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Connecting Rural Areas: an Empirical Assessment of 5G Terrestrial-LEO Satellite Multi-Connectivity

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***Abstract*—The digital transformation accomplished in recent years in the agricultural, farming, forestry, and transport industries has led to a series of emerging connectivity-based use cases that demand ubiquitous coverage. In such a scenario, Non-Terrestrial Networks (NTN), and their integration with Terrestrial Networks (TN), will play a key role to achieve global and seamless connectivity. This paper evaluates the current service provided by cellular terrestrial networks in rural areas and proposes and investigates a multi-connectivity solution for the use of TN and NTN to improve such service. Experimental data was gathered along a route covering more than 250 km in a rural area, using two multi-band cellular modems connected over public 5G non-standalone (NSA) cellular networks from two different operators and a SpaceX Starlink User Terminal (UT) connected to the Starlink Low Earth Orbit (LEO) satellite network. The multi-connectivity solution that we propose can be easily implemented, and results show that having an additional link to a satellite network avoids service degradation due to a lack of cellular coverage in up to 20 % of the route. The proposed solution also allows achieving round-trip latency targets of 100 ms with 99.99% reliability.**

***Index Terms*—Multi-Connectivity, Rural Connectivity, 5G, Non-Terrestrial Networks, Measurements**

I. Introduction

Despite the growing trend of digitalization in society and in several industries, 85% of the planet's surface still remains uncovered by cellular networks, since deploying the necessary infrastructure to provide coverage in rural and remote areas is not cost-effective [1]. Industries such as farming, agriculture, transport, and maritime, could strongly benefit from digitalization by developing new applications that may lead to a more cost-efficient, sustainable, and competitive business. The lack of connectivity hampers the development of these new applications and use cases in rural and remote areas. Satellite connectivity poses a suitable solution to bridge this digital divide. Thus, ubiquitous coverage and service continuity could be provided by integrating Terrestrial Networks (TN) and Non-Terrestrial Networks (NTN) [2].

TN-NTN integration and the use of multi-connectivity between them not only could ensure service continuity but could also contribute to achieving performance targets for certain applications [3]. The authors of [4] evaluate the opportunities and challenges of the TN-NTN integration and highlight a series of use cases that could benefit from it such as critical communications (public safety, emergency situations), massive Internet of Things (IoT) and aerial communications. Other applications such as rural communication and smart agriculture, and maritime surveillance and monitoring, are envisioned by the authors of [5], who propose a connectivity platform that integrates different technologies, including TN and NTN among others, to provide ubiquitous service. While the available literature addresses TN-NTN integration focusing on architecture definition, enabling technologies, or use cases definition, there are hardly any publications showing simulation or experimental performance results. The simulation work in [6] proposes a multi-Radio Access Technology (RAT) approach for load-balancing purposes, including a terrestrial network and a geostationary (GEO) satellite network. With the terrestrial Base Station (BS) as the anchor and the satellite as the slave node, they use multi-connectivity to prove that the terrestrial network can be offloaded using the satellite network. The authors of [7], present a testbed that allows performing multi-connectivity between a *mmWave* cellular access network and a GEO satellite network. The authors perform throughput tests in static conditions and claim that diversity can contribute to service continuity. However, performance statistics are missing in the article.

In our previous work [8], we presented a preliminary analysis of the performance of single- and multi-connectivity between a public 5G Non-Standalone (NSA) network and a LEO satellite network. Latency and throughput statistics were provided for a static test in a suburban area, showing the potential of using this multi-connectivity configuration to provide low latency and high throughput. To the best of the authors' knowledge, this was one of the very first studies jointly evaluating terrestrial and non-terrestrial network performance, and also the combination of both, in real-world operational conditions.

