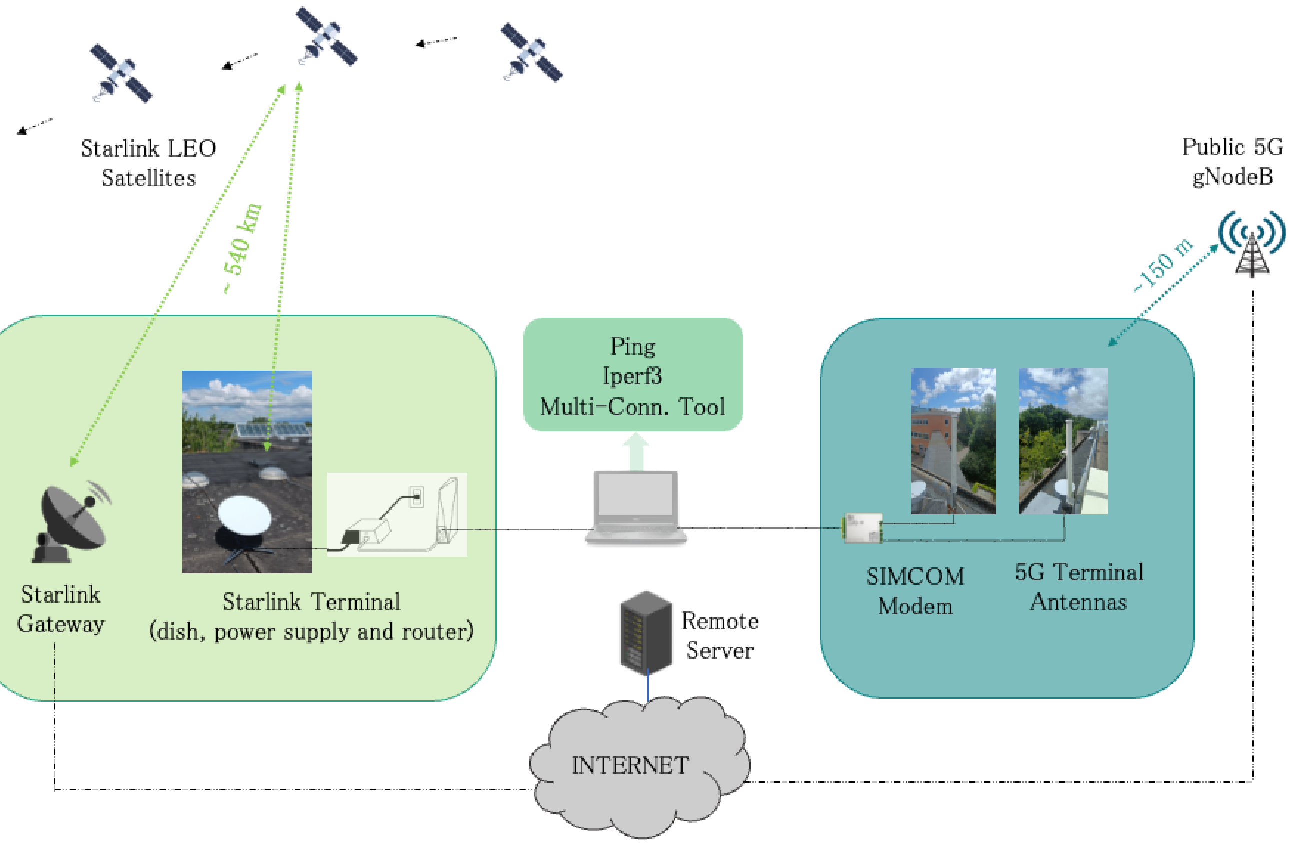


Fig. 1. Experimental setup: Starlink antenna terminal and 5G multi-band cellular modem connected to a Linux laptop.

requirements for low latency services.

The remainder of the paper is organized as follows: Section II presents the setup used to obtain the measurement data as well as the different tests performed. Experimental results are presented and discussed in Section III, and Section IV concludes the paper.

## II. Measurement Campaign

### A. Measurement Scenario and Measurement Setup

The experimental campaign was carried out at the Aalborg University campus, located in Aalborg Øst, Denmark. This is a suburban university and technological campus area with some vegetation and scattered buildings with a height ranging from 2 to 5 floors. Commercially available terminals were used to test both cellular and LEO satellite networks' performance. Both antenna terminals were located static on the roof of a building of approximately 10 $\mathrm{m}$ height. The setup is shown in Fig. 1 and details are described below.

