Satellite-IoT Integration for Digital Agriculture: Advances and Challenges

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Abstract.

Agriculture is an essential pillar of global food security, demanding continuous digital integration from seed selection and planting to post-harvest logistics and crop distribution. In this scenario, seamless communication is the primary enabler for data-driven decision-making, ensuring that critical information regarding environmental variables, soil moisture, and direct plant health indicators reaches processing platforms fast enough for agile operational responses. However, the expansion of digital agriculture is constrained by a critical connectivity gap, particularly in major agricultural producers like Brazil. In such regions, vast productive areas lack reliable 4G or 5G coverage, as traditional terrestrial infrastructure is often economically impractical due to the immense territorial scale of these rural environments.

To mitigate these limitations, satellite-based Non-Terrestrial Networks (NTNs) have emerged as a transformative solution to provide ubiquitous coverage. This paper examines the integration of satellite NTNs into IoT systems for digital agriculture, focusing on the performance and applicability of low-power satellite-based networks. The research provides a comprehensive analysis of the fundamental communication requirements of the agricultural sector, identifying the specific advantages and limitations of different communication protocols alongside the technical characteristics of various available orbital infrastructures.

This research investigates the core technical parameters essential for scalable and sustainable deployments, prioritizing a detailed transmission time analysis to assess how the propagation delays inherent to different satellite altitudes impact data freshness and system responsiveness. Furthermore, the paper evaluates the feasibility of bidirectional communication, which is crucial for remote actuator control and dynamic device configuration in the field. The analysis also addresses the energy consumption of field devices, which are typically energy-constrained and rely on long-term battery autonomy to operate in isolated areas without frequent maintenance access. The work further explores promising hybrid architectures, focusing on the integration of Wireless Sensor Networks (WSN) with satellite backhaul to bridge the gap between local sensing and global connectivity. By consolidating standardization efforts, this study identifies critical technological gaps and assists in the selection of appropriate solutions for diverse agricultural applications, providing a foundation for implementing reliable and energy-efficient satellite communication infrastructures in agribusiness.

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Keywords.

Digital Agriculture, Wireless Sensor Networks, Non-Terrestrial Networks, Low-Power Wide-Area networks, Satellite Communications

Introduction

The growth of the global population demands higher agricultural productivity, even under limited resources (FAO, 2025). Precision Agriculture (PA) emerges as a strategic response to manage crop variability. In this scenario, the Internet of Things (IoT) acts as a fundamental enabler where soil sensors, weather stations, and imagery generate continuous data for decision-making models, enabling the localized and precise application of fertilizers, water, and pesticides (Díaz et al., 2025). However, these IoT applications share technical requirements that dictate the choice of communication technologies, such as low power consumption, wide geographical coverage, low data transmission rates, and latency tolerance.

Despite advances in sensors and data analytics platforms, the effective operation of PA systems critically depends on communication infrastructures capable of connecting devices spread across large territorial expanses, often located in regions where terrestrial cellular networks are scarce or nonexistent. In Brazil, the ConectarAGRO Association, in partnership with the Federal University of Viçosa, developed the Rural Connectivity Indicator (RCI), which revealed that only 33.9% of Brazil's arable land had 4G or 5G coverage in 2025, with heavy concentration in the South and Southeast regions, evidencing a significant connectivity gap in rural areas (ConectarAGRO & UFV, 2025). On a global scale, the diagnosis is equally critical. In the United States, the FCC Task Force for Reviewing the Connectivity and Technology Needs of Precision Agriculture in the United States report prioritizes achieving Last Acre connectivity, defined as extending high-capacity internet to croplands and animal operations, and recommends expanding wireless networks, allocating more spectrum for agricultural use, and encouraging targeted development of both terrestrial and satellite connectivity to bridge remaining gaps (FCC, 2024). Australia's AgriFutures similarly points out that persistent connectivity gaps in remote agricultural regions demand alternative solutions to conventional terrestrial networks. This converging scenario demonstrates that traditional communication infrastructures are insufficient to meet the connectivity needs of the rural environment, especially for farms located in remote areas (AgriFutures Australia, 2026).

Non-Terrestrial Networks (NTN) emerge as a promising alternative to fill the connectivity gap in rural areas. Unlike satellite broadband solutions such as Starlink and OneWeb, which require high-power terminals and high data rates, LPWAN technologies adapted for direct satellite links are specifically designed for low data rate and high latency tolerance applications, intrinsic characteristics of agricultural monitoring scenarios. These solutions, classified as Direct-to-Satellite IoT (DtS-IoT), generally operate in sub-GHz frequency bands with excellent penetration through dense vegetation, offering a unique combination of ultra-low energy consumption and wide geographic coverage (Susilo & Suryana, 2023). Hybrid TN-NTN (Terrestrial-Non-Terrestrial) architectures have been proposed as the most viable path to integrate local terrestrial gateways with Low Earth Orbit (LEO) and Very Low Earth Orbit (VLEO) satellite constellations, allowing sensor data to be relayed even in the absence of nearby cellular networks.

In this work, a study of the main requirements for applications in precision agriculture and livestock farming is carried out. Subsequently, the main non-terrestrial communication topologies are presented, with a focus on satellite communication using LPWA networks for low-power operation, including the possibility of hybrid terrestrial-satellite communication architectures. The main protocols for this type of satellite application are presented, and an analysis of their key technical characteristics is performed. Analyses regarding the energy consumption of the protocol and transmission latencies are conducted. Finally, the main open challenges for the application of satellite communication in precision agriculture and its application limits are discussed.

