

Article

Satellite Backhaul for Extending Connectivity in Rural Remote Areas: Deployment and Performance Assessment

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Abstract

Limited terrestrial network coverage in rural and remote areas constitutes a significant barrier to the digital transformation of the agricultural sector. Smart and precision farming applications, ranging from conventional environmental monitoring systems to advanced Digital Twin solutions, rely on the reliable transmission of sensor data, images, and video streams from geographically isolated farms. Such data-intensive services cannot be effectively supported without a robust communication infrastructure. Non-Terrestrial Networks (NTNs), particularly satellite systems, offer both narrowband and broadband connectivity, enabling the transmission of low-rate sensor measurements, as well as high-throughput multimedia data from the field. This paper presents an experimental performance evaluation of two satellite backhauling solutions: a Geostationary Earth Orbit (GEO) system provided by SES and a Low Earth Orbit (LEO) system from Starlink. The networks were first deployed and tested in a laboratory environment and subsequently validated in an operational agricultural field setting. Their performance is benchmarked against a terrestrial cellular network to assess their suitability for supporting advanced agricultural applications. The performance assessment results indicate that both satellite backhauling solutions are reliable and capable of meeting the bandwidth and latency requirements of delay-tolerant agricultural applications. In addition to the technical evaluation, this work presents a cost–benefit analysis that further underscores the advantages of NTN-based solutions. Despite higher initial expenditures, they provide extended coverage in remote areas and enable cost sharing across multiple users, improving overall economic viability.

Keywords: satellite; backhauling; LEO; GEO; Internet of Things (IoT); NTN; extended connectivity; rural areas



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1. Introduction

Despite rapid advances in mobile network technologies and continued terrestrial deployments, the digital divide between urban and rural regions remains substantial. While cities benefit from dense fiber backhaul and high-capacity cellular infrastructure, rural and remote areas often lack basic broadband connectivity. Deploying traditional cellular and wired networks in these regions is frequently economically nonviable due to high capital expenditure and limited Return on Investment (RoI) associated with sparse populations and low traffic demand [1]. This persistent infrastructure gap restricts equitable access to digital services and constrains socio-economic development. In rural environments, unreliable

or absent connectivity limits the adoption of data-driven solutions in critical sectors such as agriculture, healthcare, and education, thereby reinforcing structural inequalities and slowing digital transformation [2].

Smart and precision farming applications, central to the digital transformation of rural communities, depend on the availability of reliable and resilient network infrastructures capable of supporting the continuous collection of sensor data, as well as the transmission of bandwidth-intensive multimedia content, including images and video streams, directly from the farm environment. While Internet of Things (IoT) technologies, particularly Low-Power Wide Area Networks (LPWANs) such as Narrowband IoT (NB-IoT) and Long-Range WAN (LoRaWAN), can provide the access network and deliver long-range, low-bandwidth connectivity suitable for many agricultural applications, a reliable backhaul link remains essential to transport the aggregated data to application servers or cloud platforms for processing and analysis.

The integration of Non-Terrestrial Networks (NTNs) with existing terrestrial infrastructures is increasingly recognized as a viable solution for extending broadband and IoT connectivity to remote and underserved areas, enabling seamless aggregation of sensor data and supporting applications where terrestrial backhaul is limited or unavailable. According to 3GPP specifications, NTNs encompass satellites, Unmanned Aerial Vehicles (UAVs), and High Altitude Platforms (HAPs); however, this study concentrates solely on satellite-based architectures.

Satellites are typically classified by their orbital altitude into Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) systems. LEO satellites, generally deployed between 500 and 2000 km, benefit from lower propagation delays and reduced signal attenuation compared to GEO and MEO satellites [2]. However, their limited coverage footprint necessitates the deployment of large constellations to achieve global connectivity. In recent years, multiple LEO systems have been launched to provide satellite-based Internet access, including Iridium, Telesat, OneWeb, and Starlink [1]. MEO satellites operate at altitudes between approximately 2000 and 36,000 km, combining the advantages of both LEO and GEO systems: they offer lower latency than GEO satellites while providing broader coverage than LEO satellites. Several MEO initiatives, including O3b and Mangata, are actively advancing to deliver high-capacity connectivity services to remote and underserved regions [3]. Finally, GEO satellites, positioned in a fixed orbit at approximately 36,000 km, provide the widest coverage of all satellite classes. However, their large propagation delays and increased path losses impose higher requirements on transmit power and antenna design, and consequently constrain the range of services and applications that can be efficiently supported [4].

1.1. Related Work

The feasibility and performance of satellite backhauling solutions have attracted significant research interest, particularly in the context of NTNs and their integration with terrestrial networks, as promising enablers of connectivity in remote and underserved regions. Several studies have explored the integration of LPWAN technologies with satellite backhaul to support IoT connectivity. Chiu et al. analyzed random access schemes for IoT-over-satellite networks, evaluating key performance metrics such as bit error rate and packet error rate under varying interference conditions [5]. In a complementary study, Kim and Jo assessed NB-IoT uplink performance over LEO-based NTNs, demonstrating the practical feasibility of LPWAN uplink transmissions via LEO satellites [6]. In [7], the authors experimentally investigated transparent 5G NTN architectures using operational LEO mega-constellations, evaluating backhaul, midhaul, and radio access relays through real satellite connectivity (Starlink) and analyzing their impact on latency, jitter, and overall system

performance. Together, these works provide foundational insights into the behavior of IoT traffic over satellite backhaul, though the majority of evaluations have been conducted through simulations or theoretical modeling rather than experimental deployments.

From a system-integration perspective, early experimental studies demonstrated the practical feasibility of combining satellite backhaul with terrestrial mobile networks. Völk et al. introduced one of the first over-the-air testbeds that integrated a GEO satellite link with 5G edge components, emphasizing architectural integration rather than detailed performance evaluation [8]. In contrast, Sami et al. focused on the performance characterization of the LEO satellite system Starlink, providing empirical measurements and analysis of network behavior and key performance metrics [9]. Together, these works are seminal in highlighting both the architectural and operational considerations of 5G–satellite convergence. In [10], the authors presented a simulation-driven assessment on the integration of TNs and NTN via an Integrated Access and Backhaul (IAB) technology to enable ubiquitous 5G/6G coverage by using satellite or airborne nodes for both access and backhaul, addressing connectivity gaps in remote areas. This Research indicates that while challenging, this hybrid approach is feasible for LEO and GEO satellites, with system-level evaluation revealing that performance is primarily constrained by satellite-link latency and discontinuous coverage rather than the IAB technology itself. Still, this research remains focused on theoretical and simulation-driven assessments.

1.2. Challenges and Contributions

Despite the growing body of research on satellite-enabled IoT and NTN integration, most studies remain focused on theoretical analysis, simulation, or modeling of network behavior rather than experimental validation in real-world deployments. However, practical deployments in rural environments introduce a range of challenges that are often not captured in simulation studies. Propagation conditions in remote areas can be highly variable due to terrain irregularities, vegetation density, and atmospheric effects, all of which can degrade link reliability and increase packet loss [11]. In addition, gateways aggregating traffic must also contend with hardware limitations, including processing capacity, memory, and antenna gain, which directly influence the volume of traffic that can be backhauled efficiently. Finally, real-world traffic is heterogeneous, comprising a mix of periodic sensor readings, event-driven alerts, and high-bandwidth payloads such as images or short video clips from drones or field cameras, often with irregular transmission patterns. This variability imposes additional demands on network scheduling, buffering, and error-control mechanisms, making it more challenging to guarantee performance metrics such as latency, reliability, and throughput in operational scenarios [12]. Collectively, these constraints underscore the need for experimental evaluation and field testing to validate the performance of satellite backhaul solutions under realistic rural workloads.