The cellular network samples were obtained using a SIMCOM SIM8202G-M2 5G multi-band modem with Release 15 support [10], connected to the public 5G Non-Standalone (NSA) network from a Danish telecom operator. The modem was connected via USB to a laptop with Linux OS. The network surrounding the measurement area (within a 1500 $\mathrm{m}$ radius) consists of 5 base stations with an Inter-Site Distance (ISD) of approximately 900 $\mathrm{m}$. The closest base station from the operator to the 5G terminal antenna was at a distance of 150 $\mathrm{m}$ with obstructed Line-Of-Sight (LOS) visibility conditions.

To obtain samples from the satellite network we used a commercial Starlink user terminal for residential use [11], which was placed on the roof with good sky visibility conditions towards the Starlink orbit. The laptop was connected via Ethernet to the Starlink router. At the time of writing, the SpaceX Starlink constellation has more than 2500 LEO satellites already deployed at an altitude of approximately 540 km [12], out of the 4408 LEO satellites that are authorized to be deployed. Currently, orbits with different orbital planes passing by the north of Germany cover almost the whole country of Denmark, including the area where the experiments were carried out, as shown in Fig. 2. The orbital pass has an average duration of approximately 7 minutes per satellite.

### B. Key Performance Indicators

Three metrics are considered for performance comparison of public 5G NSA and LEO satellite networks:

- **Latency.** The Linux ping functionality is used to evaluate the latency performance, which provides statistics on the Round-Trip Time (RTT) of the packets sent. For all tested configurations, packets of 64 $\mathrm{B}$ size were sent from the laptop through the Internet to a remote server located in Denmark with an interval of 100 $\mathrm{ms}$.

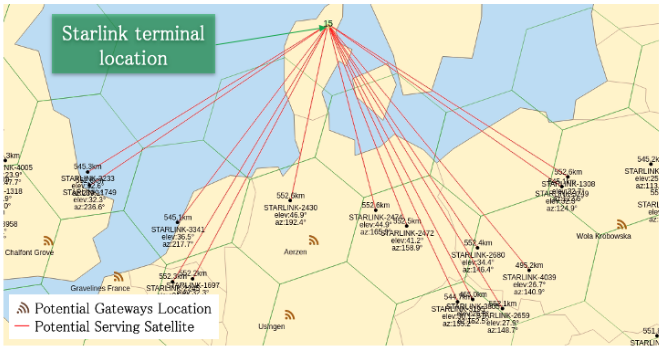


Fig. 2. Starlink terminal location, potential serving satellite links, and potential ground stations location obtained from [13].

- **PER.** Also obtained through the Linux ping functionality statistics, it indicates the percentage of correctly received packets.
- **Throughput.** The iperf3 tool [14] was used to measure network throughput. The tool is based on a client-server model and it allows measuring the maximum throughput between them. The tests were performed in reverse mode to test downlink (DL) throughput (i.e., cellular and satellite terminals downloading data from the remote server in Denmark via LEO satellite network and public 5G NSA network) and in non-reverse to test uplink (UL) performance (i.e., terminals uploading data to the remote server). User Datagram Protocol (UDP) packets were sent with a target bandwidth of 200 $\mathrm{Mbps}$. The sampling rate was set to 500 $\mathrm{ms}$.

### C. Experimental Tests

Latency and PER statistics are obtained for two scenarios: single-connectivity and multi-connectivity. The single-connectivity tests were performed simultaneously for the public 5G NSA network and the LEO satellite network.

Multi-connectivity consists in establishing two or more links between a user and two or more radio access nodes, where the paths of the links are typically spatially uncorrelated. Packet duplication is a multi-connectivity solution that is used to reduce latency and improve service reliability [7], consisting of duplicating the packets and sending one copy through each available link. This will benefit from the fact that there may be poor channel conditions in one of the links, but the packet may be successfully transmitted through the other, allowing to meet the low latency requirements of the service. To test this feature in our experimental setup, we used a multi-connectivity tunneling program developed at Aalborg University [15]. The tool performs multi-connectivity by duplicating Layer 3 packets and sending them over IP using Layer 4 packets (UDP) through both satellite and cellular systems. It provides a Layer 3 tunnel which allows to measure latency statistics by using the Linux ping tool.

Throughput performance evaluation is only performed for a single-connectivity scenario due to the current limitations of the multi-connectivity tool.