Communication Requirements in Agriculture

Communication requirements in agriculture are strongly influenced by the type of data being collected. This paper focuses on small data payloads, typically consisting of tens to hundreds of bytes, and transmit data at low reporting rates, ranging from a few times per hour to a few times per day. This is the case for the sensors listed in Table 1, which summarizes the main sensor types used in agricultural IoT applications, including soil, crop health, environmental, livestock, and plant wearable sensors. These sensors typically generate compact outputs, such as moisture percentage, temperature, pH, NDVI, chlorophyll index, and coordinates. Such data support applications including irrigation, nutrient management, crop monitoring, disease and pest detection, climate forecasting, animal welfare tracking, and plant stress detection.

To adequately understand communication requirements, it is necessary to consider not only the sensor data but also the agricultural applications in which this information is used, as communication demands vary significantly by application. For this reason, the following paragraphs describe in detail some representative agricultural applications and their corresponding communication requirements.

Table 1. Characteristics of sensors in agriculture. Adapted from (Manono et al., 2026).

Sensor Application	Parameters Measured	Typical Data Output	Application Domain
Soil	Moisture, temperature, pH, electrical conductivity/salinity, N–P–K nutrients, organic matter	% moisture; °C; pH value; ppm	Irrigation; nutrient management
Crop Health	Leaf spectral response, vegetation indices, growth rate, biomass, chlorophyll content	NDVI; chlorophyll index; vegetation indices; biomass estimates	Crop monitoring; stress detection; disease/pest detection
Environmental	Air temperature, humidity, rainfall, light intensity, wind speed	°C; % RH; mm; lux; m/s	Climate monitoring; forecast
Livestock	Body temperature; heart rate; respiration rate; location; acceleration	Activity index; coordinates; BPM	Animal welfare; tracking; health monitoring;
Plant Wearables	Growth parameters; physiological conditions	Growth rate; water potential	Plant physiology; stress detection

Smart irrigation is a relevant application in agriculture, mainly because it is directly associated with efficient water use, one of the most critical resources in agricultural production. Irrigation systems commonly use soil moisture, soil temperature, and weather information to support or automate decisions to irrigation scheduling. In this systems, messages are small, the required data rate may be on the order of a few kbps, and the tolerable latency may range from a few seconds to approximately one minute, depending on the level of automation and the criticality of the control loop (Damsgaard et al., 2022; Manono et al., 2026).

In soil health monitoring applications, sensors typically measure soil moisture, temperature, pH, electrical conductivity, salinity, and nutrients like nitrogen, phosphorus, and potassium, as well as organic matter, to provide information that supports practices such as targeted fertilization at appropriate rates, thereby improving crop productivity (Kim & Lee, 2022). In many cases, these variables evolve slowly and are associated with small payloads and low reporting frequencies. However, data reliability and temporal continuity remain important, since communication failures may compromise management decisions, especially in automated decision-making systems (Eldeeb et al., 2023).

Environmental monitoring in agriculture involves the continuous observation of environmental variables, including temperature, humidity, light intensity, solar radiation, and rainfall, to support frost risk assessment and greenhouse climate management. In general, the traffic generated by each node is low, often below 1 kbps, and the latency tolerance may be greater than one second because many decisions do not require immediate response (Manono et al., 2026; Qiang et al., 2025).

In livestock systems, cattle location tracking is an important application for extensive herd management. Devices that support GNSS can periodically transmit animal positions, enabling movement analysis, escape detection, and grazing pattern identification. Location messages are generally small, since they may include only coordinates, timestamps, and basic identifiers. The reporting frequency may be on the order of minutes, and delays on the order of seconds may be acceptable. Applications involving safety or abnormal behavior detection may require more frequent updates and lower latency (BNDES, 2017; Evstatiev et al., 2022; Qiang et al., 2025).

Animal health monitoring uses sensors capable of measuring physiological and behavioral parameters, such as body temperature, pH, activity level, rumination patterns, or other indicators associated with animal welfare and clinical condition. These systems may rely on wearable sensors or internal capsules, enabling early disease detection, stress monitoring, and feeding management support. In general, the messages generated are small and can be transmitted at intervals of hours. However, energy consumption and communication reliability are important constraints, especially because the capsules may be difficult to access for maintenance or battery replacement. An additional problem with using capsules is that the animal's body may attenuate the communication signal (BNDES, 2017; Evstatiev et al., 2022; Valadao et al., 2021).

Another relevant livestock application is the monitoring of animal weight and feeding behavior. In this case, weighing scales, smart feeders, and individual identification systems can be used to track animal development, adjust diets, and determine suitable management or slaughter periods. Unlike periodic physiological monitoring, these applications may generate bursts of messages at specific moments, for example when several animals pass through a scale or access a feeding station. The size of each message may still be relatively small, but the aggregated traffic can reach hundreds of messages per hour (BNDES, 2017).

In agricultural machines, logistics-oriented applications, such as route updates, machine positioning, tank or bin level monitoring, and operational coordination, may require moderate data rates (around 0.5 Mbps), small data blocks, and sufficient reliability to maintain consistent operational information. In these cases, the communication system must support mobility, channel variability, and coverage over large areas (Damsgaard et al., 2022).

It is important to note that the communication requirements discussed in this section may vary depending on the specific implementation and sensing utilized. For example, animal monitoring systems may rely on cameras to detect or locate animals. In this case, the data rate would be higher than the values reported. Table 2 summarizes the communication requirements of the applications discussed in this section. Overall, communication requirements in smart agriculture should not be treated as uniform. Environmental sensing, soil monitoring, irrigation, and livestock applications usually generate small, sparse, and delay-tolerant traffic, but require low energy consumption and wide-area coverage. In contrast, applications involving vehicles and remote operation demand a moderate data rate, lower latency, and greater reliability.