As a follow-up to our previous paper, here we extend the work by analyzing the performance provided by current cellular terrestrial networks in a rural scenario under mobility conditions. We focus on smart agriculture use cases to set a latency reference for evaluating performance. In [9], the authors provide a list of relevant agricultural applications where latency is a critical aspect. Examples such as vehicle platooning for joint operation, remote control of machinery, or real-time data exchange between machinery and data center, prove the need for low latency services (between 10 and 100 ms) with reliability values between 10^{-2} and 10^{-5}. With such a reference, we performed an extensive drive test to evaluate

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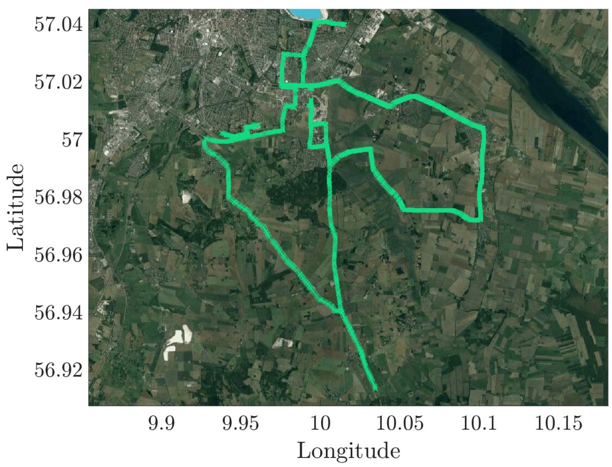

Fig. 1. Measurement scenario, including recorded samples on the road.

the performance of cellular and satellite networks over a rural area of 80 km^2 along different routes over multiple days. Finally, to overcome the poor performance observed in certain areas with the single-connectivity configuration, we propose a cellular-satellite multi-connectivity solution where packet duplication is performed over the cellular public 5G NSA and the LEO satellite networks providing continuous and seamless connectivity.

The rest of the paper is organized as follows: Section II introduces the measurement scenario and setup. Section III presents and discusses the results. Lastly, Section IV concludes the paper and elaborates on future work.

II. Measurement Campaign

A. Measurement Scenario and Measurement Setup

To evaluate the performance of cellular-satellite multi-connectivity in rural environments we conducted a drive-test measurement campaign in the north of Denmark. The scenario is mostly characterized by open agricultural fields, with small areas of forest, and a low density of single-floor households and farms. Terrain elevation in the driving area varies between -8 m and 55 m. The measurements were carried out at different times of the day during different days of the week, aiming at recording data under different network conditions. We drove more than 250 km in a rural area of approximately 80 km^2 by completing multiple times the route shown in Fig. 1.

In order to carry out the connectivity tests towards both terrestrial and non-terrestrial networks in the selected rural area, the experimental setup described in Fig. 2 and shown in Fig. 3 was used. The baseline element of the setup is an ARM-based Gateworks GW6400, a small size industrial computer that supports up to four mini-PCIe extension cards, and has five Gigabit Ethernet ports and integrated GPS support [10]. To obtain the cellular network samples we connected two SIMCOM SIM8300G-M2 5G multi-band modems with Release 15 support and four antenna ports each [11], to two of the mini-PCIe ports in the Gateworks computer. All four antenna ports were used for both modems, with a total of eight antennas connected to the modems. The modems were connected to two independent public 5G NSA networks from two different Danish telecom operators, which will be referred to as Operator A (Oper. A) and Operator B (Oper. B). From publicly available information, we know that at least four 5G NR BSs from Oper. A are deployed in or nearby the measurement area, while the count increases up to ten BSs for Oper. B.

The LEO satellite samples were obtained using a round-shape commercial Starlink Gen-1 User Terminal (UT) [12]. This antenna is meant for residential use and is not optimized for mobility performance. Therefore, the drive test was performed at a speed of 15 $\mathrm{km/h}$ since driving faster would lead to a connection drop. Furthermore, the tracking motors of the Starlink antenna were disabled to avoid tracking while moving, since connection would be lost every time the antenna would be tracking for the optimal serving satellite. This is not a drawback for our measurement purpose, as the focus is put on agricultural and farming use cases, which typically happen at low speeds as well [9]. It is also worth mentioning that, at the time of measuring, the north of Denmark is mostly covered by orbits passing over the north of Germany, so the density of the orbit is still not fully optimized.