This work is developed in the context of the Horizon Europe COMECT project [13], aiming to design innovative connectivity solutions to extend connectivity in rural and remote areas. Several use cases are explored to demonstrate the potential of TN-NTN integration to bridge the digital divide and to support new services in agriculture, livestock, and forest operations [14]. In this paper, we present the tests that were performed in the Living Lab (LL) “Digitalization of viticulture”, located in Remich, Luxembourg. This LL is developing connectivity solutions and digital tools to support winegrowers in plant protection practices and to promote efficient and sustainable vineyard management. The LL focuses on two primary use cases. The first involves in-field microclimate and crop monitoring through the deployment of multiple IoT sensors to collect weather data and track crop development. The second use case centers on the acquisition of images and videos to generate 3D maps, supporting a Digital Twin framework for optimizing vineyard

management. Both use cases have been enabled thanks to the integration of IoT with GEO and LEO satellite backhauling.

The contributions of this paper are twofold. First, we provide a comprehensive experimental evaluation of satellite backhauling solutions through both laboratory and field measurements, considering two representative traffic types: narrowband IoT data collection and broadband video upload. The performance of LEO and GEO satellite backhaul links is systematically compared against a baseline terrestrial network, enabling an assessment across heterogeneous connectivity scenarios. Second, we present a cost–benefit analysis that complements the technical evaluation and supports decision-making regarding the deployment of satellite backhauling infrastructures under different operational and scalability conditions.

The remainder of this paper is organized as follows: Section 2 provides an overview of the satellite backhauling architecture. Sections 3 and 4 present the technical evaluation of satellite backhauling in IoT and broadband connectivity scenarios. Section 5 discusses the cost–benefit analysis of the solution, and Section 6 summarizes the findings.

2. Satellite Backhauling: GEO vs. LEO

One of the major challenges in extending connectivity to rural and remote areas is the lack of affordable and reliable backhauling infrastructure. In geographically isolated regions, traditional terrestrial networks are often unfeasible due to high deployment costs, difficult terrain, or sparse population density. In such contexts, satellite backhauling emerges as a practical and scalable alternative.

Satellite backhauling uses satellite communication systems to connect remote access networks, such as IoT gateways, Wi-Fi access points, and private cellular base stations, to the core network or the Internet. Data generated by end-user devices is first transmitted to a local terrestrial base station, referred to as a satellite terminal, which then relays the data packets over a satellite link to a ground station interfacing with the broader network infrastructure. Depending on the satellite’s orbital altitude, geostationary or Low Earth Orbit, the design and configuration of the satellite terminal differ.

Although satellite backhauling provides significant advantages, such as wide geographical coverage, rapid deployment, and resilience in disaster-prone or infrastructure-deficient regions, it also presents technical challenges, including higher latency, limited bandwidth, and susceptibility to weather-related signal degradation. In this study, we evaluate two extreme satellite orbital configurations: GEO and LEO. In the following, we describe the satellite backhauling links deployed in the LIST IoT Lab, in Belvaux, Esch-sur-Alzette, and in the vineyard region of Remich, Luxembourg.

2.1. GEO Satellite

GEO satellite backhauling capabilities were provided by the satellite operator SES. In particular, the space segment was built upon the SES ASTRA 2F Geostationary Earth Orbit (GEO) satellite, operated at the orbital location 28.2° East, as illustrated in Figure 1 left.

The Radio Frequency (RF) uplink and downlink ground station corresponded to a 9 m Ku band antenna (see Figure 1 right), while the baseline satellite ground segment corresponded to the Newtec Dialog Hub, both located at SES’s teleport in Betzdorf, Luxembourg. The Newtec Dialog hub is a multiservice platform that enables IP communication between remote sites and locations using satellite links.

The activation of the carrier for transmitting and receiving through the ASTRA 2F can be seen in Figure 2, while more information about the satellite platform statistics is depicted in Figures 3 and 4.

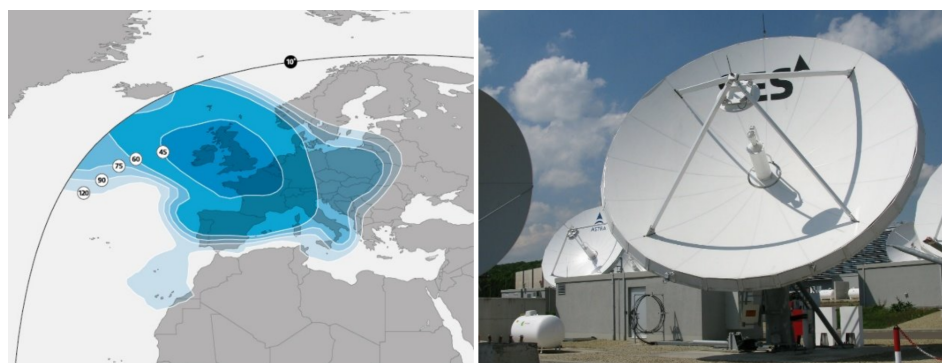


Figure 1. ASTRA 2F Europe Ku-band beam (Left). RF Uplink and Downlink ground Station: ATF #33 Antenna, Diameter: 9m, Vertex, Tx/Rx, Ku-band (right).

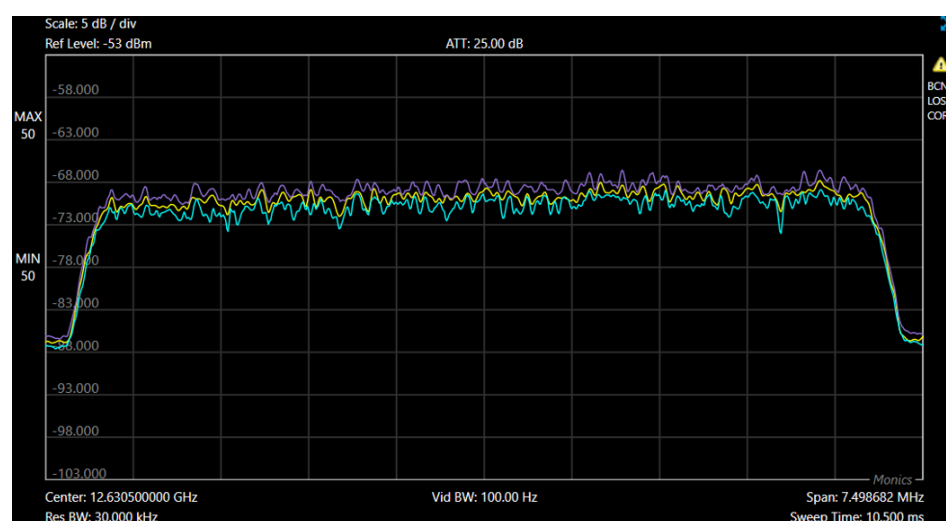


Figure 2. Carrier activation through the ASTRA 2F.

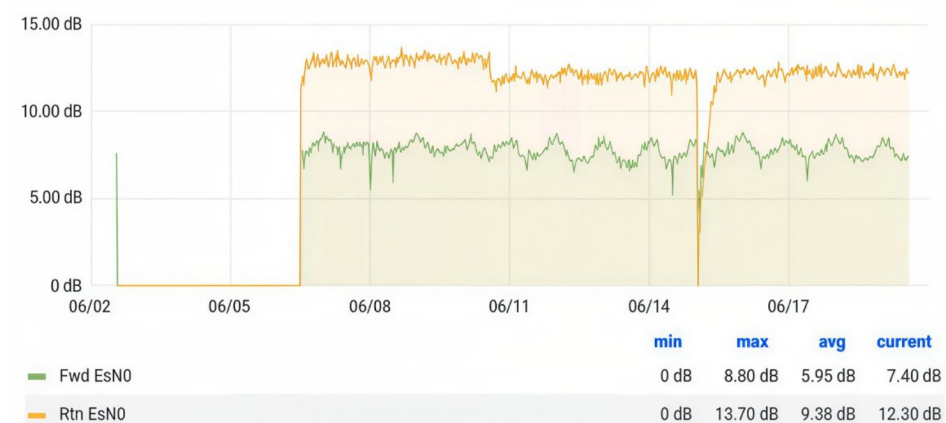


Figure 3. Forward and Return Es/No.