Table 2. Characteristics of agriculture applications.

Application	Latency	Data rate	Energy consumption
Environmental monitoring	>1 second	<1 kbps per node; small periodic packets	Low; weather stations or sensors are often battery- or solar-powered
Soil monitoring	Seconds to minutes; delay-tolerant	Low; <1 kbps per node with sparse measurements.	Very low; long-term battery operation is usually required
Smart irrigation	Few seconds to one minute	Low; few kbps for sensor readings and control messages	Low to moderate; sensors should be low power, while valves/pumps may have local power or larger batteries
Livestock tracking	Few seconds	Low; small data messages with reporting frequency of minutes.	Low; wearable tags require long battery lifetime

Animal health monitoring	Few minutes	Low; few-byte at interval of hours	Low; wearables or ingestible devices are difficult to recharge or replace.
Animal weight and feeding monitoring	Hundreds of milliseconds to few seconds	Low to moderate; small messages, but aggregated traffic may reach hundreds of messages per hour.	Low to moderate; fixed infrastructure can often use mains power, while animal identifiers should remain low power.

Non Terrestrial Networks

The typical architecture for agricultural IoT can be described in three functional. At the bottom, the physical layer comprises the sensors and actuators that capture environmental parameters from the field. Above it, the network layer provides the data path: end devices transmit exclusively through gateways, which forward the data to a network server, following a star-of-stars topology. Beyond mere relays, gateways also optimize traffic and preserve message integrity through duplication mechanisms. Finally, the application layer, typically hosted in a server, processes and filters the collected data, turning raw measurements into actionable insights for decision-making. In large fields, multiple gateways may be required to cover a high number of sensors, whereas in small deployments the architecture can be simplified (Aldhaheri et al., 2025).

Due to the lack of connectivity, many agricultural environments have limited or no access to the Internet through cellular, Wi-Fi, or other conventional networks. Therefore, connectivity must be provisioned through alternative means, leading to the emergence of non-terrestrial networks. These networks can be deployed using various platforms, such as unmanned aerial vehicles (UAVs), High-Altitude Platform Stations (HAPS), or even satellites. In these scenarios, such platforms can act as a gateway and receive data from edge devices or sensors.

UAVs can carry relays or act as aerial base stations to provide communication services for remote nodes, overcoming the need for fixed infrastructure and being more effective against channel fading. HAPS operates at around 20 km in the stratosphere with a coverage radius of up to 500 km, maintains a signal-to-noise ratio similar to terrestrial base stations, and can serve IoT nodes continuously for months using renewable energy, offering wider coverage and longer endurance compared to UAVs (Deng et al., 2024)

In addition to the communication forms previously mentioned, satellite networks have become a key enabler for connectivity in areas where traditional networks are not available, such as agricultural applications. The use of LPWAN protocols in satellite communication has gained widespread adoption due to their main characteristics, such as low energy consumption and long range. Furthermore, these characteristics meet the key requirements for connectivity in agricultural applications. In this context, both Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geostationary Orbit (GEO) satellites can be considered, each presenting different trade-offs in terms of altitude, latency, and visibility. Table 3 summarizes these characteristics. The use of these LPWAN protocols enables direct communication to the satellite, thus allowing devices in remote areas to transmit their data to cloud applications, for example.

Table 3: Satellite orbits main characteristics.

Orbit	Distance (km)	Latency	Visibility
LEO	200 - 2000	Low	~5 - 10 min
MEO	2000 - 25000	Medium	1 - 2 hours
GEO	35786	High	24 hours

In a satellite communication scenario, different communication architectures may be present. Figure 1 illustrates both direct communication between ground devices and satellites, as well as the use of satellites as a backhaul link to transmit already consolidated data to the network. The main objective is to make field-collected data available to applications, enabling, for example, data-driven decision-making. It should be noted that the figure is intended to illustrate the diversity of possible solutions. Therefore, it does not exhaustively depict all possible architectures, but rather presents only a few representative configurations for demonstration purposes.

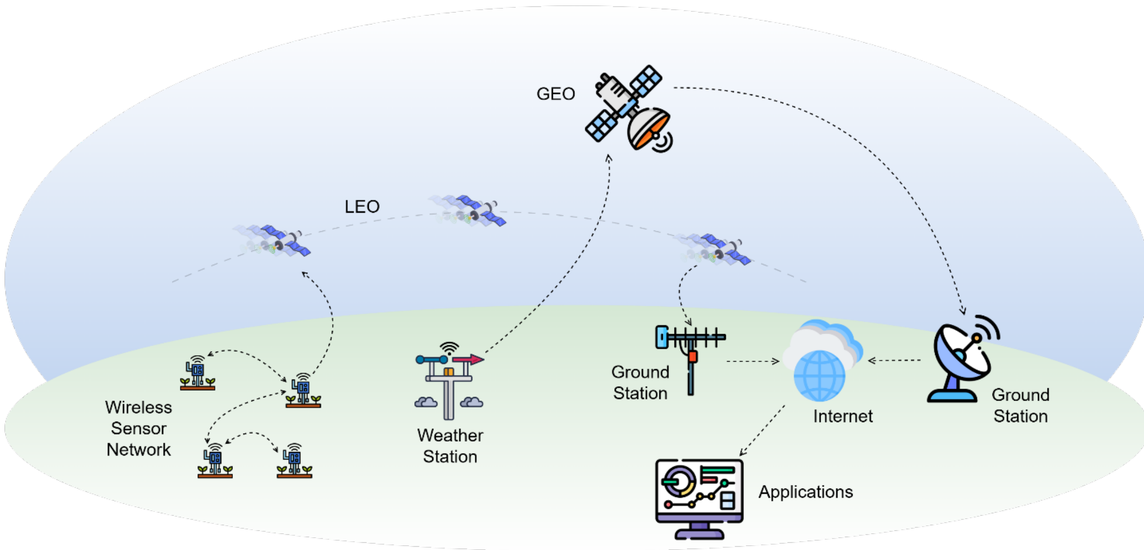

Figure 1 - Hybrid satellite communication architectures.