To collect the multi-connectivity measurements we used a software tool developed at Aalborg University, which performs packet duplication at the transport layer, allowing us to test multi-connectivity between different technologies [13]. In this article, the packets were duplicated and sent and received through three different interfaces: two cellular modems, and the Starlink UT.

B. Key Performance Indicators

In this work, we target latency as the main Key Performance Indicator (KPI) as it is one of the most relevant statistics in 5G applications [9]. Thus, latency tests were performed on the different considered terrestrial and non-terrestrial networks in an individual (single connectivity) and combined fashion (multi-connectivity). A thorough statistical analysis was performed on the experimental drive test results in order to provide further insights into connectivity performance and the observed technology availability splits.

1) Latency: Latency values were obtained using the Linux ping tool, collecting the Round Trip Time (RTT) of each of the packets sent. For both configurations (single- and multi-connectivity), packets of 64 B were sent to a server located in Denmark with an interval of 100 ms.

2) Interface Success Rate: When multi-connectivity is enabled, the Linux ping packets will be duplicated and sent over the two cellular modems and the satellite links. The tool will only return the RTT value (in ms) for the interface with the lowest latency. As shown in Eq. 1, the Interface Success Rate (ISR) indicates, for each interface i, the percentage of the number of packets with the lowest latency n_i over the total number of packets N sent with enabled multi-connectivity.

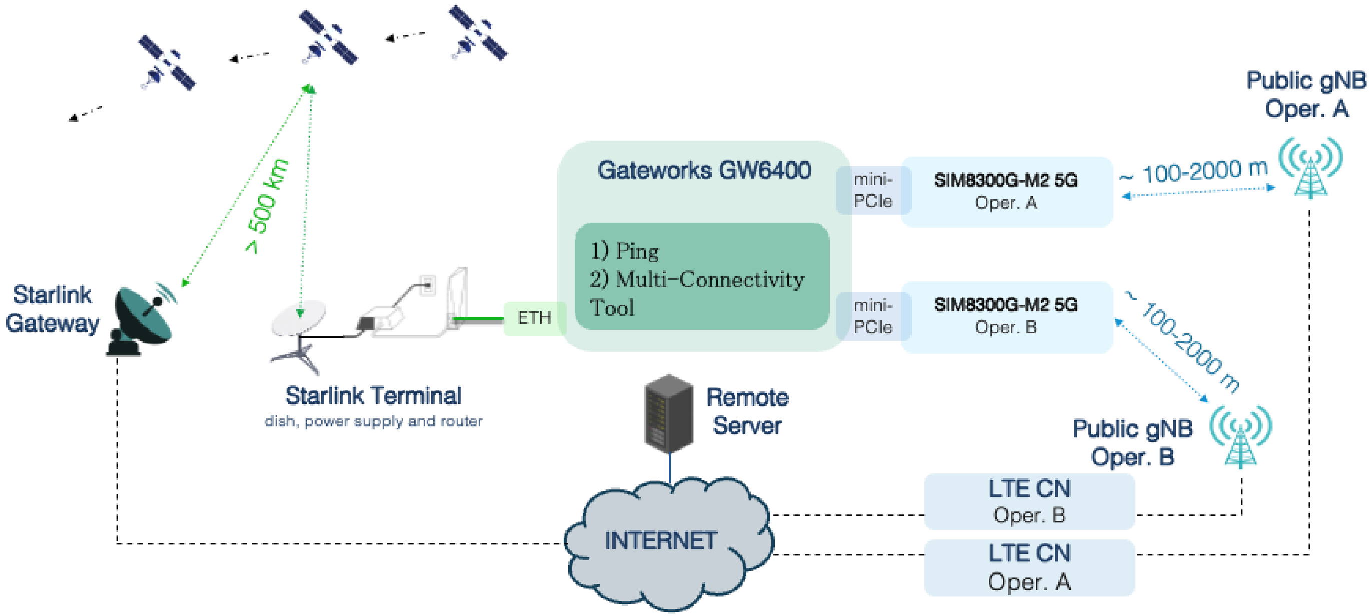

Fig. 2. Complete scheme of the experimental setup.