As shown in Figure 3, the energy per symbol to noise power spectrum (E_s/N_o) demonstrates the stability of the return (RTN) and the forward (FWD) carrier. Considering the satellite's orbital position and obstacles in the sight line between the antenna and the satellite, the average E_s/N_o of the FWD channel is 7.5 dB with a variation of ± 0.5 dB during the test period, which contributes to the availability and efficiency of the service. This behavior demonstrates the antenna's gain and the modem's adaptability regarding modulation, Forward Error Correction (FEC) and power. The RTN channel exhibits similar behavior, with an average E_s/N_o of 12.5 dB and a variation of 0.5 dB during the same

period. This results in stable performance and a low number of errored frames, as evidenced by successful data transmission despite adverse weather conditions (see Figure 4).

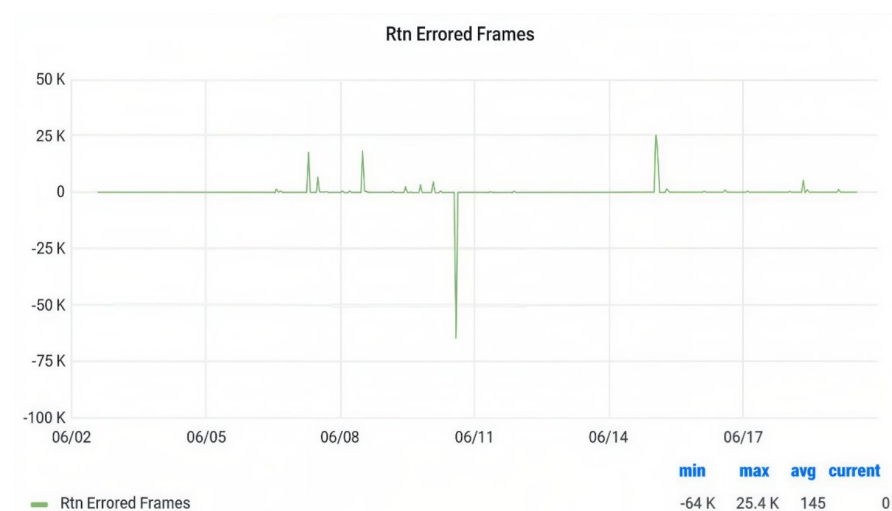


Figure 4. Return errored frames.

During the test campaign, two satellite terminals were used:

- The SatCube Ku-band small-factor transportable terminal (see Figure 5) for validation in the lab in the premises of LIST in Luxembourg. It corresponds to a lightweight, compact, portable satellite terminal that enables broadband connectivity almost anywhere on Earth.
- The TP150 flyaway terminal (see Figure 6) for the tests conducted in the vineyards, in Remich, Luxembourg. The TP150 flyaway terminal corresponds to a 1.5 m X, Ku and Ka-bands VSAT terminal and allows for simple, fast and accurate location and acquisition of the satellite, either as a manually controlled mount or as a fully autopointing and motorized system. The TP150 was preferred to the Satcube during the field tests in Remich for two reasons: (i) the TP150 antenna can provide much higher data rates, needed for the transfer of videos captured by the cameras, than the Satcube; (ii) the TP150 antenna is more stable than the Satcube in terms of the weather conditions. The antenna had to stay in Remich, installed in the vineyards, for more than one month.

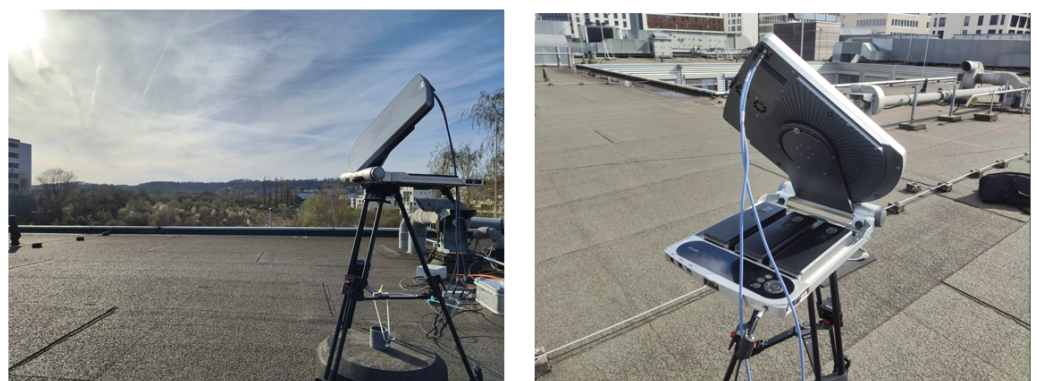


Figure 5. SatCube transportable satellite terminal installed on the rooftop of LIST building in Belvaux, Luxembourg.



Figure 6. Fixed Edge Node installation at the vineyards in Remich, Luxembourg: Outdoor Unit (ODU) + Indoor Unit (IDU).

2.2. LEO Satellite

To assess the performance of LEO satellite backhauling, this study employed the Starlink Enterprise Kit provided by SpaceX [15]. The solution provides high-throughput and low-latency Internet access, based on a growing constellation of satellites at approximately 550 km altitude. Starlink LEO satellites can connect to multiple terminals simultaneously and relay all connections to a ground station on the Ka-band link. The connection forms a direct “bent-pipe” in case the terminal and ground station lie within a single satellite’s coverage cone; otherwise, the satellites can relay within space to reach far-off ground stations via laser inter-satellite links, forming an “extended bent-pipe” [9].

The deployment involved installing a Starlink user terminal (see Figure 7) at the test site, with unobstructed visibility to the sky to ensure optimal satellite tracking and link quality. The terminal was connected to a local modem, providing an access network to serve end-user devices. The setup required only standard electrical power and basic mounting hardware, highlighting Starlink’s ease of deployment in field conditions.



Figure 7. Starlink satellite terminal installed in the garden of LIST building in Belvaux, Luxembourg.

Throughout the experiment, the satellite link was continuously monitored to assess obstruction level, which may impact link performance metrics such as throughput, latency, and packet loss. Figure 8 shows the obstructions from surrounding trees in the installation

location (right) and the evolution of the obstructions caused by the moving clouds and weather conditions during the test period (left).

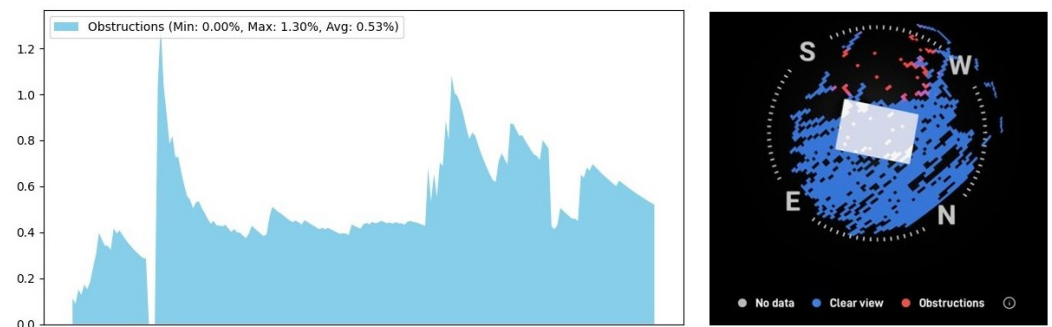


Figure 8. LEO Link obstructions.