The integration of terrestrial networks using satellite backhaul has been presented as an enabler for improving network performance. This operational approach leverages the main advantages of terrestrial networks, such as long-range communication and low energy consumption, while using centralizing devices to upload data to the satellite. The operation reduces the need for direct satellite transmissions from multiple energy-constrained devices, which minimize overall energy consumption and improve packet delivery performance. Due to the limited visibility window of a LEO satellite some problems can occur, for example, packet collisions when multiple field devices attempt to transmit during its pass. For this reason, the use of integrated networks with field data centralization also aims to reduce this type of contention problem.

In the following section, the main LPWAN protocols available for use with satellite networks are presented. Some of them already have established commercial satellite deployments, while others are still in the early stages of development.

Satellite-Based Low-Power Wide-Area Networks

This section presents the communication technologies suitable for low-data-volume and delay-tolerant IoT applications supported by satellite. As previously introduced, LPWAN technologies are particularly relevant in this context due to their long communication range, low power consumption, and ability to support a large number of devices, which are essential requirements in many digital agriculture application (Mekki et al., 2019).

LPWAN for Satellite communication

LoRa is a physical-layer technology developed by Semtech that employs Chirp Spread Spectrum (CSS) modulation in the sub-GHz ISM bands. The Spreading Factor (SF) tunes the trade-off between range and data rate, where higher SFs increase receiver sensitivity and range but raise the Time-on-Air (ToA) and lower the data rate (Mekki et al., 2019). On top of this physical layer runs LoRaWAN, the network protocol standardized by the LoRa Alliance, based on a star topology and pure-ALOHA medium access. Among its three device classes, namely A, B, and C, where class A has the lowest consumption and is the only one suited to energy-constrained satellite scenarios (LoRa Alliance, 2023). In the Direct-to-Satellite (D2S) link, high SFs, SF11-12, are typically required to compensate for the greater path loss of LEO links. However, due to the long ToA under these conditions, it is necessary to evaluate the problems caused by the Doppler effect, which can impact communication performance. Therefore, the extended range is obtained at the cost of a prolonged ToA with a direct impact on per-packet energy consumption and Doppler effect accumulated impact (Machado et al., 2025; Susilo & Suryana, 2023).

Long Range Frequency Hopping Spread Spectrum (LR-FHSS) is an extension of the LoRa physical layer introduced by the LoRa Alliance to increase network capacity and enable the D2S link at satellite scale. Unlike conventional LoRa, based on CSS, LR-FHSS employs GMSK modulation with intra-packet frequency hopping where each message is fragmented into small bursts transmitted on distinct physical channels within an Operating Channel Width (OCW), following a pseudo-random sequence. The combination of frequency diversity, header replication, and low code rate provides strong collision robustness, making LR-FHSS particularly suitable for dense networks and the satellite scenario, where hundreds of packets can be received simultaneously by an orbital gateway. However, LR-FHSS achieves a low per-device data rate. Therefore, a trade-off between collision robustness and individual data rate must be considered (Boquet et al., 2021; Ullah et al., 2022).

NB-IoT is a 3GPP cellular standard, introduced in Release 13 (2016), operating in licensed bands with a 180 kHz bandwidth per carrier, using OFDMA in the downlink and SC-FDMA in the uplink. Unlike the other technologies analyzed, which operate in unlicensed bands, NB-IoT reuses the existing LTE infrastructure, granting it higher quality of service at the cost of licensed-spectrum usage. Its extended coverage relies on transmission repetition, a mechanism that increases the energy accumulated at the receiver (Wang et al., 2017). Support for non-terrestrial networks was formalized in Release 17, with adaptations to the timing advance and Doppler-compensation mechanisms for LEO and GEO satellites, adaptations essential given the greater propagation delay and the high relative velocity of the satellites. In the satellite context, NB-IoT stands out as the only licensed option among those analyzed, offering robustness and cellular integration at the cost of greater complexity and higher per-transmission consumption arising from synchronous operation (Liberg et al., 2020).

mioty is an open standard specified by European Telecommunication Standards Institute TS 103 357 (ETSI, 2018) operating in the sub-GHz ISM bands and employing Telegram Splitting Multiple Access (TSMA). Each message is split into multiple short bursts, 24 sub-bursts in the core frame, transmitted at distinct frequencies and time instants, following a pseudo-random time-frequency pattern, which provides high robustness to interference and collisions: the channel coding allows the telegram to be reconstructed even if more than 50% of the bursts are lost (Fraunhofer IIS, 2018). MSK/GMSK modulation with a synchronization sequence inserted in each burst enables coherent demodulation at the receiver, with a gain of about 2.5 dB over non-coherent detection (Fraunhofer IIS, 2018). The mioty TSMA strategy supports a greater number of devices than other LPWAN technologies, making it particularly suitable for large-scale deployments and the high-density satellite scenario. Its support for direct satellite communication has been the subject of recent evaluation, reinforcing the protocol's position as a DtS-IoT candidate (Lee et al., 2025).