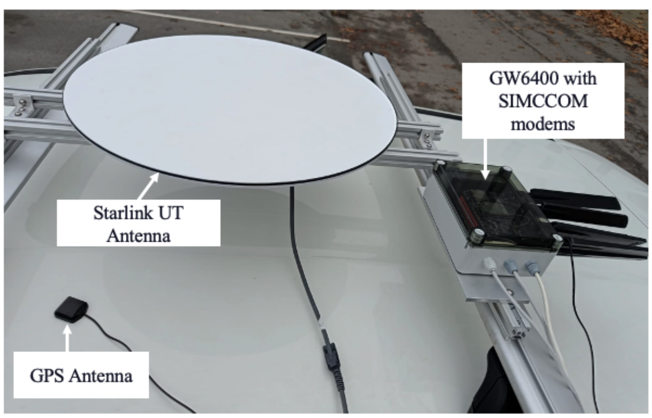

Fig. 3. Measurement campaign setup attached to the roof of the car.

$$ISR = \frac{n_i}{N} * 100 \tag{1}$$

III. Results and Discussion

We first evaluate the coverage status in the measurement area and present the percentage of availability of the studied technologies. In 5G NSA, the control plane data relies on 4G LTE, and only in areas with 5G NR coverage, the data is transferred over the 5G NSA interface. Therefore, the assessment of the anchor 4G LTE band is also relevant. Table I presents the availability of the networks along the route for both cellular networks (LTE and 5G NR) and the LEO satellite network. For the cellular results, we calculate the average between the two measured operators. As it is shown in the table, 5G NR was available only along 85.5 % of the route on average, while LTE presents a 99.7 % availability. This indicates that we observed a 0.3 % outage for the cellular networks. The satellite network, on the other hand, showed a 100 % availability along the measurement route.

TABLE I
Availability percentage of the evaluated technologies in the measurement route.

	Availability [%]
LTE	99.7
5G NSA	85.5
Satellite	100

Next, we present the latency performance statistics in the shape of Complementary Cumulative Distribution Function (CCDF) curves in Fig. 4. More than 150000 samples were collected for each of the curves shown in the figure. We first focus on the single-connectivity results. The comparison between Oper. A and Oper. B is outside the scope of this paper. However, it is worth mentioning that both operators show similar trends, with high latency values of up to 4-7 s observed in the high-reliability regions of the CCDF (approximately 0.006 % of the samples). A OnePlus 9 Pro phone was also used as a reference with a sim card from Oper. A to confirm that any irregularity observed in the results was not due to a bad performance of the cellular modems. This is confirmed by the fact that the shape of the latency CCDF for the phone is similar to the observed for the single-connectivity cases with the modems. It is difficult to explain the large tails in public 5G NSA (green, black, and blue traces in the figure) since we do not have access to network information. A potential explanation could be that despite the availability of the public 5G NSA network, the UE will be connected to both, the LTE eNodeB and the NR gNodeB, and it will use the resources provided by both. Therefore, non-