3. IoT Data Collection

Effective monitoring of microclimatic conditions is critical for predicting disease occurrence and spread in large agricultural areas, particularly vineyards. By continuously collecting and analyzing data on local weather, soil conditions, and leaf wetness, winegrowers can detect infections early and make informed decisions on the timing, dosage, and application of pesticides and fertilizers, improving crop protection and productivity.

Enabling such real-time, field-level monitoring requires a distributed network of sensors capable of gathering environmental data across wide and often remote areas. Internet of Things (IoT) technologies provide the foundation for this capability, allowing large-scale, low-power, and cost-effective deployments that connect sensors to local gateways for data aggregation.

While IoT networks such as LoRaWAN can efficiently collect and transmit sensor data locally, a reliable backhauling link is necessary to deliver the data to remote servers for processing and predictive modeling. In rural and remote regions where terrestrial network infrastructure may be unavailable or unreliable, satellite backhauling provides a practical and scalable solution to ensure end-to-end connectivity, enabling continuous data-driven decision-making for plant protection.

3.1. Experimental Setup

The first test campaign, conducted in a lab environment, aimed to assess the impact of satellite backhauling on IoT data transmission. To this end, satellite backhauling was integrated into a standard LoRaWAN network architecture, with the LoRa Server hosted remotely.

In this experiment, 36 LoRaWAN devices, specifically Milesight EM500 environmental monitoring sensors, were deployed indoors to emulate a dense sensor network representative of large-scale agricultural deployments. Each device is equipped with sensors measuring temperature, humidity, CO₂, and pressure.

The devices were configured to transmit 11-byte packets every 2 min using the same Spreading Factor (SF7), generating a total traffic of 1080 packets per hour. This configuration is sufficient to emulate dense IoT deployments and to evaluate the impact of backhauling on data transmission under realistic conditions.

IoT data from the devices is periodically collected by a RAK wireless gateway, which forwards the packets to the remote LoRaWAN server (ChirpStack) via either a terrestrial or satellite backhauling link.

For the terrestrial backhauling link (Figure 9), an Ethernet cable is connected to the lab local network that offers an upload throughput of 893.18 Mbps, download throughput

of 939.93 Mbps, and an average latency of 2.54 ms. Two satellite backhauling options are tested: GEO and LEO. The GEO satellite link is deployed using the fast deployable SatCube satellite transportable terminal from SES, using the link described in Section 2.1. The link offers an upload throughput of 4.2 Mbps, download of 5.98 Mbps, and an average latency of 343.7 ms. The LEO satellite link is deployed using the setup in Section 2.2. This link offers an upload throughput of 11 Mbps, download of 284 Mbps, and an average latency of 21 ms. The backhauling links are tested successively with the same configuration of devices in the access part, summarized in Table 1. Each configuration is running over 2 days, where the gateway is forwarding the packets to the server using a different backhauling network: Terrestrial, Satellite-GEO or Satellite-LEO. It is worth mentioning that the tests were running during a period of high levels of cloud cover with periodic rain showers. Putting the satellite link under critical weather conditions may cause some degradation in communication performance.

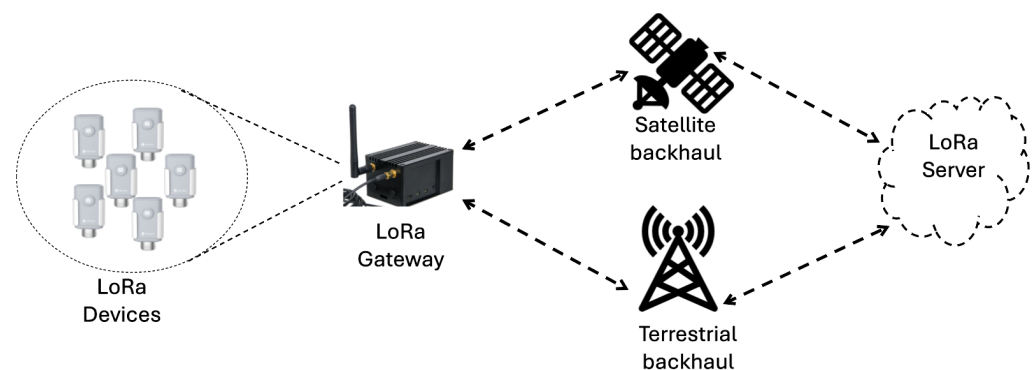


Figure 9. Satellite vs. terrestrial backhauling for sensor data collection.

Table 1. Experimental setup for IoT data collection.

Parameter	Value
Number of devices (N)	36
Payload size (PL)	11 Bytes
Spreading Factor (SF)	7
Time on Air of the packet (ToA)	62 ms
Transmission period (T)	2 min

3.2. Results

The IoT devices generate a traffic of approximately 12,000 packets during the test period with each backhauling link. The performance of the end-to-end system, under different backhauling network configurations, is evaluated in terms of the packet delivery ratio (PDR). The PDR, being the ratio of the received packets to the total number of generated packets, reflects the successful transmission over the network. Within the end-to-end network architecture, a packet can be lost in the access or backhauling segment. Being the focus of this work on the performance of the satellite backhaul link, hereafter, we analyze the losses that can originate from the radio access conditions. In the access network, if the signal strength is not enough to reach the gateway, or if different transmissions collide in time and frequency, the packet can not be correctly decoded by the gateway, and consequently, can not be forwarded to the LoRa Server through the backhaul (See Figure 9).

Concerning signal strength, the transmit power and propagation environment were configured to ensure the Received Signal Strength Indicator (RSSI) from end devices is above the gateway sensitivity. All the devices were deployed close to the gateway, inside

the lab, and using high transmit power to avoid signal attenuation. However, since all the devices were using the same SF and frequency channel, collision could occur and generate some packet loss.

Given the periodic IoT data transmission and ALOHA-based MAC access of Lo-RaWAN devices, the probability p to have a collision in time and frequency can be formulated following the Poisson model as follows:

$$p = 1 - \exp\left(\frac{-ToA}{T}\right) \quad (1)$$

where T is the transmission periodicity, and ToA is the time on the air to transmit the data packet [16]. Thus, the probability of missing a packet in this network because of collision is the complement of the event that none of the $(N - 1)$ devices collide:

$$P_{Collision} = 1 - (1 - p)^{(N-1)} \quad (2)$$

Numerically, there is up to a 2% chance that a packet is missed in the access network because of collision. Thus, when analyzing the PDR of the backhauling link, presented hereafter, an uncertainty of 2% loss can be due to the access network.

Figures 10 and 11 show the PDR experimented by each device and the variation of PDR during this test campaign. The end-to-end PDR exhibits high median values across all evaluated links, indicating generally reliable performance for IoT applications. Specifically, the median value of the PDR is approximately 97% using GEO satellite backhauling and around 99% using terrestrial and LEO satellite backhauling. However, the distribution of the results reveals non-negligible variability. While terrestrial and LEO satellite backhauling achieve higher median performance, they also present occasional extremely low values, indicating the presence of outliers under certain conditions, which may relate to the uncertainty and change in the access network.