Comparative overview and use cases

Table 4 summarizes the presented communication technologies in terms of modulation, data rate, maximum payload, range, and bandwidth, supporting the selection of a protocol according to the requirements of a given application. All technologies have native or in-development support for NTN, particularly LEO satellites (Susilo & Suryana, 2023).

Communication technologies selection depends on the application requirements. In smart irrigation, which uses soil moisture and temperature measurements to automate watering scheduling, messages are small and the tolerable latency ranges from a few seconds to about one minute, depending on the criticality of the control loop; technologies such as LoRaWAN can be employed, with the final choice depending on coverage area, available infrastructure, energy consumption, and reliability requirements (Manono et al., 2026).

Table 4. Technical characteristics of LPWAN protocols with satellite communication support (Boquet et al., 2021; Fraunhofer IIS, 2018; Lee et al., 2025; Mekki et al., 2019).

Protocol	Modulation	Data rate	Max. payload	Range (urban / rural)	Bandwidth
LoRa / LoRaWAN	CSS	0.3-50 Kbps	243 B	5-20 km	125 / 250 kHz
NB-IoT	QPSK	up to 200 kbps (DL)	1600 B	1-10 km	180 KHz
LR-FHSS	GMSK + freq. hopping	162 / 325 bps	~58 - 123 B	5-20 km	137 / 336 kHz
mioty	MSK / GMSK (TS-UNB)	2380 sym/s (ULP)	255 B	5-15 km	25 / 100 / 725 kHz

In environmental and soil monitoring, the per-node traffic is low (often below 1 kbps) and the delay tolerance is high; networks such as LoRaWAN and NTN-based solutions can provide coverage in remote areas, with the integration of terrestrial and non-terrestrial networks being relevant where conventional infrastructure is insufficient (Qiang et al., 2025).

In livestock systems, GNSS-based animal location tracking transmits small messages (coordinates, timestamps, and identifiers) at minute-scale intervals. IoT-over-NTN solutions are relevant alternatives for this scenario, given their wide coverage and low-power operation. In animal health monitoring, with wearable sensors or internal capsules measuring body temperature and activity patterns at hourly intervals, energy consumption and reliability are important constraints, and LPWA and NB-IoT solutions are commonly considered (BNDES, 2017; Qiang et al., 2025).

Energy consumption

In remote, battery-powered agricultural IoT devices, data transmission is one of the main sources of active energy consumption, and its relative weight in the overall budget grows with the transmission frequency; for long reporting intervals, sleep-mode consumption may become dominant (Sanchez-Vital et al., 2024). To compare protocols under the same reporting pattern, the Time-on-Air (ToA) is the parameter that determines the energy spent per packet: since the current during transmission is essentially the same for a given radio hardware, approximately 38 mA at 13 dBm for the SX1276 chip, the per-packet consumption is directly proportional to the ToA (Robert & Lauterbach, 2026).

In LoRa, the ToA grows steeply with the spreading factor. While other parameters (e.g., bandwidth, coding rate, payload size) also affect transmission time, the impact of the SF itself is significant. For a given configuration, SF7 requires approximately 62 ms, whereas SF12 requires approximately 1483 ms (Robert & Lauterbach, 2026). In satellite applications, where high LoRa SFs are mandatory to compensate for path loss, this ToA increase translates directly into higher per-packet consumption. Among the three LoRaWAN classes, only Class A, which opens two short receive windows after each uplink and remains asleep otherwise, is energy-viable in satellite scenarios, the lifetime estimates in this study are based on it. The Adaptive Data Rate (ADR) mechanism dynamically lowers the SF when link quality allows, reducing ToA and consumption (LoRa Alliance, 2023; Mekki et al., 2019; Robert & Lauterbach, 2026).

NB-IoT exhibits higher per-transmission current consumption than the other LPWAN protocols, owing to its synchronous communication, QoS support, and OFDMA/SC-FDMA structure, which demands a higher peak current (Mekki et al., 2019; Oh & Shin, 2017). This profile is offset by the PSM and eDRX power-saving modes, which keep the device in deep sleep between transmissions. Real-hardware measurements show that, with proper traffic configuration and under good coverage, the battery life can approach 10 years; under poor coverage, however, the large number of required repetitions significantly reduces this figure (Sorensen et al., 2022). This behavior makes NB-IoT competitive in low-reporting-frequency applications, albeit at the cost of greater complexity and dependence on licensed spectrum.

LR-FHSS, by employing frequency hopping with header replication, has a characteristic transmission overhead. Each physical header lasts 233 ms and, in DR8 mode (CR 1/3), is transmitted three times, accumulating ~700 ms before the payload; the total frame transmission time for a small payload reaches ~1573 ms. Real-hardware measurements, using a 230 mAh coin-cell battery and accounting only for the radio module, indicate a battery life of ~2.5 years for a 50-minute notification interval, extending up to ~16 years for daily intervals in the most efficient configuration. Like LoRa, LR-FHSS operates in Class A, and its main gain lies in network capacity rather than in the energy profile (Sanchez-Vital et al., 2024).

mioty, in turn, benefits from its fixed symbol rate (2380 sym/s in ULP mode) and the coherent demodulation enabled by the synchronization signals inserted in each burst. The on-air time of a 10-byte core frame is only ~363 ms, and the inter-burst pauses reduce the peak current (Fraunhofer IIS, 2018). Under the same reference conditions used for LoRa (1000 mAh battery, 96 packets per day, radio module only), the estimated battery life for mioty is ~8.9 years, against ~2.4 years for LoRa SF12, a direct reflection of its lower ToA and operation close to the theoretical performance limits (Robert & Lauterbach, 2026).