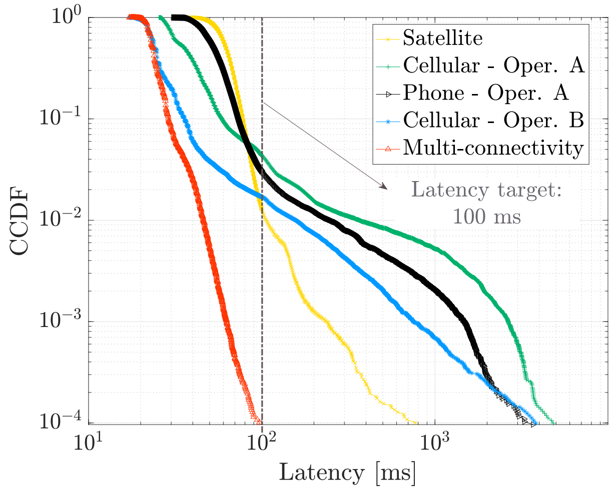

Fig. 4. Latency CCDF for single- and multi-connectivity samples collected during the measurement campaign.

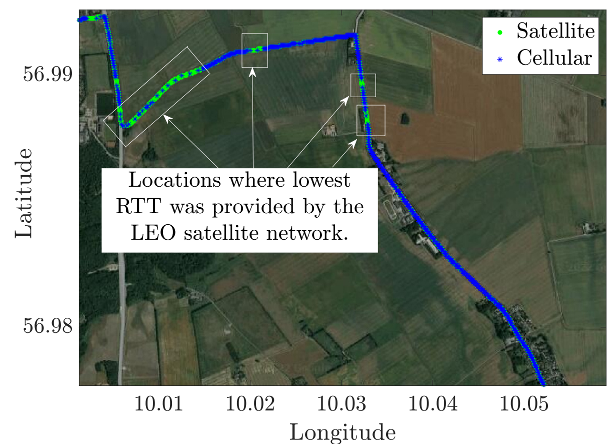

Fig. 5. Example of areas in the route where the multi-connectivity configuration presents lower RTT through the LEO satellite network than through the cellular networks.

homogeneous coverage of anchor LTE band and 5G band, non-optimized mobility triggers, and uplink (UL)/downlink(DL) mismatches due to 5G NSA procedures (e.g. using 5G NR for DL transmissions and 4G LTE for UL transmissions) could explain the long-latency tails. Regardless of the serving technology, Fig. 4 shows the current performance of cellular networks in a rural environment, which would not be able to fully meet the latency requirements of some smart agriculture applications, with latency requirements of 100 ms and 10^{-4} reliability. The best latency performance for cellular networks when single-connectivity is considered shows latency values below 100 ms with a 98.3% reliability. Results for single-connectivity with LEO satellite networks show lower latency tails in the high-reliability regions, with a 98.7% probability of providing latency values below 100 ms. This performance is better than the cellular networks at the 10^{-4} reliability level, and very close to the aforementioned latency targets for typical smart farming and agriculture use cases.

In this work, we propose a solution that integrates terrestrial and non-terrestrial networks to reduce the average latency values observed in the single-connectivity configuration and improve the service experienced by the user. The multi-connectivity solution that we present can be easily implemented in the higher layers and, as it will be shown in the following, strongly improves latency performance. By having an additional LEO satellite link, we overcome the lack of cellular connectivity or poor performance of cellular networks in certain areas of the rural routes. A good example of this is Fig. 5, where we present an example from our measurement route where the integrated TN-NT multi-connectivity over the LEO satellite link aided the connectivity service over the route.

The large improvement compared to the single-connectivity case can also be seen in the CCDF for multi-connectivity in Fig. 4. The long-latency tails observed with single-connectivity are completely removed, providing latency values of 100 ms with 99.99% reliability. The time and spatial macro diversity of the three independent network links led to resilience to potential network failures or performance degradation, improving the average latency by 20.5% as compared with the best single-connectivity performance. These results show the benefits of integrating TN and NTN to meet the aforementioned requirements of smart agriculture applications.