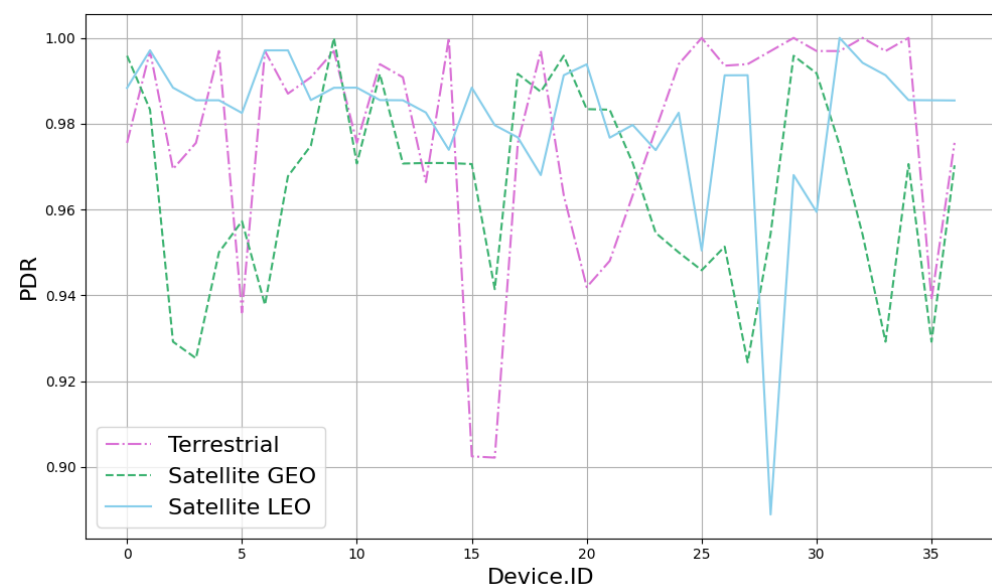


Figure 10. PDR per device.

The dispersion analysis further highlights an interquartile range (IQR) of 3% for both terrestrial and GEO satellite links, whereas the LEO satellite link shows a narrower IQR of 1%, suggesting a more stable performance for the majority of the observations despite the presence of rare extreme events.

Despite temporal variability and uncertainties in radio propagation conditions, since the experiments were conducted on different days and these factors can affect the access segment, the evaluated links consistently provided reliable backhaul performance for IoT data transmission. These results demonstrate the feasibility of multiple satellite backhauling solutions to support precision agriculture applications in remote areas where terrestrial connectivity is unavailable.

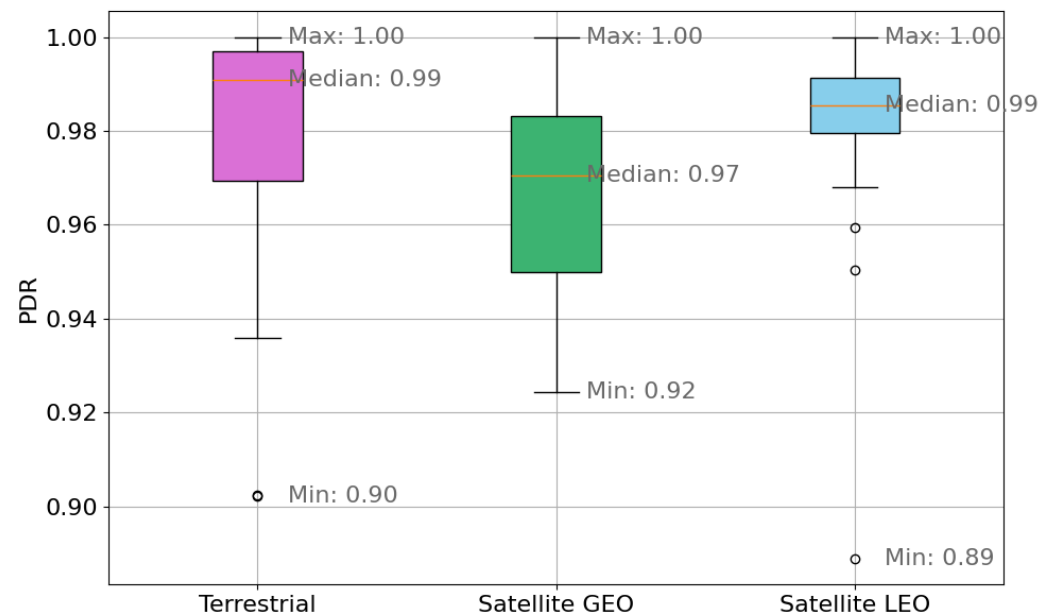


Figure 11. PDR variation per backhauling link.

4. Broadband Connectivity

Besides small IoT sensor data, large data is also required to allow rural and remote areas to benefit from more advanced digital solutions in agriculture. For instance, a digital representation of the farm (i.e., a Digital Twin, DT) can support farmers in managing their vineyards more efficiently. To build an accurate DT of the vineyard for this use case, data with high temporal and high spatial resolution generated by different sensors and cameras in the field is needed. Cameras mounted on tractors can collect video streams while farmers perform their daily work. These high-resolution videos and images are processed to generate a 3D representation of the vineyard, allowing an accurate representation of stems, leaves and grapes.

An extended and reliable connectivity platform is needed for this use case to transmit the video streams collected using the camera mounted on the tractor, but also to allow the acquisition of GNSS correction data by a Real-Time Kinematic (RTK) service, ensuring maximum spatial precision at each moment of the frame acquisition. Consequently, the field should have a network infrastructure with extensive and stable coverage within the tractor activity period. Wi-Fi access points can be used in the field to extend the access network. While a backhauling link, terrestrial or satellite, can ensure an internet connection to acquire RTK data and supports video upload.

This data, combined with IoT data, can be used to simulate the growth and development of vines in real time, predict diseases and build a digital replica of the vineyard. Thus, the operations conducted in the field can be optimized, and preventive actions can be performed promptly.

4.1. Experimental Setup

This use case is implemented and tested in the field in the COMTECT Living Lab in Remich, Luxembourg. Data is collected by a smart device, mounted on the tractor, composed of a smartphone with an integrated camera and an RTK antenna (see Figure 12a). While the tractor moves along the rows, the real-time positioning from the RTK antenna together with video of each row is recorded using at least the standard resolution of the phone camera. The device connects to an RTK server to retrieve GNSS correction data, so the GNSS signal acquired by the antenna is improved to a precision of up to 3 cm in longitude, latitude and altitude. The antenna sends a constant stream of data to the smartphone, containing the geolocation sampled every 5 ms, as well as a timestamp matching this precision. This high temporal resolution requires a constant and stable connection to the RTK and satellite services, which is guaranteed by the backhauling setup. For each recorded row, a high-resolution video and a JSON file containing geolocation data and timestamps are generated, stored, and then uploaded to the remote server.

To ensure the network coverage while the tractor is moving in the field (for an accurate RTK geolocation data acquisition), a local Wi-Fi network is deployed in the field using a Point-To-Point (PTP) network extender with two Access Points (APs): one mounted on top of the tractor (Figure 12b) and the second (Figure 12c) connected to the modem providing connection to the backhaul: terrestrial or satellite.



Figure 12. Video acquisition and upload in the field.

The TP150 flyaway terminal is used to provide GEO satellite backhauling, and the Starlink terminal is used to provide LEO backhauling. To compare the performance of the suggested connectivity platform with a terrestrial network, cellular backhauling is also tested using a router with a SIM card from the operator providing the best coverage in the considered rural area in Remich. The experiments were conducted in the field over multiple days and consisted of two phases: on-site video recording and subsequent video upload via different backhaul links. The satellite capacity was reserved for two separate periods, spanning two weeks in April and an additional two weeks in June. The measurements, therefore, capture a range of environmental conditions, including rainy and overcast days, as well as clear-sky conditions. In addition, seasonal changes in vegetation were observed over the measurement period. In particular, increased foliage density in June, due to vine and tree growth, required adjustments to the infrastructure deployment, including the positioning of the satellite terminal and terrestrial repeaters.