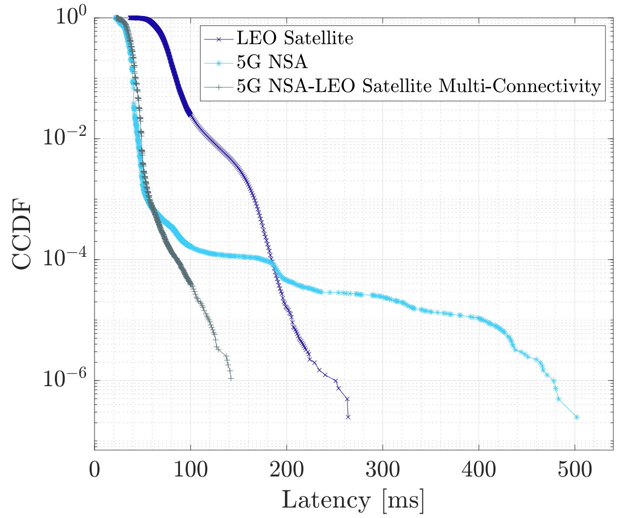


Fig. 3. Empirical RTT latency CCDF for single-connectivity LEO satellite and cellular, and LEO satellite-cellular multi-connectivity.

All tests were performed at different times of day and days of the week, intermittently collecting data for 3 weeks. More than 2 million samples were collected for the latency statistics of each tested configuration, providing sufficient statistical significance to evaluate high-reliability regions. For throughput statistics, more than 300000 samples were obtained for each evaluated technology (5G cellular and LEO satellite).

## III. Results and Discussion

We first present the results of the latency evaluation. Fig. 3 shows the Complementary Cumulative Distribution Function (CCDF) of the RTT observed for each tested configuration (i.e., cellular, satellite, and cellular-satellite multi-connectivity systems). Latency requirements may vary for different low latency application, with values typically between 1 $\mathrm{ms}$ and 100 $\mathrm{ms}$ [16]. For delay-tolerant real-time applications, a maximum latency of 100 $\mathrm{ms}$ is considered. Therefore, a 100 $\mathrm{ms}$ latency is used in this study for performance evaluation reference.

Considering the topology of the LEO satellite network (physical link distances of 540 $\mathrm{km}$, ground stations, and potential inter-satellite links), the satellite link will experience higher wireless propagation delay than the 5G cellular link. Therefore, results for the LEO satellite network present higher but bounded latency values, where RTT latency is contained below 100 $\mathrm{ms}$ 97.6% of the time. In the case of 5G NSA, RTT latency is below 100 $\mathrm{ms}$ 99.98% of the time. However, the 5G NSA CCDF tail shows considerably high latency values (200-500 $\mathrm{ms}$). A summary of the statistics is presented in Table I. The observed statistics indicate that the public 5G NSA network by itself leads to improved performance in terms of minimum and median latency. The minimum RTT observed in the cellular network is 21.6 $\mathrm{ms}$, while for the LEO satellite network, that value is 36.9 $\mathrm{ms}$. In terms of median value, the public 5G NSA network exhibits 29.9 $\mathrm{ms}$, 53% lower than the 63.9 $\mathrm{ms}$ experienced in the LEO satellite network.

TABLE I
LATENCY STATISTICS FOR THE STUDIED CASES

| | 5G NSA | LEO Satellite | Multi-connectivity |
|---|---|---|---|
| **Min.** [ms] | 21.6 | 36.9 | 22.7 |
| **Max.** [ms] | 593 | 317 | 180 |
| **Mean** [ms] | 30.5 | 65.2 | 35.3 |
| **Median** [ms] | 29.9 | 63.9 | 34.8 |
| **Std. Dev.** [ms] | 6 | 10.3 | 6.5 |

TABLE II
PACKET ERROR RATE STATISTICS FOR THE STUDIED CASES

| | 5G NSA | LEO Satellite | Multi-connectivity |
|---|---|---|---|
| **PER** | 0.018% | 0.144% | 0.004% |

However, when analyzing the performance at the lower percentiles (reliability region), it is observed how the current public 5G NSA struggles to provide deterministic latency. A large tail, leading to a maximum latency of approximately 0.5 $\mathrm{s}$, is captured. In contrast, the LEO satellite network provides more stable latency in the lower percentiles, bounded below 300 $\mathrm{ms}$ at the $10^{-6}$ reliability level.