It is important to note that the battery-life estimates reported in the literature are not directly comparable to one another, as they derive from distinct experimental conditions, in particular, different battery capacities, transmission intervals, and coverage scenarios. Only the LoRa SF12 and mioty values, obtained under the same assumptions, a 1000 mAh battery and 96 packets per day (Robert & Lauterbach, 2026), allow a direct comparison. For NB-IoT, the ~10-year battery life assumes proper traffic configuration and good coverage, under poor coverage, the large number of repetitions significantly reduces this figure (Sorensen et al., 2022). For LR-FHSS, the value ranges from ~2.5 years, with a 50-minute notification interval, to ~16 years, for daily intervals in the most efficient configuration, always with a 230 mAh battery and accounting only for the radio module (Sanchez-Vital et al., 2024). The values should therefore be interpreted as orders of magnitude rather than equivalent measurements.

In summary, the comparison reveals a trade-off between capacity, robustness, and autonomy. Under identical conditions, mioty offers the longest battery life among the unlicensed-band protocols, a direct result of its lower ToA and coherent demodulation. NB-IoT, despite its higher per-transmission consumption, compensates with deep-sleep modes that make it competitive in low-reporting-frequency applications. LoRa and LR-FHSS show autonomies of the same order of magnitude, with LR-FHSS being advantageous for its aggregate capacity in dense networks rather than for its energy profile. Protocol selection therefore depends on the transmission frequency, payload size, coverage requirements, and available satellite infrastructure. Table 5 summarizes the parameters, with each protocol's conditions indicated in the corresponding cell.

Table 5. Energy comparison of LPWAN protocols with satellite NTN support. Adapted from: (Fraunhofer IIS, 2018; Robert & Lauterbach, 2026; Sanchez-Vital et al., 2024; Sorensen et al., 2022).

Protocol	Power-saving mechanism	Typical ToA (10 B)	Est. battery life
LoRa SF12	ADR, Class A, duty cycle	~1,483 ms	~2.4 years (1000 mAh, 96 pkt/day)
NB-IoT	PSM eDRX	Variable (CE)	~10 years (5 Wh, good coverage)
LR-FHSS	Frequency hopping, duty cycle	~1,573 ms (DR8)	~2.5–16 years (230 mAh, 50 min–1 day)
mioty	TSMA, coherent demod., inter-burst pauses	~363 ms	~8.9 years (1000 mAh, 96 pkt/day)

Integration of Terrestrial and Non-Terrestrial Networks

NTNs have operated as complementary or standalone communication infrastructures, mainly used to provide connectivity in remote areas. However, recent advances have motivated a shift toward the integration of Terrestrial Networks (TNs) and NTNs. In this context, TN–NTN integration refers to the combination of terrestrial communication infrastructures, such as 4G, 5G, Wi-Fi, and fiber-optic networks, with aerial and spaceborne platforms to form a unified communication system (Sacchi et al., 2026). This concept is also commonly associated with Space-Air-Ground Integrated Networks (SAGINs) (Liu et al., 2018) and three-dimensional network architectures.

The main objective of TN-NTN integration is to allow devices, users, and applications to be served by the most suitable communication infrastructure according to network availability, coverage, latency, capacity, reliability, energy consumption, and service requirements. Instead of relying exclusively on either terrestrial or non-terrestrial connectivity, integrated architectures enable flexible access to multiple communication segments. This is particularly relevant for rural, remote, and large-scale environments, where terrestrial infrastructure is often sparse and where satellite or aerial platforms can complement terrestrial-based networks.

The integration of TNs and NTNs offers advantages. First, it extends network coverage by enabling connectivity. Second, it improves network resilience by providing redundant communication links. When terrestrial connectivity is degraded or unavailable, satellite or aerial links can maintain service continuity. Third, integrated TN-NTN architectures can improve overall network performance by dynamically selecting or combining communication paths according to application requirements. This flexibility is especially relevant for IoT scenarios, in which devices may have heterogeneous requirements in terms of latency, reliability, energy consumption, and data rate.

Recent studies have demonstrated the benefits of TN-NTN integration. In (Goyal et al., 2025), the authors propose a hybrid terrestrial and non-terrestrial architecture that combines 5G New Radio (NR), LPWANs, and satellite/HAPS connectivity to provide reliable rural coverage for agriculture and smart grid applications. The authors also develop a QoS-aware path selection algorithm selects the most suitable communication path according to latency, reliability, energy consumption, and cost. The results show that the integrated TN-NTN approach outperforms TN-only and NTN-only solutions in terms of latency, energy consumption, packet loss, and throughput. Similarly, in (Ramírez-Arroyo et al., 2025), the authors experimentally evaluate multi-connectivity using a testbed deployed in a moving terrestrial vehicle, integrating Starlink satellite connectivity with terrestrial cellular connectivity from two mobile network operators. Their results indicate that single-connectivity solutions based only on terrestrial 5G or satellite networks are often insufficient for demanding use cases due to unstable throughput and high latency. In contrast, multi-connectivity strategies provide more stable latency, below 100 ms, as well as more stable uplink and downlink data rates.