To give an overview of the latency statistics we also include Table II, where the values for the best-performing configuration are highlighted in bold. The table confirms what was previously observed in the CCDFs. The minimum values are similar for all configurations, where Oper. B and multi-connectivity show the lowest value (17.2 ms). The maximum value statistics show the benefits of multi-connectivity. While maximum values of the magnitude of several seconds are observed with single-connectivity, the maximum latency observed when enabling multi-connectivity is 120 ms, nearly 50 times lower than the lowest single-connectivity value. Despite the lower latency in the tails of the single-connectivity configuration for LEO satellites, the statistics show that the mean and median latency values are higher than for the cellular operators. It is also noticeable that, for the single connectivity configurations, the LEO satellite network presents the most stable results, with a standard deviation of 30.6 ms compared to the best-performing cellular configuration, with 72.2 ms. Multi-connectivity, on the other hand, shows a standard deviation of 5 ms, showing the low variability of the collected samples, and the *stability* provided by this configuration. These statistics demonstrate that multi-connectivity between cellular networks and LEO satellite networks can contribute to minimizing latency, increasing availability, resilience, and reliability, and, therefore, meeting the low latency requirements of certain applications in rural environments.

Lastly, we include the interface success rate, which shows, for each interface, the percentage of latency samples presenting the lowest latency, i.e., an indicator of how many times an interface was the fastest. The statistics of the first and

TABLE II
LATENCY STATISTICS FOR SINGLE- AND MULTI-CONNECTIVITY SAMPLES COLLECTED DURING THE MEASUREMENT CAMPAIGN.

	Mean [ms]	Median [ms]	Max. [ms]	Min. [ms]	Std. Dev. [ms]
Cellular Oper. A	54.9	35.8	6895	25.5	160.2
Cellular Oper. B	31.2	23.9	5696	**17.2**	72.2
Satellite	64.2	62.1	6868	38.6	30.6
Oper. A + Oper. B + Satellite Multi-Connectivity	**24.8**	**23.6**	**120**	**17.2**	**5**

TABLE III
INTERFACE SUCCESS RATE FOR BOTH CELLULAR AND SATELLITE NETWORKS WHEN EVALUATING MULTI-CONNECTIVITY.

	Test 1	Test 2	Average
Satellite	29.2 %	15.3%	22.2%
Cellular	70.8 %	84.7 %	77.8%

second days of measurement are shown in Table III. Different results are observed for the two measurement days, probably due to different network conditions in both the cellular and the satellite networks. As stated, even though communication distances are 100 times larger for the satellite case, the LEO satellite network was the primary interface almost 30% of the time on the first day, and around 15% of the time on the second day. These percentages are considered meaningful and confirm the need for satellite networks and their integration with cellular networks to meet stringent latency requirements in rural environments.

IV. CONCLUSIONS AND FUTURE WORK

In this article, we use experimental data to evaluate and propose connectivity solutions for low latency-requiring applications in rural areas. We first evaluate the coverage availability of cellular and LEO satellite networks in a rural area in the north of Denmark. The measurement data is collected using two multi-band modems with 5G capabilities and a Starlink User Terminal. Single-connectivity results show that, on average, LEO satellite networks provide higher median latency than cellular networks. However, longer tails are observed for the latter.

In order to improve the connectivity performance in rural areas and meet latency requirements of 100 ms at 10^{-4} reliability levels, we propose a solution for integrating terrestrial (TN) and non-terrestrial networks (NTN). By performing multi-connectivity in the higher layers, allowing packet duplication between the two different technologies, an average 20.5 % improvement in latency performance can be achieved as compared to any of the single-connectivity options. Additionally, we show that, for an average of 22.2% of the time, the LEO satellite interface is the one providing the lowest latency when the multi-connectivity configuration is enabled, demonstrating the value of integrating TN and NTN to enhance connectivity in such areas, providing a push towards achieving ubiquitous coverage.

Future investigations will include a new experimental campaign to evaluate throughput statistics and investigate whether an additional LEO satellite link can help meeting also the requirements of high data rate smart agriculture applications (up to 100 Mbps).

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