The advantages of using multi-connectivity based on packet duplication are also shown in Fig. 3, where the long latency values observed in the public 5G NSA network are removed since each packet is sent through both links, and only the one with the lowest latency is considered. This leads to an improved and more deterministic performance. The maximum RTT observed when using cellular-satellite multi-connectivity, as seen in Table I, is 180 $\mathrm{ms}$. These results demonstrate that multi-connectivity is beneficial for low-latency services: when current 5G NSA cellular connectivity is unavailable or not meeting the latency requirements, the combination with a LEO satellite link will be able to provide the service with a guaranteed latency below 100 $\mathrm{ms}$ 99.99% of the time, and below 150 $\mathrm{ms}$ 99.9999% of the time. This is specifically useful for use cases where there is poor or no cellular radio coverage, and LEO satellite connectivity can provide continuous service while meeting the low latency requirements.

The statistics obtained for PER analysis are shown in Table II. An improved PER of 0.018% is obtained when transmitting through the 5G cellular network compared to the 0.144% resulting from the LEO satellite network. The use of multi-connectivity, results in a significant decrease in PER compared to single-connectivity, confirming the benefits of combining TN and LEO satellite networks. Further study would be required to explain the differences observed between single-connectivity with the 5G cellular network and single-connectivity with the LEO satellite network.

Throughput performance results are displayed in Fig. 4, where the Cumulative Distribution Function (CDF) is shown. We first focus on the DL results, where the increased throughput obtained with the LEO satellite network compared to the cellular network is shown. Fig. 5 summarizes the relevant throughput statistics. A maximum DL throughput of 266 $\mathrm{Mbps}$ is observed with the satellite network, while a maximum of 215 $\mathrm{Mbps}$ is obtained when using the public 5G NSA network.

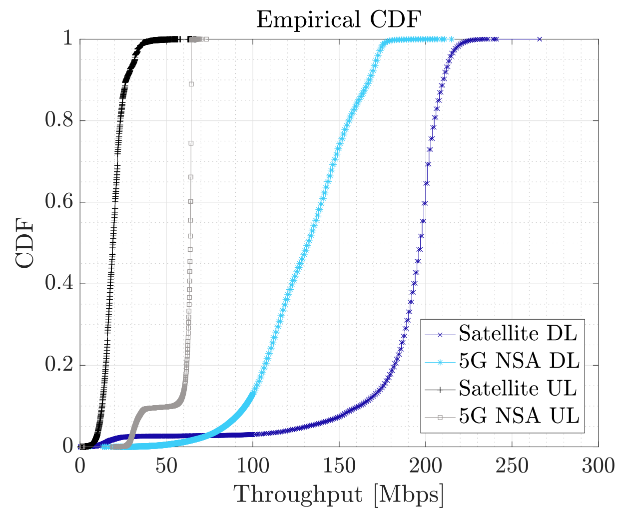


Fig. 4. Empirical throughput CDF for single-connectivity cellular and LEO satellite

The public 5G NSA network shows a minimum DL throughput of 5.8 $\mathrm{Mbps}$, while for the LEO satellite network that value is 0.3 $\mathrm{Mbps}$. On average, satellite DL throughput is 47.6% higher than DL cellular throughput, proving that the satellite network could not only complement TN radio coverage but could also outperform cellular networks for services requiring high DL throughput. This may be due to a lower network load in the satellite network. According to [17], the Starlink network counts more than 400000 subscribers over the world, 80% of them located in North America. This suggests a low user density in North Europe, where the tests were performed. A low number of users per cell can result in low network load and, therefore, better DL throughput per user.

In the UL throughput case, the results displayed in Figs. 4 and 5, show that cellular networks provide higher UL throughput than LEO satellite networks. The mean UL throughput for the public 5G NSA network is 60.3 $\mathrm{Mbps}$, while for the LEO satellite network, that value is 19.6 $\mathrm{Mbps}$. This difference compared to the DL case may be explained by the fact that the link budget is more limited in Earth-to-LEO links. For the DL case, the satellite antenna can allow to transmit high power to compensate for the distance to the receiver. For UL, the satellite antenna terminal has limited transmitting power capabilities, and poor channel conditions may lead to the use of lower modulation schemes and result in lower UL throughput. This is not the case for the cellular network, where the distance between the base station and the 5G modem is shorter (approximately 150 $\mathrm{m}$), and better channel conditions allow for higher MCS. Considering that throughput requirements may vary depending on the application use case, we consider the example of real-time video transmission, with a minimum requirement of 10 $\mathrm{Mbps}$ UL throughput. For that case, the LEO satellite network will be able to deliver 10 $\mathrm{Mbps}$ with 97.2% reliability, while the cellular network guarantees that upload speed with more than 99.99% reliability.