Despite these benefits, TN–NTN integration introduces challenges. The authors (Liu et al., 2018) provide a broader perspective on SAGIN, highlighting open challenges, including handover management, traffic offloading, and routing. Unlike terrestrial networks, where traffic offloading mechanisms are relatively mature, offloading traffic between terrestrial, aerial, and satellite segments remains difficult due to heterogeneous network characteristics and dynamic topologies. The mobility of nodes is one of the reasons for the network's dynamism, which also leads to frequent handovers, making efficient inter-segment handover management essential for seamless service continuity. Furthermore, routing remains a critical issue because space and aerial segments present specific constraints, such as non-uniform traffic distribution, limited onboard processing capability, and restricted energy availability.

One major issue is the network orchestration, which requires the coordinated management of heterogeneous segments. In (Sacchi et al., 2026), the authors propose an architecture in which the communication infrastructure is orchestrated through a layer that integrates Software-Defined Networking (SDN), cloud computing, and Artificial Intelligence (AI). In this architecture, AI modules generate predictions and insights to support network management decisions by an SDN controller, which can perform actions such as reconfiguring traffic routing and redistributing computational workloads among network nodes. The cloud operates in a complementary way, coordinating global aspects and long-term optimization.

To address the challenge of limited battery capacity, recent research has explored the concept of Simultaneous Wireless Information and Power Transfer (SWIPT), which enables wireless devices to harvest energy from radio frequency signals while simultaneously receiving information. By converting part of the received RF energy into usable electrical power, SWIPT can extend the operational lifetime of energy-constrained nodes and reduce their dependence on battery replacements or recharging. In (Li et al., 2025), the authors propose a SWIPT-based strategy for integrated satellite and terrestrial networks in which a power-constrained terrestrial user terminal collects energy transmitted by a terrestrial Amplify-and-Forward (AF) relay. The user terminal use this collected energy to operate as a relay node, extending connectivity to IoT devices located beyond the coverage area of the AF.

Computation management is another relevant challenge in TN–NTN and satellite-based IoT systems. In this context, one promising research direction is the integration of edge computing capabilities on satellite networks. In (Nasruddin et al., 2024), the authors comparer a satellite-based edge computing approach with conventional terrestrial networks under different user densities, considering scenarios with 10, 50, and 100 users. The results show that the edge computing approach improve data transmission efficiency. However, the study also indicates that edge computing on satellite is more suitable for small-scale scenarios, since their performance becomes less stable as the number of users increases to 50 or 100.

Performance Analysis and System Constraints

Theorical and Simulated Propagation Delay in NTN

In an NTN, the propagation delay is the single most distinctive constraint separating satellite access from terrestrial deployment. It arises from the physical distance between the user terminal and satellite, which is governed by the slant range and is therefore shortest at zenith and longest at the minimum elevation of 10° assumed in the 3GPP reference scenarios (3GPP, 2023). Because this distance is orders of magnitude larger than in terrestrial networks, the delay grows from the sub-millisecond range of a terrestrial to hundreds of milliseconds for a geostationary link.

Under a transparent (bent-pipe) payload, the baseline architecture standardized in 3GPP Release 17 (3GPP, 2025), in which the gNB resides on the ground, the end-to-end path concatenates two links: the feeder link (gateway–satellite) and the service link (satellite–UE). Since the RTT accounts for both links traversed in each direction, the round-trip spans four propagation segments, which is what raises the RTT to the values in Table 6. Under a regenerative payload, where base-station functions are placed on board the satellite, the feeder link is removed from the NR radio interface, and the RTT contribution is approximately halved.

Table 6. NTN scenarios versus delay constraints (3GPP, 2023).

NTN scenario	Satellite altitude	Min. RTT contribution (gNB-UE)	Max. RTT contribution (gNB-UE)
GEO, transparent payload	35786 km	477.48 ms	541.46 ms
GEO, regenerative payload		238.74 ms	270.73 ms
LEO, transparent payload	600 km	8 ms	25.77 ms
LEO, regenerative payload		4 ms	12.89 ms

The latency of NB-IoT over a GEO link was studied by (Barbau et al., 2020) through an event-driven simulator reproducing the full communication process over a transparent GEO scenario. The study reports an end-to-end communication delay, measured from the first preamble to the correct reception of the data, on the order of a few seconds: starting around 3.4 seconds for small payloads and rising beyond 4.0 seconds as the payload grows, consistently several seconds above an equivalent terrestrial cell. For the delay-tolerant typical of digital agriculture, where soil, environmental, and crop-health variables evolve over minutes to hours, a latency budget of a few seconds is perfectly acceptable, and the continuous visibility of a GEO link removes the satellite-revisit gaps that affect sparse LEO constellations.

Experimental Latency Evaluation

The field measurements were carried out in São Leopoldo, Rio Grande do Sul, Brazil, over the

Inmarsat-3 geostationary satellite, a commercial system in active operation, so that the measured figures reflect the latency of a real satellite network rather than emulated or laboratory conditions. As shown in Figure 2, the remote node consisted of a Raspberry Pi connected over UART to an evaluation board (EVB) carrying a Quectel NB-IoT NTN module, deployed in a fixed position. The node transmitted a 10-byte frame, comprising the application sensor reading together with the associated protocol overhead, toward a UDP server in the cloud. These tests were intended as an initial characterization of the network, quantifying its end-to-end latency rather than optimizing performance.