To evaluate the performance of the connectivity platform, videos with different resolutions and lengths are used. Videos of different rows are recorded with resolutions from Standard Definition (SD) to Ultra-High Definition (UHD), also known as 4K, and uploaded

to the server using the three backhauling networks. The upload time to download each video is calculated for the different tests, as well as the latency of the network during the video upload. Each video upload is repeated three times using the three different backhauling links and the same script. Video uploads are performed using an HTTPS-based client implemented in a Python 3.10.12 script, relying on HTTP POST requests to the remote server. The upload consists of the transmission of a single video file together with associated JSON sensor data. Data transfer relies on standard TCP transport mechanisms, with reliability and retransmissions handled at the transport layer; no application-level rate control, segmentation, or adaptation is implemented. A fixed client-side timeout of 300 s of inactivity is configured to accommodate high delays in satellite links, and no explicit application-layer retry or resume mechanism is used. Each upload attempt consists of a single transaction per link condition. The upload time is measured as the elapsed wall-clock time between initiation of the HTTP request and reception of the server response corresponding to the end of upload.

4.2. Results

Figure 13 presents the experimented upload time for videos of different sizes, using the three backhauling links. Note that since we focus on the analysis of the network under load, we only consider successful uploads and exclude failed attempts resulting from client-side timeout and network disconnections. Each successful upload is mapped to an upload time (presented in circles, squares and triangles). An average experimental throughput is calculated from the different uploaded videos and used to present the average upload time as a function of the video size, with a continuous line. Test results show that the cellular network provides a higher average experimental UL throughput: 10.90 Mbps vs. 7.10 Mbps for the GEO satellite and 8.30 Mbps for the LEO satellite network. However, it is worth mentioning that the cellular network is not stable, and not all the video uploads are successful from the first attempt. Also, despite providing the lowest throughput in this experiment, GEO satellite backhauling is the most stable, it has the lowest inter-quartile range of throughput, see Figure 14.

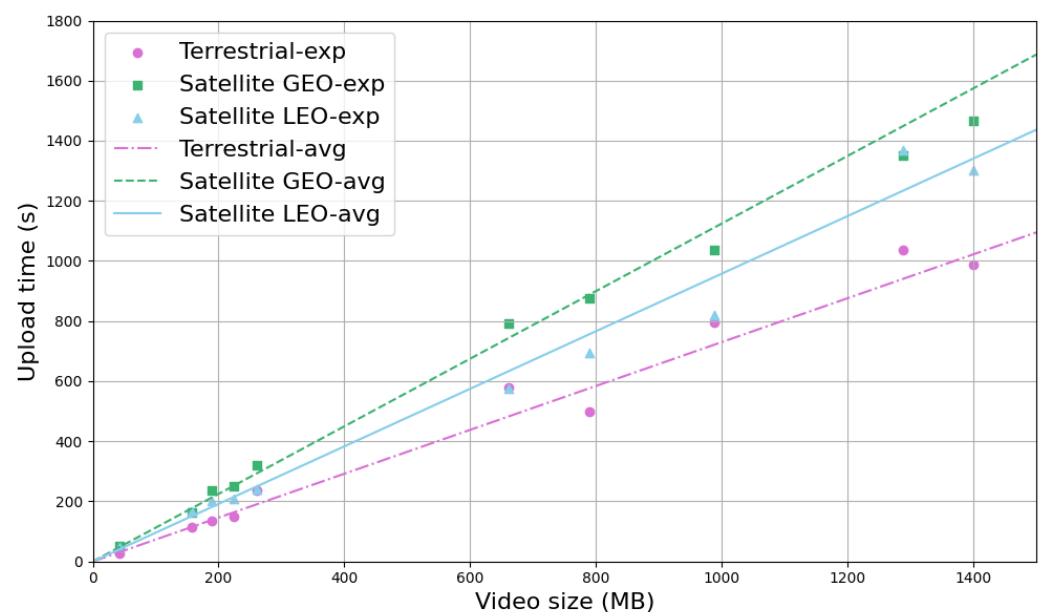


Figure 13. Upload time for videos of different sizes.

This instability of the terrestrial cellular network is explicitly measured by the latency introduced in the network under load. Ping packets are continuously sent in parallel with

the video upload experiment. Latency measurements are performed using the Linux ping with 56 bytes of data. ICMP Echo Requests are sent to the public Google DNS server at IP address 8.8.8.8. as a stable Internet endpoint at a regular interval of 1 s. No application-level retransmissions are performed, and missing responses are directly reflected as missed packets. Finally, Round-Trip Time (RTT) metrics are computed only from successfully received replies. RTT values are presented in Figure 15. The fluctuation of the RTT values in the cellular network is very frequent, and latency values deviate too much from the average value: the RTT Average value is 699 ms, while the standard deviation is 844. This instability of the cellular network impacts the quality of the collected data: For the videos recorded using the cellular backhauling link, up to 30% of the RTK correction stream is lost, while for the ones recorded using the satellite link, the RTK signal is always available at 100%.

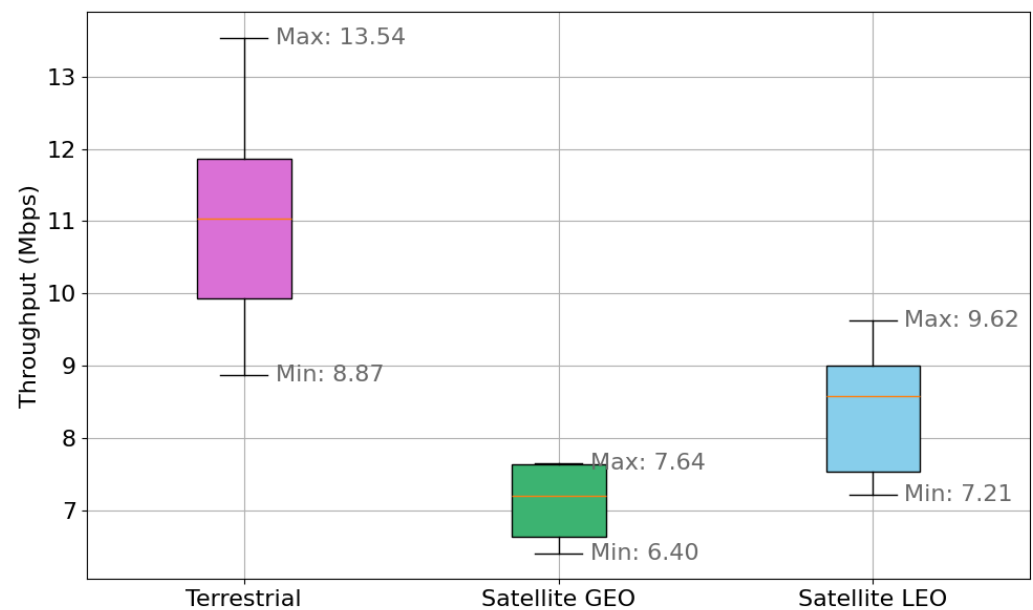


Figure 14. Experimental throughput.