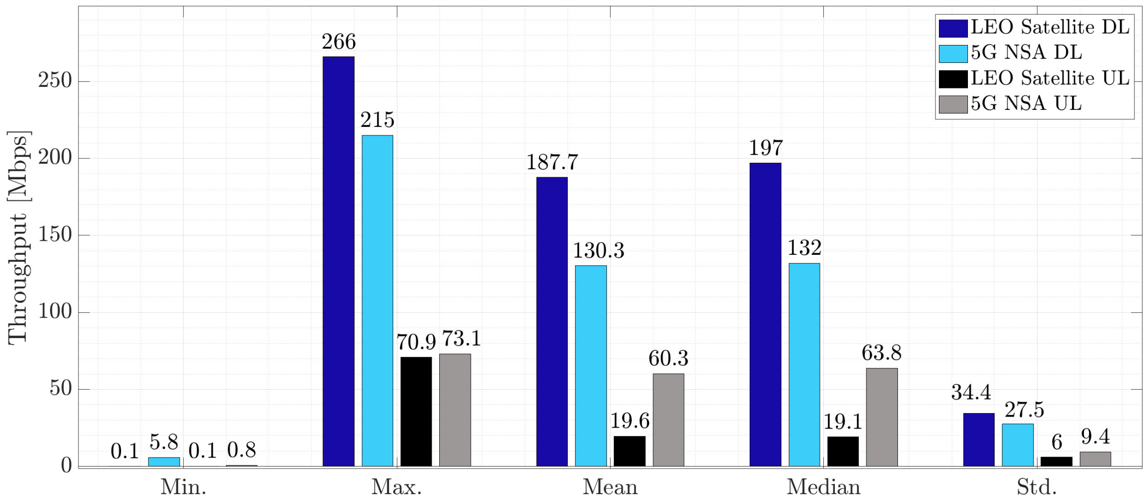


Fig. 5. Relevant throughput statistics for single-connectivity cellular and LEO satellite.

Despite throughput having been only analyzed for the single-connectivity case, multi-connectivity could improve the throughput performance similarly to the latency metric. However, aggregating throughput from both networks would result in increased latency values. Nonetheless, considering that the observed latency values are well bounded for the LEO satellite network, combining throughput from 5G cellular and LEO satellite networks would still be a promising option. Further work in the multi-connectivity tool should be done to enable throughput statistics and validate the formulated hypothesis. The performance analysis conducted in this paper is the first step toward integrated cellular-satellite networks and suggests that multi-connectivity can be used to enhance service continuity and availability to meet real-time application requirements.

## IV. Conclusions and Future Work

In this paper, we performed the first experimental study that compares and combines 5G cellular and LEO satellite networks' performance. The data is obtained using a 5G NSA multi-band modem and Starlink antenna terminal for residential usage. The latency results show that the LEO satellite network provides, on average, higher latency values than the public 5G NSA network. However, the maximum RTT values observed with the public 5G NSA network are higher than the maximum values observed for the LEO satellite network. The long latency values observed with the single-connectivity configurations can be completely removed using multi-connectivity. Therefore, applications requiring a latency below 100 $\mathrm{ms}$ could be served with a 99.99% reliability. Similar results are observed for the packet error rate statistics, where a significant improvement is obtained from using multi-connectivity. Furthermore, throughput performance is investigated in a single-connectivity scenario, showing that the LEO satellite network provides, on average, higher download throughput but lower uplink throughput than the public 5G NSA network.

These results suggest that LEO satellite networks are a potential alternative to provide reliable connectivity in areas where terrestrial cellular coverage is poor or non-existent. Additionally, the results shown indicate that the integration of TN and NTN, and the use of multi-connectivity between them, would be beneficial to provide seamless connectivity for low latency and high-reliability services.

This preliminary investigation is performed in a suburban location with good visibility conditions, in a static position where cellular radio coverage is always available. As part of future work, latency and throughput tests will be performed in different relevant scenarios such as rural and urban, with different radio network coverage conditions. Furthermore, mobility conditions will be investigated, to further analyze the benefit of the multi-connectivity solution.

## Acknowledgement

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