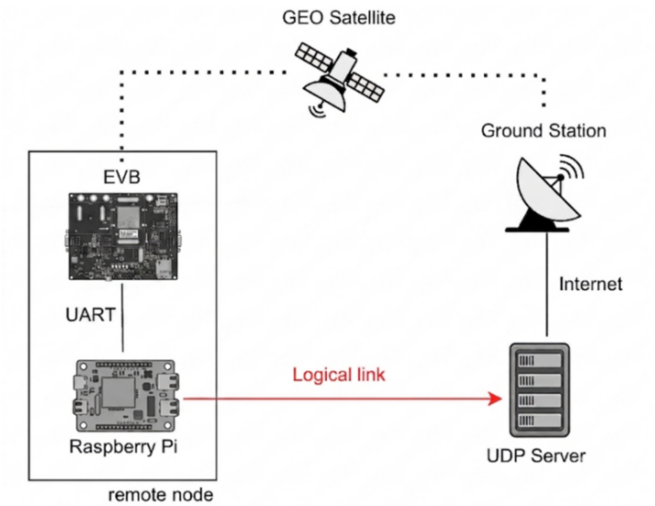

Figure 2 - System architecture and measurement path.

End-to-end latency was measured over the logical link between the remote node and the UDP server, shown in red in Figure 2 defined as the interval between the instant the node initiated the transmission and the instant the frame was received by the server. This path spans the complete chain: Raspberry Pi, EVB, satellite radio link, ground station, and terrestrial backhaul to the cloud server, so the measured value is an end-to-end aggregate in which propagation and protocol effects are combined. A total of 1000 transmissions were performed, of which 931 (93.1%) were successfully received; the latency statistics reported in Table 7 are computed over these.

Table 7. End-to-end latency over Inmarsat-3.

Metric	Value
Number of transmissions	1000
Successfully received	931 (93,1%)
Mean latency	27947.72 ms
Median latency	9100.85 ms
Minimum latency	5364.31 ms
Maximum latency	499 s
Standard deviation	72,5 s

Across the 931 received transmissions, the latency varied widely: the median was 9.1 s, whereas the mean 27.9 s was inflated by a small number of extreme outliers reaching up to 499 s. The median is therefore the representative measure of the link's typical latency, while the best case of 5.4 s already lies in the multi-second range, showing that even an error-free transmission incurs several seconds of protocol and access overhead.

The measured median latency of 9.1 s exceeds the few-seconds range (3.4 – 4 s) obtained analytically by (Barbau et al., 2020), yet it far exceeds the ≈0.5 s round-trip propagation of Table 6, showing that the delay is driven by protocol-level mechanisms rather than signal travel time. This gap is expected, since our measurement spans the full path from the device to a cloud application over a commercial satellite network in real operating conditions, whereas the simulated values cover only the satellite radio segment under idealized conditions. A latency of a few seconds is nonetheless well within the needs of digital agriculture, where the monitored variables evolve over minutes to hours.

Open Challenges and Research Directions

Despite the advantages of satellite communication for agricultural IoT, several limitations and challenges must be considered. In D2S scenarios, the satellite replaces the terrestrial gateway, eliminating the need for local infrastructure but introducing inherent link challenges such as Doppler effect, limited visibility windows, and a more restricted link budget (Susilo & Suryana, 2023). LEO satellites, while offering lower latency, move constantly relative to the Earth, resulting in short visibility windows of approximately and requiring frequent satellite handovers (Deng et al., 2024). During these short passes, packet collisions may occur when multiple field devices attempt to transmit simultaneously. GEO satellites provide continuous coverage to a specific region, but at the cost of significantly higher transmission latency due to their greater distance. Furthermore, the overall system must contend with intermittent connectivity, higher path loss in certain bands, and the need for energy-efficient protocols to maximize battery life. Satellite communications are also affected by the Doppler effect, particularly in LEO systems due to the relative velocity between the satellite and the user equipment (Machado et al., 2025).

Regarding the integration of terrestrial and NTN, several open problems remain. First, efficient handover mechanisms are required to support mobility across terrestrial, aerial, and satellite segments without excessive signaling overhead or service interruption. Second, adaptive resource allocation and routing strategies are needed to account for dynamic channel conditions, heterogeneous link capacities, propagation delays, and energy constraints. Third, orchestration frameworks must be developed to coordinate different network domains that were not originally designed to operate as a unified system. Finally, integrated TN-NTN systems require scalable architectures capable of supporting massive IoT deployments while maintaining reliability, energy efficiency, and application requirements.

Beyond direct field applications, there is also the possibility of extending the use of satellite networks as an alternative during logistics processes. In many cases, food traceability is critically important, and ensuring connectivity throughout the entire journey is essential. Devices in these scenarios must be capable of switching between terrestrial and satellite networks, so that when trucks or even ships have no terrestrial network coverage, they can switch to satellite connectivity, ensuring uninterrupted data transmission.

Conclusion

This work presented an overview of satellite communication architectures for agricultural IoT, with emphasis on LPWAN protocols, and their suitability for remote sensing applications. The main technical characteristics of these protocols were analyzed, including energy consumption and transmission latency. The integration of terrestrial and non-terrestrial networks was also examined as a strategy to combine the advantages of both domains. Open challenges remain, including efficient handover mechanisms, adaptive resource allocation, Doppler effect compensation in LEO systems, and the development of scalable integrated TN-NTN architectures. Addressing these challenges is essential to enable reliable and energy-efficient satellite connectivity for precision agriculture in areas where traditional networks are not available.

DECLARATION OF AI USE

The authors acknowledge the use of AI to assist with grammar correction and sentence structure adjustments of selected portions of the text. All AI-assisted text was reviewed and revised by the authors to ensure accuracy and clarity of meaning.

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