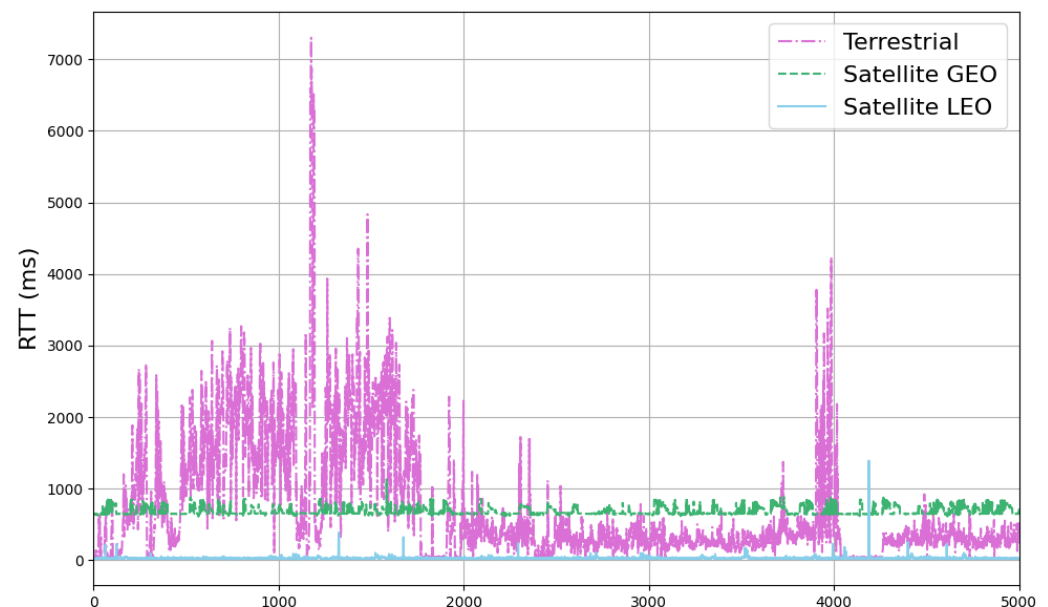


Figure 15. Network latency under load.

Figure 16 presents a graphical distribution of the network latency in different backhauling solutions. GEO satellite backhauling appears to be the most stable and well-behaved network, with a tight inter-quartile range and moderate skewness; latency values vary in a narrow and controlled range. This makes this backhauling link ideal for applications requiring consistent measurements. The cellular network shows significant variability and moderate outlier influence, with the presence of several large values far from the center, which reflects a more diverse or noisy measurement scenario. LEO satellite measurements show the lowest median value of latency and a narrow inter-quartile range. Although the median RTT and dispersion metrics indicate relatively consistent latency for most measurements, occasional large RTT outliers are observed. These transient spikes are consistent with LEO satellite handover events, during which the active satellite serving the terminal changes as satellites move across the sky. Such handovers may involve brief buffering or routing updates, resulting in short-lived latency increases. Consequently, while the LEO latency can be considered stable for the majority of the time, rare handover-related events introduce significant but infrequent deviations that are reflected in the RTT tail behavior.

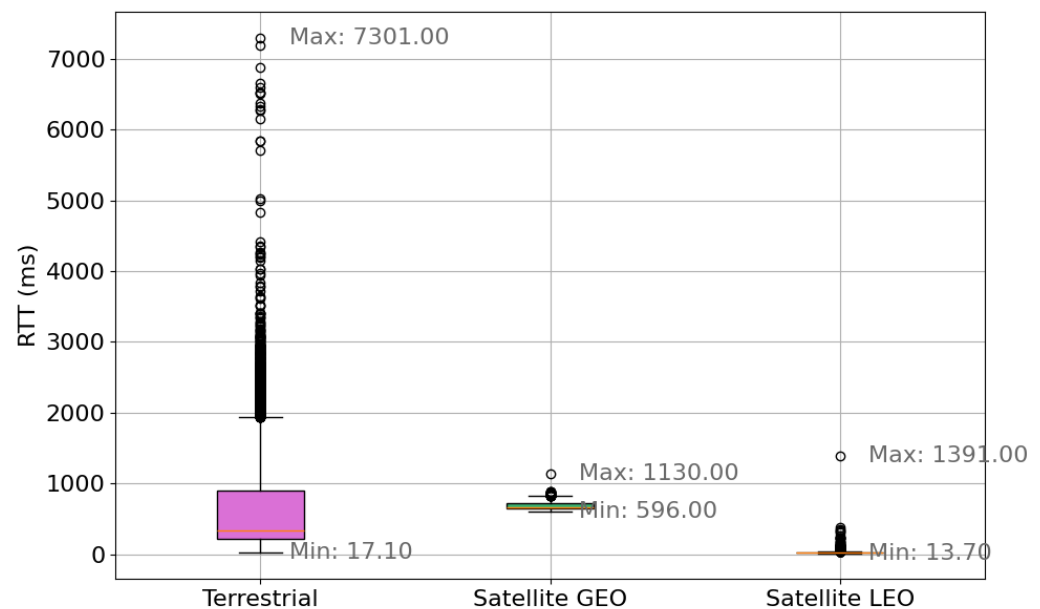


Figure 16. Network latency distribution.

To conclude, these tests demonstrate that the local Wi-Fi over satellite backhauling is a robust and stable solution to record and upload videos in the field. The average latency is high, this is expected given the distance the signal is traveling, but stable over time: the RTT average value is 685 ms, while the standard deviation is only 56 for the GEO satellite, and 28 ms with a standard deviation of 20 for the LEO satellite.

5. Cost–Benefit Analysis

Access to reliable connectivity infrastructure in remote areas remains a critical prerequisite for bridging the digital divide and enabling the digital transformation of rural communities. Beyond small and periodic IoT data transmissions, emerging applications such as DT require continuous connectivity and significantly larger data streams. While LPWAN technologies can provide sufficient uplink and downlink capacity for sensor data over wide coverage areas, and additional broadband technologies are necessary to meet the higher bandwidth demands associated with uploading images and video content. This highlights the need for a robust backhauling network capable of supporting heterogeneous

traffic with diverse performance requirements, particularly in locations where terrestrial networks are unavailable or inadequate.

In this context, satellite backhauling emerges as a compelling solution. Results from the previous experiments demonstrate that both LEO and GEO satellite systems successfully supported the two use cases under analysis, characterized by small and large data volumes, delivering a stable and consistent connectivity solution.

Furthermore, recent technological advancements in the satellite industry, combined with the availability of rapidly deployable terminals such as SatCube for GEO and Starlink for LEO, are significantly lowering the barriers to adoption. Several satellite operators are now offering a new generation of satellite backhauling solutions featuring plug-and-play terminals and scalable bandwidth options.

However, the cost of satellite equipment and recurring bandwidth fees generally remains higher than those of cellular networks, when the latter are available. From a unit-cost perspective, cellular backhauling solutions typically appear more economical. However, satellite operators increasingly offer subscription plans with fees comparable to basic cellular services, while the upfront investment per terminal typically ranges between 400 and 1200 euros [15].

Nevertheless, when costs are evaluated in relation to the actual demand of the use cases and applications, rather than on a per-unit basis, the cost structure appears more favorable. Results from the previous experiment show that the first use case on environmental monitoring generated approximately 1.4 GB of uploaded data over a two-day period. This data volume can be comfortably supported by entry-level connectivity plans offered by satellite operators, with monthly subscription fees typically ranging from 40 to 60 euros. When such a connectivity solution is deployed over large agricultural areas where IoT sensors are distributed across wide fields and can be aggregated through long-range technologies such as LoRaWAN, whose coverage in open environments can extend over several kilometers, the cost of the satellite terminal can be efficiently amortized. In this context, a single terminal can serve a large number of end devices, significantly improving the overall cost efficiency of the solution.

Figure 17 presents the cost of three different configurations, where IoT data collection can be enabled with different technologies to cover 50, 100, and 500 End Devices (ED) in an area within the gateway coverage. In the first scenario (presented in pink), all the EDs send sensor data directly using a cellular network, both in the access and backhaul segment. IoT data plan costs vary largely, depending on the region, data usage, and operator-bundled IoT plans (NB-IoT, LTE-M solutions or simple data plans with minimum subscription cost). For this analysis, to cover all these options, we assume a subscription cost ranging from 2 to 10 euros per month per device. In the second (green) and third (blue) scenarios, the sensors are covered with a LoRaWAN gateway supported by a cellular backhauling link or satellite backhauling link, respectively. Table 2 summarizes the costs considered for this analysis:

Table 2. Connectivity infrastructure costs.

Connectivity Infrastructure	Range of Cost (Euros)
Satellite Terminal	400–1200
Satellite Monthly subscription	40–60
LoRaWAN gateway	200–500
Gateway cellular Monthly subscription	5–15
Cellular ED Monthly subscription	2–10

The bars in Figure 17 show the average cost of the different solutions, while the error bars show the variation of the cost considering the range of prices in Table 2. As the number of deployed devices increases, the cost of the overall connectivity solution scales accordingly, particularly when each device requires an individual wide-area subscription. In this context, the use of a LoRaWAN gateway becomes advantageous, as it aggregates data from multiple end devices and forwards the consolidated traffic through a single backhaul link. It is also important to mention that in an “All Cellular” configuration, all the costs are recurring as a monthly subscription. While with the other solutions, 93% to 97% of the costs are paid only once. As a shared infrastructure, where the covered EDs are installed in several fields belonging to different farmers, it is clear that the costs of the LoRa gateway and satellite terminal are quickly amortized. This architecture makes these solutions more cost-effective than a basic cellular alternative, where each farmer would otherwise pay a monthly subscription for each device.

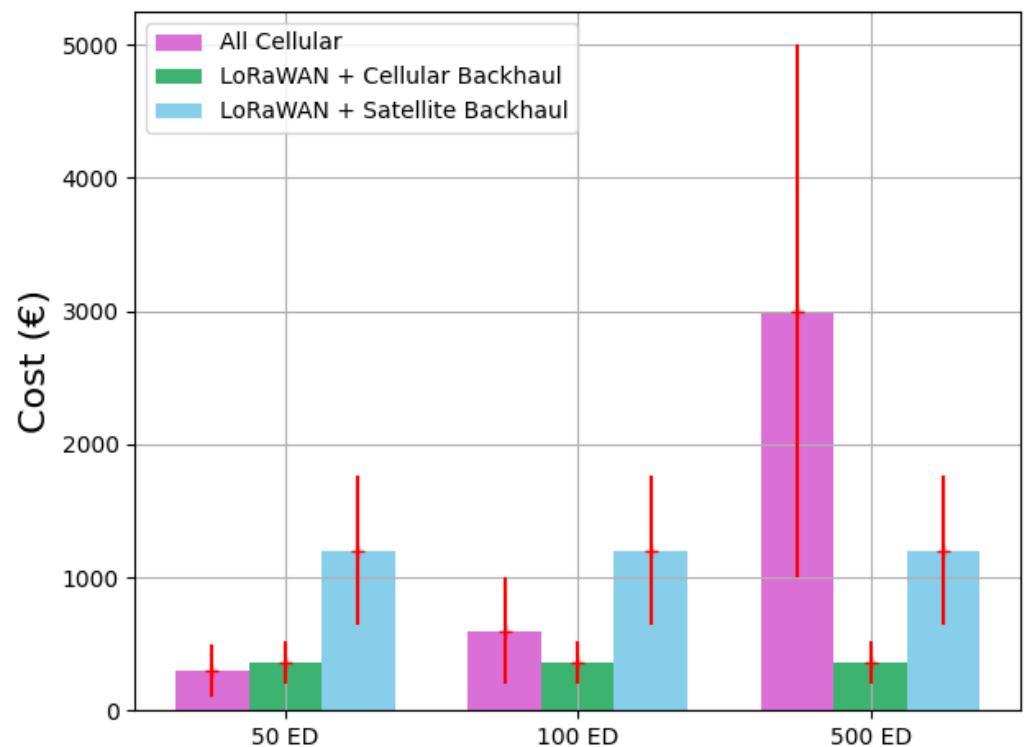


Figure 17. IoT connectivity solutions: cost breakdown.

In the second use case, a video recorded along a single crop row of 80 m has an average size of approximately 500 MB. To assess the volume of data generated in this scenario, we consider two agricultural fields of different sizes: 80 × 300 m and 500 × 1500 m, assuming an average row spacing of 2 m. Under these assumptions, the first field would generate approximately 75 GB of video data, whereas the second field would produce about 2.25 TB.

As the size of the cultivated area increases, both the volume of generated data and the associated bandwidth requirements grow significantly. For individual small-scale farmers, connectivity solutions based on low-cost, rapidly deployable satellite terminals may be sufficient and relatively affordable, particularly when the value extracted from the uploaded data offsets the terminal cost. However, as data generation scales up, recurring subscription fees for satellite services can surpass the initial infrastructure investment and become the dominant cost factor.

In this context, solutions based on high-end satellite terminals become more cost-efficient. Although such terminals can cost up to 5000 euros, with subscription fees reaching

approximately 300 euros per month, they provide substantially higher bandwidth and can support multiple users and applications simultaneously. This type of solution enables both use cases to operate in parallel: wide-area IoT data collection and broadband connectivity for large-scale video uploads.

The costs of infrastructure can be amortized when a broader perspective is adopted. Deploying a shared connectivity infrastructure across a large area, composed of several agricultural fields, makes the use of high-end satellite backhauling link the most efficient solution, from both technical and economic perspectives.

However, the deployment of satellite backhauling links, similarly to terrestrial cellular infrastructures, involves practical challenges that must be considered during implementation. Installation in remote areas may require careful planning regarding equipment transportation, power supply, and infrastructure placement, particularly in agricultural environments where accessibility and vegetation conditions vary over time. Terminal alignment, regulatory compliance, and logistical aspects, such as hardware provisioning and technical support, add to deployment constraints that also affect the expansion of cellular networks in underserved regions and contribute to the persistence of the digital divide. Maintenance considerations, including environmental exposure and periodic equipment inspection, are likewise common across connectivity technologies. Within this context, satellite backhauling should be viewed as a complementary solution capable of extending connectivity where terrestrial deployments remain economically or technically challenging.

6. Conclusions

This paper investigates the use of satellite backhauling to extend connectivity in rural and remote areas, enabling the widespread digitization of agriculture. Both GEO and LEO satellite links were evaluated across multiple use cases and benchmarked against terrestrial networks through laboratory experiments and field trials. In the lab, end-to-end delivery of IoT data packets remained stable across all backhaul options, demonstrating that LoRaWAN deployments supported by satellite links can reliably enable monitoring applications over large, isolated agricultural fields.

Beyond low-bandwidth IoT traffic, satellite backhauling also proved to be effective for high-bandwidth applications. Field trials involving in situ video capture and upload showed consistent and reliable performance over satellite links, whereas public cellular networks exhibited unstable behavior despite occasionally higher average upload speeds. These results highlight the capability of satellite backhaul to support both IoT telemetry and bandwidth-intensive applications, bridging connectivity gaps in areas underserved by terrestrial networks.

Besides technical performance, this study includes a qualitative cost–benefit analysis, providing critical insights into the economic feasibility and scalability of the satellite-enabled connectivity solution. Although satellite communications may involve higher per-unit costs compared to terrestrial solutions, cost efficiency improves when satellite infrastructure supports multiple applications or serves a shared community of users, amortizing deployment expenses. By enabling reliable end-to-end connectivity, satellite backhauling provides the foundation for data-driven agricultural decision-making, supporting sustainable and resilient rural development.

Author Contributions: S.S. led the work by defining the testing methodology, deploying the back-hauling solutions, and testing them both in the lab and the real environment (vineyards). She was also in charge of the draft preparation and analysis of the results. M.R.P. closely supervised the work, reviewed and edited the draft, and was in charge of securing the research funding to conduct the work. J.D.N.C. was in charge of the installation and configuration of the SES satellite terminal. He supported the draft writing, with the description of the GEO satellite backhauling. C.P. supervised and coordinated the work at SES, among different teams, for the set-up of the GEO satellite backhauling. He also discussed the results and reviewed the paper. All authors have read and agreed to the published version of the manuscript.

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